IGNEOUS INTRUSIVE ROCKS OF THE PEAKE AND DENISON RANGES WITHIN THE ADELAIDE GEOSYNCLINE

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Statement of Originality:

I hereby certify that this thesis does not incorporate, without acknowledgement, any material which has been previously submitted for a degree or diploma in any university, and, to the best of my knowledge and belief, it does not contain any written or published material by another person, except where due reference is made in the text.

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Fronticepiece:

Margin of a monzogabbro body of the Bungadillina suite in the Peake and Denison Ranges showing an abundant felsic dyke network. The felsic dykes increase in size and density towards the contact, but are truncated with brecciated Burra Group sediments. Monzogabbro body is dominated by coarse grained euhedral amphibole and smaller clinopyroxene. Dykes are thought to have originated by a filter-pressing mechanism where late-stage residual felsic melt is progressively squeezed out towards the margin of a ferromagnesian crystal-rich magma.

Location: Northeast of sample locality [7516] (Map E).

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ABSTRACT

The Adelaide Geosyncline is one of the best preserved examples of Late Proterozoic stratigraphy in the world. Although a relatively minor component, the plutonic and volcanic rocks within this exceptionally ancient basin reflect successive tectonic stages of the basin's history.

One of the largest and best preserved suite of plutonic rocks is found within the Peake and Denison Ranges; a series of Adelaidean inliers located approximately 1000km north of Adelaide in the South Australia. This suite of over fifty individual plutons is composed of a wide range of lithologies ranging from syenogabbros and monzogabbros to quartz syenites and quartz monzonites and their altered equivalents, which intruded Early to Middle Adelaidean sediments and *diapiric breccia*. The largest pluton measures approximately three kilometres in diameter, but most plutons measure less than one kilometre in diameter.

The material comprising this so-called "diapiric breccia" is a very important feature of the igneous intrusive rocks of the Peake and Denison Ranges as the plutons both intrude the breccia and have had their contacts altered by further breccia mobilization. The breccia is best explained by syn-depositional diapirism and deformation by Early Adelaidean evaporite beds which have been subsequently remobilized during the Cambro-Ordovician Delamerian Orogeny. The location of Early Adelaidean evaporite deposition corresponds to linear faults which controlled initial palaeo-basin development. Diapirism and Delamerian remobilization were focused along these planes of crustal weakness. Many smaller igneous intrusive bodies in the Adelaide Geosyncline occur within these diapiric bodies, and may be exhumed remnants of Willouran volcanism. Due to Delamerian remobilization, original contact relations have been displaced. However, undisturbed intrusive relations in the Peake and Denison Ranges suggest a pre-remobilization age for pluton emplacement.

Contradicting structural evidence is present, supporting both a pre-tectonic and post-tectonic timing for emplacement. There is no evidence to indicate syn-tectonic plutonism. Geochronological investigations (both Rb-Sr and U-Pb) of the intrusives of the Peake and Denison Ranges have failed to reveal the age of the plutons.

Nonetheless, the timing of emplacement may correspond to a period of Early to Middle Cambrian volcanic activity which was prevalent throughout Australia, Tasmania and Antarctica, which is expressed as a brief period of extensional tectonism. In the Adelaide Geosyncline, late Early to Middle Cambrian volcanism is represented by the Truro Volcanics, the Warburton Volcanics and those found within the Billy Creek Formation in the Arrowie Basin. The presence of dolerite dykes intruding fault lines and fold hinges (post-Delamerian magmatic activity), suggests pluton emplacement occurred over a broad period of time.

The geochemistry of the intrusives of the Peake and Denison

Ranges are best classified as a metaluminous to slightly peralkaline alkali-calcic suite. These rocks are characterized by high large ion lithophile element concentrations (with a positive Sr anomaly), low light rare earth element concentrations, and low high field strength element concentrations. The geochemistry is more similar to "I-type" granites than either those of "A-type" or "S-type" parentage. Although the intrusives of the Peake and Denison Ranges can be classified as "anorogenic", they lack the trace element enrichment of "A-type" granites. These unique chemical characteristics indicate that "pre-tectonic" intrusives may be somewhat different than either "post-tectonic" ("A-type") or "I-type" granites. Alternatively, the volume of magma for the Bungadillina suite may have been too small to retain any mantle-related chemical inhomogeneities, and was readily re-eqilibrated to a typical alkali basaltic chemical signature.

Mineralogical and geochemical evidence of the intrusives of the Peake and Denison Ranges indicates that initial crystallization took place in the upper mantle or near-mantle. It is in these conditions where clinopyroxene and magnetite crystallized from an alkali basaltic magma with a high degree of oxygen fugacity. Early formed olivine and most of the chromite fractionated from the melt at this stage. The magma was then emplaced into middle crustal levels corresponding to the change from ductile to brittle crustal rheology (approximately at a depth of 24 km). The influx of water into the ponded magma encouraged the crystallization of hornblende. At this level, or nearer to surface, the crystal mush separated, forming cumulate-rich and cumulate-depleted phases.

Clinopyroxene and then amphibole fractionation largely controlled the melt composition. The inability for amphibole to be re-incorporated into the melt prevented the formation of a strongly silica undersaturated and felsic (feldspathoidal) phase. Biotite was the last ferromagnesian mineral phase to form, crystallizing *in situ* by influxing of surrounding groundwater into the relatively anhydrous magma.

There are few contact metamorphic aureoles, concentrated at the stratigraphic base of zoned plutons. Marginal plutonic phases are characterized by sodic metasomatism and the formation of albitites, without the chemical characteristics of *fenites*. This style of alteration has been attributed to syn-emplacement interaction of a hot, relatively anhydrous magma with circulating meteoric water at sub-surface levels, causing localized albitization and within the pluton and inhibiting the development of a contact metamorphic aureole. The thickness of the strata above the pluton level has been estimated to be 7km (Ambrose *et al.*, 1989). However, without control on the age of emplacement, it is difficult to firmly adhere to a specific depth of final emplacement. The style of alteration and small pluton sizes indicate a shallower depth of emplacement.

A period of Early to Middle Cambrian magmatism was initiated in response to reactivated extensional tectonism, exemplified by the formation of the Kanmantoo Trough. The intrusives of the Peake and Denison Ranges may have formed during this pre-Delamerian regime, which resulted in the intrusion of mantle-derived melt along deep-seated crustal fault (Karari Fault Zone). The chemical similarities between the intrusives of the Peake and Denison Ranges and concomitant Middle Cambrian volcanics also indicate that the intrusives of the Peake and Denison Ranges may represent the exhumed roots of a major Cambrian volcanic centre, occurring immediately prior to the onset of the Delamerian Orogeny.

The intrusives of the Peake and Denison Ranges form a basis to compare and contrast the variety of intrusive material throughout the Adelaide Geosyncline. Altered leucocratic intrusive bodies in the Willouran Ranges and in the Arkaroola region are closely associated with Callanna Group volcanics. Similar chemistries indicate that a volatile-enriched felsic differentiate phase, represented by these altered bodies, may have evolved immediately from what is largely continental tholeiitic flood basalts, occurring in response to initial rifting (Willouran time) of the Adelaide Geosyncline.

In contrast, the Anabama and Bendigo Granites are petrographically and geochemically similar to the syn-tectonic (Delamerian) granites of the Mt. Lofty Ranges. These are "S-" and "I-type" granites and granodiorites formed in response to elevated pressures and temperatures, and with the possible assistance from mantle-derived magma, in the compressional at the height of the Delamerian Orogeny. Mantle-induced magmatism continued into post-Delamerian settings with the intrusion of "A-type" (post-tectonic) granites along the margins of the zone of greatest Delamerian metamorphism.

Deep crustal faults which initiated rifting and volcanism in the Adelaide Geosyncline continued to influence magmatic activity throughout its development. Even after Delamerian tectonism, reactivation of these faults was in part reponsible for Jurassic dolerites and kimberlite intrusions, and more recent seismic activity in South Australia.

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Methodology and Scope of Research:

It was the original intention of this thesis to compare and contrast the varied and vast array of intrusive igneous rock of the Adelaide Geosyncline and those intruding Kanmantoo Group metasediments in the southern Adelaide Fold Belt. As many presently regarded bodies of this nature were emplaced and crystallized during the Cambro-Ordovician Delamerian Orogeny, there appeared to be little need to chronologically separate these intrusives. The Delamerian Orogeny provided a convenient common denominator. However, upon examination of the intrusives of the Peake and Denison Ranges and the Willouran Ranges in the far north of South Australia, by invitation from the Regional Geology Division of the Department of Mines and Energy of South Australia, the hypothesis of a common age for emplacement was seriously reconsidered. Substantially more research into the intrusive rocks of these regions was required than was originally anticipated. Not only were the intrusives themselves of a different variety from the well-known examples in the southern reaches of the Adelaide Geosyncline, but the stratigraphic and tectonic environment of intrusions, as well as the style of alteration, were unique. Thus the direction of research was re-organized and integrated to accommodate these variables.

This inquiry concentrates upon the intrusives of the Peake and Denison Ranges and to a lesser extent those of the Willouran Ranges. From this foundation, it is then possible to competently compare and contrast other documented igneous bodies within the Adelaide Geosyncline, including those of the Kanmantoo Trough. It should be noted that detailed examinations of the intrusives of the Kanmantoo Trough are currently being undertaken by postgraduate researchers at the University of Adelaide.

Perplexing problems associated with the study of the intrusives of the Peake and Denison Ranges included: a) age and nature of emplacement; b) style of alteration; c) possible association with diapiric breccia; d) effects of the Delamerian Orogeny, and; e) tectonic environment.

Comparative work has been focused on the igneous occurrences, both plutonic and volcanic, within the Adelaide Geosyncline. In some cases, sufficient data is available (*e.g.* Anabama granite and intrusives of the Arkaroola region), but sketchy in others (*e.g.* Mt. Painter region). In the Willouran Ranges, where very little data was available, the author has undertaken limited mapping, petrography and geochemistry.

To aid in solving these problems, detailed mapping by ground traverses was accomplished utilizing 1:20,000 scale B&W air photographs from the South Australia Department of Mines and Energy, and 1:10,000 scale colour air photographs from which the enclosed maps are based. Sampling of the intrusives of the Peake and Denison and Willouran Ranges was conducted, followed by extensive petrographical (greater than 300 thin sections examined and subsequent electron microprobe work) and whole-rock geochemical (12 major oxides, 15 trace elements, Rb-Sr, U-Pb and C-O isotopes) analyses. This work formed a comprehensive database for classification and identification of the igneous suite, application of petrogenetic constraints, and comparison with other known occurrences.

As this thesis is largely concentrated on the intrusive bodies, structural mapping of the Peake and Denison Ranges had to be limited. Many of the smaller plutons intrude zones of intense structural complexities due to (a) localized diapirism, (b) igneous intrusion, (c) Delamerian tectonism and (d) diapiric breccia remobilization. The differeniation of these contrasting modes of deformation was discovered to require intense detailed structural mapping, moreso than could be accomplished during the course of fieldwork for this volume. This thesis attempts to deal with these structural facets on a broader scale than the structures warrant, and in keeping with the main subject matter; the plutons themselves.

The conclusions of this work are intended to thoroughly document igneous activity in the Peake and Denison Ranges and provide a more rigorous framework for the evolution of the Adelaide Geosyncline.

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Terminology, Nomenclature and Classification:

The term *Adelaide Geosyncline* refers to the paleo-basin into which were deposited sediments of Adelaidean age in South Austalia, subsequently folded during the Cambro-Ordovician Delamerian Orogeny. It is within the Adelaidean sediments of the Peake and Denison Ranges that occur a suite of plutonic rocks. Ambrose *et al.* (1981) nominated this suite as the *Bungadillina Monzonite*. However, as has been observed since Brown (1884; *cf. ch.*3 precursor), there are many different intrusive lithologies which can cause confusion in using the umberella term "Monzonite". Thus for the purposes of this dissertation, the term has been extirpated in favour of the *Bungadillina suite*, or more simply as the *intrusives of the Peake and Denison Ranges*.

The terminology for classification of rocks as found in the literature quoted in this thesis has been retained to avoid incorrect translation. Qualitative petrographic comparisons of igneous rocks by different authors based on name alone may be misleading. Thus whenever possible, the quanitative analyses (*e.g.* geochemical characteristics) were relied upon for comparisons.

Presently, the most popular and widely used classification of igneous plutonic rocks is Streckeisen's (1976) scheme based on modal percentage of major felsic mineral constituents: quartz, alkali feldspar and plagioclase. However, the igneous lithologies discussed within this text have been ubiquitously altered to varying degrees. If metasomatism involves recrystallization of the felsic mineralogy, such as albitization, then misleading classification would ensue. Some authors prefer to use the prefix *meta* in describing altered igneous rocks, but then confusion arises between structurally deformed rocks in metamorphosed terrain and those that have been simply metasomatized.

For the purposes of this thesis, Streckeisen's (1976) classification scheme is followed as closely as possible but with the "plagioclase" apex including albite (An_{00-05}). Rocks with albite as the sole feldspar accounting for greater than 90% of the rock are referred to as *albitite* and rocks with greater than 35% mafic constituents are described with the suffix *gabbro* (i.e. monzo*gabbro*, syeno*gabbro* of Sorensen, (1974)).

For geochronology, the Rb-Sr systematic decay constant lambda is equal to 1.42.

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Chapter One: Synopsis of the Adelaide Geosyncline.

> "The term *Adelaide Geosyncline*, used in the broad sense of a complex basin of deposition in which there was a thick accumulation of sediment that later became folded metamorphosed, intruded and uplifted, has long been accepted by the Geological Survey...
> ...terms such as *Adelaide Rift* and *Adelaide Aulacogen* are not considered applicable to the whole basin throughout its continued evolution.
>
> Preiss (1987) defining the Adelaide Geosyncline (p. 14-15).

1.1 Introduction.

It is intended in this chapter to introduce the uninitiated reader to the geological setting for the igneous intrusive rocks of the Adelaide Geosyncline; identifying major stratigraphic units with emphasis on the volcanic constituents and their respective stratigraphic correlations. These volcanics are compared and contrasted to the intrusive lithologies in subsequent chapters. Diapiric breccia, a prominent feature with respect to the intrusives of the Peake and Denison Ranges, is discussed in greater detail. For a more complete account of the geology of the Adelaide Geosyncline or the surrounding crystalline basement, the reader is encouraged to confer with Preiss (1987), Fanning *et al.* (1988) and Webb *et al.* (1986).

The term *Adelaide Geosyncline*, coined by David & Brown (1950), refers to an epicratonic basin containing a thick succession of Late Proterozoic to Cambrian sediments within south-central Australia. This sequence of sediments, which includes the Precambrian stratigraphic type section of the *Adelaidean System* (Mawson & Sprigg, 1950), were folded and metamorphosed during the Cambro-Ordovician *Delamerian Orogeny*, and later uplifted to form an enormous mobile belt encompassing more than 102,000 square kilometers, or approximately 13% of the State of South Austalia (Thomson, 1969). The Adelaide Geosyncline remains a prominent and important crustal feature of the Australian continent, and one of the best preserved and exposed examples of late Proterozoic and Cambrian stratigraphy in the world.

Delamerian folding of the Adelaide Geosyncline (and associated Cambrian Kanmantoo Group sediments) has resulted in the formation of a sigmoidal fold belt trending north-east from it's southern-most exposure in Kangaroo Island through the Mount Lofty Ranges towards Broken Hill in New South Wales. From the southern Flinders Ranges, the Adelaide Geosyncline extends north then northwest encompassing the Willouran Ranges and the Peake and Denison Ranges (Figs. 1.1 & 1.2). These series of ranges, the result of Cenozoic uplifting and fault-block tectonics, seldom exceeds 600 metres in elevation, but in conjunction with South Australia's semi-arid climate, provides sufficient topographic relief to adequately expose most sections of the Adelaide Geosyncline.

The Adelaide Geosyncline is bounded on its northeastern margin by Middle Proterozoic crystalline basement, the *Curnamona Cratonic Nucleus*, which incorporates the Willyama and Mount Painter basement Inliers, and is bounded to the west by the Archaean to Middle Proterozoic *Gawler Craton*. A major north-south lineament, the *Torrens Hinge Zone* (Thomson, 1970), is interpreted as a complex fault structure defining the western limit of Cambro-Ordovician Delamerian Orogenic activity and the eastern margin of the Gawler Craton. It also defines the transition from the thick folded strata of the Adelaide Geosyncline to the thinner near-horizontal Adelaidean sequence of the *Stuart Shelf*, which overlies the stable Gawler Craton.

The northern and southern extent of the Adelaide Geosyncline is uncertain. Rutland *et al.* (1981) and Preiss & Forbes (1981) postulated that during the Late Proterozoic, the Adelaide Geosyncline may have extended northward from the Peake and Denison Ranges to connect with the east-west trending sediments of the Amadeus Basin, Georgina Basin or Officer Basin in central Australia.

To the south, a shallow subsurface extension of folded and metamorphosed Cambrian sediments of the Kanmantoo Group, the *Padthaway Ridge*, runs roughly parallel to the Coorong from Murray Bridge to Naracoorte (Rochow, 1971). Numerous authors (Griffiths, 1974; Veevers & McElhinney, 1976; Grindley & Davey, 1982; Stump *et al.*, 1986; Foden *et al.*, 1989) have used this extension, in part, to hypothesize on the the continuation of the Delamerian fold belt from the Padthaway Ridge to the Glenelg River Complex in western Victoria, and perhaps further into orogenic belts in Antarctica.

Mawson & Sprigg (1950) subdivided the stratigraphy of the Adelaide System utilizing type sections described from the vicinity of Adelaide. These include the oldest sequence, the *Torrensian*, followed by the *Sturtian* which contain glaciogenic strata, and the youngest succession; the *Marinoan*. Sprigg (1952) later used the term *Willouran* to describe pre-Torrensian strata from the Willouran and Flinders Ranges. From recent reappraisals of radiometric data, the base of the Willouran has been estimated to be 830+/-50 Ma, the top of the Sturtian estimated to be 713+/-38 Ma, and the top of the Marinoan estimated to be 593+/-32 Ma (Jenkins, 1989). There are presently no Torrensian dates.

1.2 Pre-Adelaidean Crystalline Basement.

1.2.1 Introduction.

Rocks of Archaean to Middle Proterozoic age form the basement to the Adelaide Geosyncline. These rocks are best described as metamorphic complexes with intruded post-tectonic (Middle Proterozoic) granites. They comprise the Gawler Craton to the west of the Geosyncline, and the Curnamona Cratonic Nucleus to the east. Fanning *et al.* (1988) believe that the Curnamona Craton is an extension of the Gawler Craton, and that the Adelaide Geosyncline is probably underlain by similar crust. Within the Geosyncline itself occur inliers of similar crystalline basement. These include the Houghton, Yankalilla, Myponga and Hahndorf Inliers of the southern Mount Lofty Ranges (*cf. ch.* 1.2.4).

In the following discussion, the crystalline basements of the Adelaide Geosyncline and contiguous areas are outlined. This basement, directly or indirectly, was involved with magma genesis for many Adelaide Geosyncline intrusives, such as providing possible melt source or melt contaminant, and in determining means of transport and final emplacement.

1.2.2 The Gawler Craton.

The Gawler Craton has remained a large stable platform for at least 1400 Ma (Webb *et al.*, 1986). The earliest recorded orogenic activity in the Gawler Craton, the Sleafordian Orogeny (*ca.* 2300-2500 Ma) instigated the formation of basement gneisses and granites (Cooper *et al.*, 1976; Webb & Thomson, 1977). An orogenic hiatus (1960-1840 Ma; Fanning *et al.*, 1988) allowed for the deposition of sediments of the Hutchison Group which were folded and metamorphosed along with the

Sleaford basement during the 1820 Ma Kimban Orogeny (Parker *et al.*, 1981). Abundant igneous activity accompanied metamorphism (1790-1740 Ma; Fanning *et al.*, 1988). The cessation of orogenic activity was followed by the voluminous eruption of the Gawler Range Volcanics at about 1592 Ma (Giles, 1977 & 1980; Fanning *et al.*, 1988), and accompanied by continental sedimentation (Daly, 1984; Flint & Parker, 1982). The last major phase of felsic magmatism is represented by the intrusion of anorogenic granites such as the Charleston Granite (*ca.* 1576 Ma; Fanning *et al.*, 1988), the Hiltaba Suite (*ca.* 1514 Ma; Cooper *et al.*, 1986), and granites of Spilsby Island (*ca.* 1447-1576 Ma; Webb *et al.*, 1986). Dates acquired from rocks immediately adjacent the Adelaide Geosyncline may have been partially reset due to nearby, Early Adelaidean continental volcanism (Webb *et al.*, 1986).

1.2.3 Curnamona Cratonic Nucleus.

Unlike the Sleaford Complex of the Gawler Craton, there is no known Archaean basement in the Olary and Broken Hill regions which comprise the crystalline basement to the east of the Adelaide Geosyncline (Rutland *et al.*, 1981). Stevens (1986) envisaged the formation of a continental-type crust synchronous with that of the Sleaford Complex (2300-2100 Ma), upon which were deposited sediments and volcanics of the Early to Middle Proterozoic (1820 Ma) Willyama Supergroup (Pidgeon, 1967; Shaw, 1968). Intense metamorphism and the formation of anatectic granites resulted from the 1660 Ma Olarian Orogeny (Glen *et al.*, 1977; Reynolds, 1971; Gulson, 1984). Gawler Range Volcanic equivalents were found to have the same date as the Gawler Range Volcanics (*ca.* 1599 Ma), indicating once contiguous occurrences (Fanning *et al.*, 1988). The intrusion of granites and pegmatites at 1490 Ma completed cratonization of the Willyama domain. Harrison & McDougall (1981), however, recorded a 561 Ma (K-Ar) date for the emplacement of alkaline ultramafic plugs and dykes in the craton. The subsequent Cambro-Ordovician Delamerian Orogeny was responsible for low grade metamorphism, deformation and partial recrystallization of these alkaline intrusives (Etheridge & Cooper, 1981), and possibly resulted in the intrusion of small dolerite bodies.

The crystalline basement of the Mount Painter Inlier, the *Mount Painter Complex* (Sprigg, 1945), consists predominantly of metasediments with possible interbedded acid volcanics, which have been intruded by two suites of granites; the Middle Proterozoic "Older Granite Suite" and the Cambro-Ordovician (Delamerian) "Younger Granite Suite" of Coates & Blissett (1971). The less metamorphosed sedimentary sequence of the Mount Painter Complex is similar to the metasediments of the Willyama Complex, while the 1500-1645 Ma dates for the "Older Granite Suite" are comparable to the anatectic intrusives of the Olarian Orogeny in the Broken Hill and Olary Blocks.

1.2.4 Inliers of the Mount Lofty Ranges.

The inliers of the Mount Lofty Ranges extend in a linear manner from Williamstown, thirty kilometres northeast of Adelaide, to Yankalilla on the Fleurieu Peninsula. They are collectively referred to as the *Barossa Complex* (Benson, 1909). The largest single inlier, the *Houghton Inlier*, is composed of gneisses, schists and mylonites (Spry, 1951; Talbot, 1963). The contrast in metamorphic grade with the surrounding lower greenschist facies Torrensian sediments, which unconformably overly the Houghton Inlier with a basal conglomerate, indicates that it is pre-Adelaidean basement. The "Houghton diorite", occurring within the Houghton Inlier, has been variously identified as a Precambrian intrusive (Benson, 1909), a granulite derived from metamorphism and metasomatism of original calcic sediments (Spry, 1951) and a feldspar gneiss (Talbot, 1963). Recent U-Pb dating indicated that this rock is a metamorphosed sediment (Preiss, 1987).

The Warren Inlier, located five kilometres east of the Houghton Inlier and covering an area of 6.5 km^2, consists of schists of amphibolite facies. The Warren Inlier has abundant intrusive pegmatitic bodies. The contact with the metasedimentary Adelaidean sequence is a sharp angular unconformity with some basal conglomerate (Mills, 1973).

1.2.5 The Peake and Denison Ranges.

Crystalline basement in the Peake and Denison Ranges was first mapped by Reyner (1955). It was later named the *Peake Metamorphics* by Thomson (1969) and is composed of Early Proterozoic metasediments and volcanics (Tidnamurkuna Volcanics *ca.* 1806+/-21 Ma; Fanning *et al.*, 1988) which have been intruded by the Middle Proterozic *Wirriecurrie Granite* (*ca.* 1648+/-21 Ma; Ambrose *et al.*, 1981). Thomson (1970) combined the "Denison Block" with the Willyama and Mount Painter Blocks, forming a major crystalline basement feature presumably interconnected via the *Muloorinna gravity ridge*. Webb *et al.* (1986) tentatively correlated the Peake Metamorphics with the volcano-sedimentary sequence of the Gawler Craton (later confirmed by Fanning *et al.*, 1988).

1.2.6 The Flinders and Willouran Ranges.

The only outcropping of crystalline basement material in the Flinders Ranges occurs within diapiric structures (*cf. ch.* 1.5), a summary of which can be found in Mount (1975). The most thoroughly studied example is the granitic rock exposed in the Blinman Diapir. Coates (1964) claimed that this foliated granite resembles the "Older Granite Suite" of the Mount Painter Block. White (1971) suggested that such material is an *in situ* "basement high"; a similar claim to that of Murrell (1977) for altered igneous bodies in the Willouran Ranges. However, the most widely accepted theory (Webb, 1961; Coates, 1964; Daily & Forbes, 1969) is that it represents an exhumed crystalline basement raft, transported into position within a rising evaporitic diapir. This basement occurrence also indicates that Early to Middle Proterozoic crust underlies the entire Adelaide Geosyncline.

1.3 Adelaidean and Cambrian Stratigraphy.

The Adelaide Geosyncline provides the Australian stratotype for the Late Proterozoic *Adelaidean Period*. After Mawson & Sprigg (1950), Thomson *et al.* (1964) developed a more detailed system of subdivision of the Adelaide Geosyncline, and refined by Preiss (1983) (Fig. 1.3). The *Callanna Group* comprises the basal *Willouran Series*, the Torrensian and Early Sturtian includes the *Burra Group*, and the *Umberatana Group* consists of Sturtian and Early Marinoan glacials and interglacial sediments. The *Wilpena Group* refers to Marinoan post-glacials (Dalgarno & Johnston, 1964). The Callanna and Burra Groups have been combined into the *Warrina Supergroup*, and the Umberatana and Wilpena Groups have been similarily combined into the *Heysen*

Supergroup. These two Supergroups are separated by a regional unconformity. The *Moralana Supergroup* incorporates the sediments of Cambrian age comprising the Kanmantoo Group of the Mt. Lofty Ranges, and the Hawker and Lake Frome Groups in the Flinders Ranges (Preiss, 1982; Fig. 1.3).

1.3.1 Callanna Group.

Mawson (1927) named the thick sequence of quartzites and slates of the Willouran Ranges the *Willouran Series*, which Sprigg (1952) later defined as occurring stratigraphically below the Torrensian. The presence of abundant evaporite casts and interbedded volcanics are a characteristic feature of this sequence. Thomson *et al.* (1964) named this basal sequence of the Adelaide Geosyncline the *Callanna Beds*. This nomenclature was refined by Forbes *et al.* (1981) as the *Callanna Group*. There is no known outcrop of the Callanna Group in the Mount Lofty Ranges.

In the Mount Painter region, the Arkaroola Subgroup consists of 1.2 km of a basal pebbly quartzite (*Paralana Quartzite*), minor siltstone, talus and carbonate (*Wywyana Fm.*) which was deposited in a fluviatile or shallow marine environment. In the Peake and Denison Ranges, the Arkaroola Subgroup is represented by 100m of basal conglomerate (*Younghusband Conglomerate*; Thomson, 1966) and carbonate (*Coominaree Dolomite*; Ambrose et al., 1981). In the Willouran Ranges, the Arkaroola Subgroup is composed of the *Black Knob Marble*. The lower Callanna Group sediments in the Willouran and Peake and Denison Ranges are disrupted by diapiric activity and invaribly contain halite pseudomorphs (Preiss, 1985).

The top of the Arkaroola Subgroup is characterized by widespread basalts and minor acid volcanics; *Noranda Volcanics* in the Willouran Ranges, *Cadlareena Volcanics* in the Peake and Denison Ranges, *Wilangee Volcanics* in the Barrier Ranges, the *Beda Volcanics* on the Stuart Shelf, the volcanics at Depot Creek, the *Boucaut Volcanics* south of the Anabama Granite and the *Wooltana Volcanics* in the Mount Painter region (Preiss, 1987; Forbes *et al.*, 1981). Linear geophysical anomalies on the Stuart Shelf followed by drilling have revealed a dolerite dyke swarm, the *Gairdner Dyke Swarm* (Mason *et al.*, 1978; Goode, 1970), intruding the pre-Adelaidean *Pandurra Formation* and extending to the Musgrave Ranges. Similar abundant dolerite dyking within the underlying Wywyana and Paralana Formations are considered to be a feeder system to the Wooltana Volcanics; a situation analogous to the Gairdner Dyke Swarm and the Beda Volcanics on the Stuart Shelf (Hilyard, 1986; Preiss, 1987). Comparative geochemistry (*cf.* Table 1.3.1) of the Wooltana and Beda Volcanics reaffirms their consanguinity (Woodget, 1987; Hilyard, 1986), although Woodget (1987) suggested that the dykes are from a more evolved source which intruded further away from the rift-zone and are not simply the feeder system to the more primitive Beda Volcanics. The stratigraphic positions of both the bimodal Boucaut Volcanics and the volcanics at Depot Creek remain uncertain (Preiss, 1987). Chemical similarities supports the consanguinity of the Depot Creek volcanics within the Callanna Group (Woodget, 1987), but the strongly bimodal Boucaut volcanics cannot be so readily aligned, and may be Cambrian in age.

Igneous activity persisted into the upper sequence of the Callanna (the *Curdimurka Subgroup*) with the conformable deposition of the 15-60m thick *Rook Tuff* in the Willouran Ranges. The southern-most exposure of Curdimurka Subgroup strata (in the *Spalding Inlier*, 150 km north of Adelaide) also contains minor basalt at the base of the sequence, referred to as the *River Broughton Beds* (Preiss, 1974). The intrusion(?) of dolerites in the Worumba Anticline may be a contemporaneous event (Preiss, 1985).

The age of the base of Adelaidean sedimentation remains a persistent problem due to the paucity of suitable rocks for geochronology and the questionable overprinting effects of the Delamerian Orogeny. Dating of the Beda Volcanics has yielded an age of 1076+/-34 Ma with an initial $^{87}Rb/^{86}Sr$ ratio of 0.7059+/-0.0007, suggesting a minimum age for the beginning of the Adelaide Geosyncline (Webb *et al.*, 1983). Preliminary results for Rb/Sr geochronology of the Gairdner Dyke Swarm record a similar age (1050-1100 Ma) with a lower initial ratio (Preiss, 1987). Unpublished data suggests a younger age for the Gairdner Dyke swarm (975 Ma, initial $^{87}Sr/^{86}Sr$ ratio = 0.7034; J.D. Foden, *pers. comm.*).

Compston *et al.* (1966) aquired a much younger isochron for the Wooltana Volcanics of 830+/-50 Ma with an initial $^{87}Rb/^{86}Sr$ ratio of 0.711. U-Pb radiometric dating of the overlying Rook Tuff in the Willouran Ranges, has given an accurate age of 802 Ma (Fanning *et al.*, 1986). Although the age of complete cratonization of the Gawler Craton (and probable basement to the Adelaide Geosyncline) is well defined at about 1450 Ma (Fanning *et al.*, 1988), the variety of ages recorded of 800 Ma to 1200 Ma leaves a precise date for the base of the Adelaidean System unresolved.

The early Callanna Group sediments, consisting of immature clastics and stromatolitic carbonates, were deposited in shallow, elongate and restricted basins under evaporitic conditions. Although no known evaporite sequence is preserved in the Callanna Group, the abundance of evaporite pseudomorphs attests to their previous existence.

Fissure eruptions of voluminous, subaerial and largely mantle-derived continental tholeiitic flood basalts occurred throughout much of the Adelaide Geosyncline, marking the end of deposition of the Arkaroola Subgroup. If volcanism occurred after evaporite deposition, they may have effectively provided a semi-impermiable cap for the evaporite sequence, preventing immediate dissolution into the deepening waters of the palaeo-basin(s). Massive subsidence occurred immediately after the cessation of volcanism, initiating widespread deposition of the clastics and carbonates which formed the overlying Curdimurka Subgroup (Hilyard, 1986).

1.3.2 The Burra Group.

The *Burra Group* refers to the sequence of sediments in the Adelaide Geosyncline that are of Torrensian to Early Sturtian in age. In the Mount Lofty Ranges and the Arkaroola region, the Burra Group rests unconformably on Middle Proterozoic basement. The Burra Group - Callanna Group contact is complicated by diapiric disturbances in the Peake and Denison Ranges (*Murrana Beds*) and in the Worumba Anticline (*Wirreanda Dolomite Beds*). In the Willouran Ranges, structural complications prevent an accurate recording of the nature of the Callanna Group - Burra Group contact. In the Spalding Inlier, however, the *River Broughton Beds* of the Callanna Group pass conformably into the basal Burra Group *Rhynie Sandstone* (Preiss, 1985). The basal sequences of the Burra Group in the mid-north of the Flinders Ranges comprise the *Emeroo Subgroup* in which occurs a 100m thick, apparently conformable amygdaloidal basalt. Emeroo Subgroup volcanics have also been reported in drill core; the *Port Pirie Volcanics* (Woodget, 1987; *cf.* Table 1.3.2).

In comparison with the Callanna Group, the more spatially extensive Burra Group features cyclic and repetitive lithologies of sandstone, siltstone, shale and carbonate, notably lacking in any evidence of evaporites. Deposition in cohesive basins of the largely clastic basal sequence (Uppill, 1980) was followed by the deposition of thick (up to 4000m), extensive carbonates and black shale (*Skillogalee Dolomite*) (Wilson, 1952; Murrell, 1977). Deposition of shale featured in the southern and deeper part of the Adelaide Geosyncline (*i.e.* the *Woolshed Flat Shale*). Up to 3600m of siltstones and quartzites dominate the upper section of the Burra Group, the *Belair Subgroup*, which is separated from the overlying Sturtian to Early Marinoan *Umberatana Group* by a regional disconformity (Coats, 1964) caused by widespread faulting.

1.3.3 Umberatana Group.

The Umberatana Group is characterized by abundant glaciogene sedimentation into fault controlled basins. The Umberatana Group (and overlying Wilpena Group) are thickly developed within the Adelaide Geosyncline and transgressed periodically onto the Stuart Shelf. The regional unconformity, separating the Burra and Umberatana Groups, has been considered analogous to the breakup unconformity between rift and post-rift sequences in modern passive continental margins (Preiss, 1983).

In the Peake and Denison Ranges, the Umberatana Group is restricted to the core of a syncline (Box Creek Syncline) and as a single large raft(?) in diapiric breccia at the southern end of the Margaret Inlier (Ambrose *et al.*, 1981). In the *Nackara Arc* (*cf.* Fig. 1.2), the Umberatana Group is host to the largest pluton of the Adelaide Geosyncline; the *Anabama Granite*, and its smaller associate; the *Bendigo Granite* (*cf. ch.* 2.2.2).

The *Wantapella Volcanics* are tholeiitic flood basalts (Table 1.3.3) up to 290m thick found in the northwestern region of South Australia in the Officer Basin, covering an area encompassing over 1000 square kilometres. Although not directly involved with the Adelaide Geosyncline, they are considered to be Umberatana Group equivalents (Preiss, 1987).

1.3.4 Wilpena Group.

A post-glacial transgression marks the conformable basal boundary of the Late Marinoan *Wilpena Group* (Dalgarno & Johnston, 1964). Two major transgressive - regressive marine cycles deposited in excess of 6km of predominantly siliciclastics with minor carbonates in shelf and basin environments. Marinoan sedimentation ceased with a major regression that eroded thick sequences in some areas, creating a major disconformity (Haines, 1987).

1.3.5 Moralana Supergroup.

The term *Moralana Supergroup* was introduced by Preiss (1982) to describe the sequence of Cambrian sediments in the Flinders and Mount Lofty Ranges which overlie Late Proterozoic strata by a regional disconformity (Daily, 1956). The contact between the Proterozoic and

Cambrian sediments in the Mount Lofty Ranges has been reported by Daily *et al.* (1976) to be irregular with channel structures. Immediately southeast of the Adelaide Geosyncline, a quickly deepening Cambrian trough (*Kanmantoo Trough*) provided for the deposition of an immense thickness of (*Kanmantoo Group*) sediments, dominated by flysch deposits, and tectonically thickened with assistance from Palaeozoic (?Delamerian) thrust faulting (Jenkins, 1986).

In the Flinders Ranges, the Early Cambrian *Hawker Group* is dominated by thick carbonate sequences, within which occur minor local tuffaceous acid volcanics and thicker basaltic sequences. Volcanics include basalts and trachytic basalts of the *Truro Volcanics* in the Mt. Lofty Ranges, and those interbedded in the Early to Middle Cambrian *Billy Creek* and *Wilkawillinna Formations* (Daily, 1956 & 1976) of the Arrowie Basin in the central Flinders Ranges. The latter of which has been dated (U-Pb) at 532+/-12 Ma (Fanning, 1987). The tuffs and tuffaceous sediments in the Arrowie Basin are composed of shards of quartz, feldspar and altered mafics reflecting rhyodacite or rarely dacitic origins (Moore, 1979). Moore (1979) suggested that volcanism along the "Mt. Wright Volcanic Arc", located 120km northeast of Broken Hill and extending northward to Mt. Arrowsmith (Scheibner, 1972), was responsible for the pyroclastics of the Billy Creek Formation. The Early Cambrian *Truro Volcanics*, with the type section exposed 11km north of Truro, are composed of over 490m of interbedded andesite, basalt and volcanic breccia (Forbes *et al.*, 1972). The stratigraphically equivalent *Mooracoochie Volcanics*, comprising some 960m of tuffs, trachyte, rhyolite and obsidian of Early Cambrian age, were deposited in the Cambro-Ordovician Warburton Basin in the northeast of South Australia (Gatehouse, 1983). A synopsis of the geochemistries for these volcanics is presented in table 1.3.5. Such widespread Early to Middle Cambrian volcanism has been well documented throughout Gondwanaland including New Zealand, Australia and Antarctica (Shergold *et al.*, 1985; Varne & Foden, 1987).

1.4 Structural Evolution of the Adelaide Geosyncline.

1.4.1 Introduction.

The two most critical events in the history of the Adelaide Geosyncline are the Late Proterozoic continental rifting that initiated the basin formation, and the folding and metamorphism of the sedimentary pile during the Cambro-Ordovician Delamerian Orogeny.

Howchin (1922) noted that the thick accumulation of ancient sediments in the Mount Lofty Ranges was the result of "... the great South Australian rift valley." Such a "rift valley" envisages a simple trough or linear basin into which sediments were deposited. Kay (1947) envisaged the Adelaide Geosyncline to be a miogeosyncline. Sprigg (1952) expanded the concept incorporating sediment deposition on a passive continental margin. The detrital provenance was from the uplifted western crystalline basement of the Gawler Craton accompanied by complementary uplift and erosion of the eastern crystalline basement represented by the Willyama block.

Coats (1965), Dalgarno & Johnson (1968) and Thomson (1966) have shown that sediment deposition was in part controlled by localized vertical basement block tectonics. The importance of syn-depositional graben faulting in facies variations was indicated by Stewart & Mount (1972). Thomson (1970) and Stewart *et al.* (1973) noted that this fault pattern belongs to a present zone of intense seismic activity, and suggested that these faults have had a long-standing and continuing influence of the geology of the region.

1.4.2 Pre-Delamerian Tectonism.

Prior to the cessation of sedimentation at the onset of the Cambro-Ordovician Delamerian Orogeny, the Adelaide Geosyncline was undergoing almost continuous basin adjustment by means of block faulting. Preiss (1983) recognized that

> "...on two occasions epeirogenic movements caused sedimentation to cease entirely, and when re-established, sedimentation reflected a new palaeogeography and tectonic setting".

The structural changes in the Adelaide Geosyncline coincided with the broad downwarping of the crust in response to extended rifting. Sedimentation styles reflected tectonic changes in the basin. For example, the evidently evaporitic basal Callanna Group and associated volcanics which formed in the early rifted basin, were replaced by deeper, open water lacustrine Burra Group clastics as the basin expanded and deepened (Uppill, 1980).

An erosional unconformity between the Burra and Umberatana Groups indicates a period of tectonic activity most prominent in the Central Flinders Ranges where the strata was tilted, faulted and modified by diapirism (Preiss, 1983). Progressive tectonic subsidence of the Geosyncline allowed for continued Umberatana Group sedimentation onlapping onto the Stuart Shelf and thickening towards the eastern margin. Preiss (1983) suggested that the transition of the Adelaide Geosyncline from a rift environment to a passive continental margin was marked by an unconformity between the Warrina and Heysen Supergroups.

Thomson (1969) reported minor volcanics in Umberatana sediments in the northeastern Mount Lofty Ranges. These were attributed to minor tectonism (*Duttonian Folding*) which resulted in a brief period of widespread uplift, forming an unconformity between Precambrian and Cambrian strata. This was soon followed by the *Waitpinga Subsidence* which saw the rapid fault-controlled subsidence of the south and southeastern margin of the Mount Lofty Ranges, creating the Kanmantoo Trough. Cessation of sedimentation in the Adelaide Geosyncline coincided with the Cambro-Ordovician *Delamerian Orogeny*.

1.4.3 The Delamerian Orogeny.

The foremost event that was responsible for the regional folding and metamorphism of the Adelaide Geosyncline and Kanmantoo Trough sediments was the Cambro-Ordovician Delamerian Orogeny. The age of this Orogeny has been recorded by radiometric dating of both the metamorphosed sediments and syn-tectonic granites by many authors (*e.g.* Milnes *et al.*, 1977; Webb, 1976; White *et al.*, 1967). Ages of granite suites have also provided evidence for postulated tectonic correlations between the Delamerian event and events in western Victoria, western Tasmania and Victorialand, Antarctica (Foden *et al.*, 1989; Turner, 1986; Stump *et al.*, 1986; Jago *et al.*, 1977; Milnes *et al.*, 1977).

Talbot (1963) demonstrated that more than one period of folding occurred in the Kanmantoo Group during the Delamerian Orogeny. Fleming & Offler (1968) and Offler & Fleming (1968) proposed that three periods of deformation and metamorphism had taken place in the southern Mount Lofty Ranges. The resultant sinusoidal form of regional folding encompassing the Mt. Lofty - Olary Arc has been referred to as the *Adelaide Fold Belt*; a term also used to describe the present folded configuration of the Adelaide Geosyncline. These deformations produced "usually upright, moderately tight second and third generation folds which may show a well developed axial plane crenulation cleavage" with four progressive zones of metamorphism from Miyashiro's (1978) chlorite zone to andalusite zone. Fleming & White (1984) presented evidence for early (pre-F_1) partial melting (migmatization) in the Palmer area, which persisted up to or after the F_3 event. Metamorphism is thought to have commenced prior to deformation, peaking after the first phase of folding, and continued until after the third deformation event (F_3). A study of slaty cleavage by Mancktelow (1979) indicated peak metamorphism occurred immediately prior or during the second deformation event with a continuous increase in temperature through the first deformation. Mancktelow (1981) suggested that the sinusoidal structural fabric of the Adelaide Fold Belt is in keeping with "...an overall flattening of the mobile belt against a curved cratonic margin during the slaty cleavage and fold forming event".

The granites of Encounter Bay both concordantly and discordantly intrude the sediments of the Kanmantoo Group. These granites have provided the oldest dates for Delamerian intrusion (504+/-8 Ma and 495+/-6 Ma; Milnes *et al.*, 1977). Detailed study has shown that the granites were emplaced postdating the initiation of regional Delamerian folding (F_1) but predating F_2 and the first penetrative fabric (S_1) (Daily & Milnes, 1973; Milnes *et al.*, 1977). The surrounding strata experienced andalusite-staurolite-cordierite and higher grades of metamorphism. The lack of any significant contact metamorphic aureole indicates that the host rock was heated prior to intrusion. K-Ar data suggested orogenic activity diminished between 475-459 Ma with a possible minor resurgent event 420-386 Ma (Milnes *et al.*, 1977). Foden *et al.* (1989) have identified and aligned Delamerian syn- and post-tectonic intrusives in the Mt. Lofty Ranges, Padthaway Ridge and western Victoria on the basis of geochemistry, suggesting extentional tectonism resulted in post-tectonic granites whereas a compressional regime was in operation for the syn-tectonic granites.

Rutland *et al.* (1981) have divided the Adelaide Geosyncline and Kanmantoo Trough into six "tectono-stratigraphic zones" related to the nature of folding, metamorphism and sedimentation (Fig. 1.2). The Mount Lofty - Olary fold belt of Campana (1955) is separated into three arcuate zones. The central *Houghton Anticlinal Zone* separates the moderately metamorphosed basinal *Nackara Arc* to the southeast, from the slightly metamorphosed labile shelf sediments of the *South Flinders Zone* to the northwest. To the north, the *Central Flinders Zone* features a pattern of broad open folding, while the *North Flinders Zone* encompasses the Willouran and Northern Flinders Ranges. The strongly metamorphosed Cambrian strata of the Kanmantoo Trough in the southern Mount Lofty Ranges and Kangaroo Island has been designated the *Outer Fleurieu Arc*. The precise allotment of the Peake and Denison Ranges within this structural framework is uncertain.

Jenkins (1986) postulated the presence of Delamerian basement mantling thrust faults in the Mt. Lofty Ranges, active in the Delamerian Orogeny, which resulted in extensive thickening of the Kanmantoo Group Cambrian strata, mylonitization, migmatization, and localized occurrences of small basic igneous bodies. Clarke & Powell (1988) estimated Kanmantoo Group tectonic thickening to be in the order of 15km to explain progressively higher metamorphic grade strata overlying older material. The chronology of aluminosilicate polymorphs indicates the Kanmantoo Group was cooling while the Burra Group was heating up. They suggested that hot allochthonous slabs were obducted onto autochthonous Burra Group sediments during the Delamerian Orogeny.

Regional structural lineaments throughout the Adelaide Geosyncline have been recognized by numerous authors, the most instructive of which are based on gravity trends, or the "gravity corridors" of O'Driscoll (1981). In consideration of igneous intrusives of the Adelaide Geosyncline and Kanmantoo Group strata, it is of interest to note that the largely NE-SW compressional direction for early Delamerian folding corresponds to O'Driscoll's G2 corridor which extends from the Peake and Denison Ranges to the Padthaway Ridge. Likewise, the later and largely NW-SE compressional tectonism of the Nackara Arc corresponds to the G7 corridor (*cf.* Preiss, 1987 p. 261). These corridors have been interpreted as basement crustal features which have been reactivated through Delamerian tectonism. Although these structural lineaments were first used to identify metallogenic occurrences, they also appear to correspond to the major igneous intrusive bodies of the Peake and Denison Ranges, Kanmantoo Trough and the Padthaway Ridge (G2 corridor), the Anabama and Bendigo granites (G7) and the Mt. Painter region (G8). If these corridors are indeed basement features, then credibility is lent to the strong hypothesis that magmatism within the Adelaide Geosyncline was dominated by structural planes of (re)mobilization (?weakness) in the underlying crystalline basement.

Delamerian Orogenic activity in the Willouran Ranges is recorded by the development of cleavage and the tightening of syn-depositional folds (Murrell, 1977). In the Peake and Denison Ranges, Delamerian tectonism folded, faulted and metamorphosed Adelaidean strata to lower greenschist facies, but lacking in cleavage (Ambrose *et al.*, 1981). In contrast, the Adelaidean strata immediately surrounding the Mt. Painter block has undergone lower amphibolite grade metamorphism (Preiss, 1987). Adjacent the Olary Inlier, Berry *et al.* (1978) reported two phases of Delamerian metamorphism and deformation affecting the overlying Burra and Umberatana Group strata. Block faulting was accompanied by the formation a schistose fabric in strongly folded Adelaidean sediments. The metamorphic grade has been defined by biotite, chlorite and actinolite as *Barrovian type* upper greenschist facies. Folding appears to be confined to Adelaide Geosyncline strata with folds abutting the Willyama Inlier to the east and the Gawler Craton to the west, suggesting *decollement* and limited involvement of basement material with the Delamerian activity (Preiss, 1987; Daily *et al.*, 1973).

The present topographic profile of the Adelaide Geosyncline is in part due to mild Cainozoic tectonism which resulted in the widespread reactivation of ancient faults.

1.5 Diapirs and Diapirism in the Adelaide Geosyncline.

1.5.1 Introduction.

One of the more perplexing geological controversies of the Adelaide Geosyncline concerns zones of brecciated and disrupted strata, commonly referred to as *intrusive breccia, megabreccia, carbonate breccia, diapiric breccia* or *tectonic breccia*. This is here referred to as "diapiric breccia" (Webb, 1960). Although the term has genetic connotations, it essentially describes the most consistent of features; the intrusion of older, predominantly sedimentary and volcanic blocks into overlying strata.

The igneous intrusive rocks comprising the Bungadillina suite in the Peake and Denison Ranges, as well as many smaller igneous occurrences in the Willouran and Flinders Ranges, are often intimately associated with diapiric breccia. In this section, it is intended to more thoroughly describe and discuss the breccia with respect to previously published material and to that which was examined in the Peake and Denison Ranges. A more clarified view of the petrogenesis of this diapiric breccia is essential to unravel often complex intrusive relations of the Bungadillina suite, and to provide additional insite to other igneous occurrences in the Adelaide Geosyncline.

Numerous theories have been proposed to explain the origin of diapiric breccia, including basic magmatic activity, fault scarps, large scale sediment slumping, *decollement* and piercement folding, thrust-bound pop-up structures, carbonatite activity and evaporite doming (Howard, 1951; Sprigg, 1952; Murrell, 1977; Burns *et al.*, 1977; Clarke & Powell, 1988; White, 1971; Dalgarno & Johnson, 1966 & 1968; White, 1983; Lemon, 1985). Eventhough the theories are highly contrasting, the actual description of the breccia, regardless of location in the Adelaide Geosyncline, remains remarkably uniform. The diapiric breccia is invariably composed of clasts of Callanna Group sediments, and to a lesser extent Burra and Umberatana Group sediments, commonly enclosed in a coarsely crystalline carbonate matrix. The clasts are usually subangular to subrounded, and range from pebble to boulder size, with some clasts over 2km in diameter (Mount, 1975).

Mount (1975, 1980) has reported more than 180 occurrences of diapiric breccia in the Adelaide Geosyncline (*cf.* Fig. 2.1). In the Peake and Denison Ranges, diapiric breccia is spatially a prominent geological feature. Reyner (1955) described the breccia as the "oldest sediments in the Adelaide System" occupying "crush zones" and a "highly contorted zone" in the vicinity of Mount Margaret. Ambrose *et al.* (1981) mapped its extent and noted different styles of brecciation.

Exposures of diapiric breccia are often poor due to the easily erodable nature of the carbonate-cemented and brecciated material. In the Willouran Ranges, differential erosion has obliterated contact relations between diapiric and gabbroic bodies. However, the deeply cut gorges on the eastern side of the Margaret Inlier in the Peake and Denison Ranges, first noted by East (1889), reveal detailed cross-sections of diapiric breccia, providing an unsurpassed insight into the structure and style of brecciation.

1.5.2 Previous Work.

Howchin (1916) conducted a petrographic study on what is now known as the Mt. Remarkable Diapir (Mount, 1975). He postulated that brecciation resulted from the actions of a system of "Great Faults". Mawson (1923) briefly described "intruded rocks of the Adelaide Series" near Umberatana in reference to igneous intrusives in the same locality and Howchin (1922) commented on "curious breccias" in the

Willouran Ranges which he later described as "crush zones" in the Orroroo district (Howchin, 1930). Spry (1952a,b) described lower Adelaidean brecciated sediments as "great masses of crush breccia", transported perhaps over 4km to their present stratigraphic position in the central and western limbs of the Worumba Anticline. Spry (1952a) demonstrated that these were intruded by dolerite bodies.

Webb (1960) introduced the concept of diapirism to explain these breccia zones, and identified brecciated material as Willouran sediments emplaced into Sturtian Series strata at a locality near Willochra. Webb (1960) also suggested that the core of the Blinman Dome is a diapiric structure. This is contrary to Howard's (1951) treatise that argued for brecciation and deformation in response to emplacement of basic igneous bodies. Geophysical data in the form of a gravity survey across the diapir failed to measure the presence of a basic igneous mass at depth, indicating that the igneous bodies are individual rafts carried into position within a rising diapir (Mumme, 1961). Coats (1965) and later Dalgarno & Johnson (1966; 1968) expanded on the concept of diapirism, proposing that brecciation was the consequence of *decollement* followed by piercement folding and the intrusion of former Callanna Group evaporites into the overlying sedimentary sequence. Coats (1965) attributed the initiation of diapirism to a mild Torrensian orogenic event, while Thomson (1966) suggested that basement block faulting provided the impetus for diapirism.

Dalgarno & Johnson (1968) invoked a refined, evaporite-controlled, diapiric brecciation model. They proposed that Callanna Group evaporites were mobilized under hydrostatic stresses originating from differential loading and were intruded into domes and planes of structural weakness. Burns *et al.* (1977) challenged the evaporite mobilization model for brecciation in favour of a *decollement* model involving basal piercement structures causing brittle deformation during the Delamerian Orogeny without invoking diapirism or intrusion of the breccia into overlying rocks. The structural-tectonic argument for breccia origin is augmented by Clarke & Powell (1988) in recognition of thrust-bound pop-up structures which formed in response to the compressional regime during Delamerian folding. This style of piercement structure is considered to have been initiated by wrench-faulted crustal shortening accompanied by basement-cover *decollement*.

Murrell's (1977) study of the breccias in the Willouran Ranges concluded that

> "The chaotic structures in the Callanna Group are considered to be the results of instabilities generated in the sedimentary pile by basement warping and enclosed evaporites",

speculating formation by pre-Torrensian syn-sedimentary slumping. Detailed studies of individual diapiric bodies by Scotford (1984) and McPherson (1984) attested to syn-sedimentary doming, which resulted in localized facies changes, slumping, soft sediment deformation and reworked Callanna clasts in adjacent sediments.

Mount's (1975) thorough work on diapiric breccia concentrated on the Arkaba Diapir in the southern Flinders Ranges. He concluded that although there are invariably *decollement* processes involved in evaporite mobility, the passive, partially syn-tectonic intrusion of evaporite diapirs was the prime cause in the formation of these bodies.

Preiss (1985) has provided a synthesis of the "carbonate" breccia in the Worumba Anticline in association with concepts of diapirism in the Flinders Ranges. Like Mount (1975), Preiss (1985) observed that the carbonate breccia has been passively emplaced into the Adelaidean sequence along fault lines and fold hinges with sharp, apparently intrusive contacts. Xenoclasts are mainly derived from the Callanna Group sediments and basic volcanics but also include clasts from Burra and Umberatana Group strata. The carbonate breccia is also host to a low grade metamorphic mineral suite including talc, chlorite, and magnesio-riebeckite.

Evidence indicates that fault-initiated syn-sedimentary doming and diapirism involved basal Callanna Group evaporite mobilization along preferential planes of structural weakness within the Flinders Ranges (Lemon, 1985). Exotic clasts were exhumed during evaporite mobilization. These include crystalline basement material and Callanna Group volcanics, representing the insoluble residue presently observed in breccia zones.

1.5.3 Diapiric Breccia of the Peake and Denison Ranges.

Within the Peake and Denison Ranges, Ambrose *et al.* (1981) identified

> "zones of disruption containing disoriented, rafted blocks of varying size and lithology incorporated in a carbonate-matrix breccia"

and

> "narrow zones of carbonate breccia (*viz.* carbonate-matrix breccia) intruded as sills, plugs, and more rarely dykes. Diapiric breccia is often intruded along faults and anticlinal fold hinges".

They noted that this breccia is:

(1) not consistent, but varies in the severity and extent of brecciation and disruption of strata;

(2) characterized by intense contortion of incompetent strata showing "extremely plastic deformation";

(3) intruded into basement rocks along faults and;

(4) often emplaced as sills in relatively undisturbed sedimentary sequences.

They also suggested that one 2-3km wide zone of brecciation

> "coincides with the intersection of two major anticlinal fold hinges. Faulting, intrusion of carbonate (*viz.* diapiric) breccia, brecciation, and plastic deformation are characteristic".

It is within this zone that they recorded "intrusive albitites, diorites, syenites and monzonites".

Much of the area delineated by Ambrose *et al.*, 1981 as diapiric breccia is composed of a number of different types of breccia, some of which may not necessarily be diapiric. It is apparent from detailed mapping in this study that the most widespread form of "brecciation" in the Peake and Denison Ranges is not that which is often described being in associated with a coarse, crystalline carbonate matrix, but is rather composed of highly distorted and contorted beds of less competent (siltstone and shale) Burra Group strata within more competent (quartzite) Burra Group strata (*e.g.* Plate 1.5.G).

At least five different types or "stages" of breccia, representing progressive deformation and brecciation, have been observed in the course of this research. The precise tectonic/diapiric allotment to each stage of breccia development remains speculative, especially in reference to Delamerian activity.

The onset of diapiric deformation (*Stage 1*) results in compression of strata surrounding the intruding evaporite diapir. As the sediment still contains much inter-layer pore water and has not been deeply buried, lateral compression can lead to the development of *chevron* or *kink* folds (Plate 1.1 Top Left and Bottom Left). In kink folding, the horizontal strength of individual beds is greater than the lithostatic confining pressure, resulting in brittle zig-zag buckling (layer-parallel shortening combined with layer-parallel shear; Ramberg & Johnson, 1976). It is unlikely that this style of folding would have been caused by Delamerian tectonism due high lithostatic pressures prior to deformation (apparent overburden thickness of more than 14km; Preiss, 1987).

Progressive deformation of kink-folded strata results in (*Stage 2*) the separation of folded strata along fold hinges and limbs of layer-sheared beds, forming rhombohedral-shaped individual clasts. This stage in deformation is recognized by the dominance of very angular monolithologic clasts, often forming juxtaposed blocks, and lacking in matrix material (Plate 1.1 Top Right). One problem in recognizing this style of deformation is that if these deformed beds are insufficiently exposed, as they often are due to preferential weathering, they give the impression of being widely spaced clasts and thus resemble mobilized diapiric breccia. The angularity and lack of matrix in this stage indicates very little displacement took place.

Significant displacement of the breccia (*Stage 3*) results in the formation of clast-supported breccia (Plate 1.1 Centre Right). The clasts remain angular and monolithologic, indicating limited transport. Further displacement of breccia develops (*Stage 4*) matrix-supported breccia (Plate 1.2 Bottom Left), indicating extended transport of of a greater variety of more rounded clasts. The matrix is commonly carbonate-cemented sand and silt. Possible Bungadillina suite clasts as well as occasional basalt clasts (Cadlareena Volcanics?) have been recognized within these stages of brecciation (Plate 1.2 Top Right).

The final form of diapiric breccia (*Stage 5*) is represented by the more widely described carbonate-hosted breccia. This type of breccia is composed of rounded polylithologic clasts in a coarse carbonate-cemented matrix (Plate 1.2 Bottom Left). The actual spatial extent of this stage in breccia mobilization is restricted and usually confined to narrow, more linear planes (*e.g.* fault lines and fold hinges), indicating syn- or post-Delamerian timing for mobilization. The contacts with this style of breccia are sharp, suggesting passive emplacement (Plate 1.2 Top Left).

Recognition of these different deformation styles is essential in determining possible modes of formation, and their relation to the congrous plutonic bodies of the Bungadillina suite. The immediate contacts of plutons were carefully examined, and it was noted that the "diapiric breccia" of many plutons is invariably composed of contorted and distorted Burra Group sediments (Stages 1 and 2; Plates 1.1 Bottom Left and Top Right), and not composed of carbonate-supported (Stage 5) breccia. There is no indication that pluton emplacement has caused widespread brecciation, as distorted, contorted and brecciated beds exist without intrusive bodies present. Igneous bodies in contact with carbonate-matrix diapiric breccia have not caused skarns or contact metamorphic aureoles, although the igneous bodies themselves may exhibit a chilled margin. There is *no* situation where igneous bodies are unequivocally intrusive to carbonate-supported (Stage 5) breccia, although biotite lamprophyre was noted intruding Stage 3 breccia

(Plate 1.2 Bottom Right). Thus timing of the intrusion of the Bungadillina suite must postdate the formation of Stage 1, Stage 2 and Stage 3 breccia, but predate Stage 5.

Contacts between the diapiric breccia and Burra Group strata are very sharp (*e.g.* Plates 1.1 Bottom Right; 1.2 Top Left), as exemplified by the lack of significant localized disturbances of the host sequence, which supports Mount's (1975, 1980) argument for *passive* diapirism. The omission of "trains" of igneous material extending from igneous bodies, or brecciated igneous margins within diapiric breccia supports this contention. Flow-lineated Stage 5 breccia forming dykes and sills is analogous to fluid-supported or plastic transport (remobilization?).

Thick veins of coarsely crystalline carbonate are found along fine structural fissures in the distorted and contorted beds (*e.g.* along tight fold hinges). Similar material is found intruding undisturbed strata as small dykes and sills. Isotopic analyses of these materials [7597-8] have found them to be very similar with $d^{13}C$ (PDB) varying from 1.108 to 1.253 and $d^{18}O$ (PDB) -12.334 to -11.806, suggesting consanguinity from a similar source. The $d^{18}O$ values for carbonate are strongly dependent on the $d^{18}O$ value of the water from which it has formed (Faure, 1977). The near-identical $d^{18}O$ values from both vein and breccia carbonates indicate carbonate crystallization from a similar groundwater source. The source for the carbon isotope values is comparable to marine carbonates of Cambrian to Tertiary age ($d^{13}C$ 0.56+/-1.55‰) (Faure, 1977), indicating low temperature formation from groundwater precipitation (*cf.* Table 5.6.2).

1.5.4 Discussion.

It is well documented that thick evaporite deposits readily form during the process of geosyncline formation at the onset of basin subsidence (*e.g.* Kinsman, 1975). The subsequent mobilization of salt into diapirs is similarly well documented in geophysical surveys of continental slopes and marine basins. Salt diapirism will occur soon after burial in the presence of a density inversion, and will increase upon nucleation of salt into domes. Busch (1907) observed that salt expanded into voids under at least 300m of overburden. Trusheim (1960) noted that 300m of salt would start to flow under a sediment overburden of 1000m.

A rising salt diapir will behave as a visco-plastic body, forcibly intruding along a subvertical line or plane of least resistance (Fig 1.5.4). The top of the diapir is commonly composed of an insoluble calcite-anhydrite *caprock* which often contains sediment clasts (Walker, 1974). Deformation around the immediate vicinity of the diapir is known as the *shale sheath*, which is composed of clay-like gouge of the surrounding sediments which has been sheared out against the salt body (Hanna, 1953; Johnson & Bredeson, 1971; Kupfer, 1974).

Outward from the shale sheath, there is a zone of brecciation extending for hundreds of metres caused by domal pressure (Kerr & Kopp, 1958) or osmotic fluid pressure (White, 1965; Dickinson, 1942). It is here that the diapir can cause warping and buckling of the host beds without physical contact of the rising diapir (Stage 1). The subsequent displacement of buckled strata (Stage 2) is often recognized in the Adelaide Geosyncline by locally disturbed and contorted host sediments without a carbonate matrix. In the Peake and

Denison Ranges, and to a lesser extent in the Willouran Ranges, this type of breccia commonly hosts the smaller intrusive bodies. Further displacement of the breccia results in Stages 3 and 4 respectively (clast-supported breccia and matrix-supported breccia) (Fig. 1.5.4).

Other types of breccia may be present. Within the margins of the salt dome, a boundary salt shear zone can incorporate foreign clasts 0-10m in diameter. These zones have been found to be up to 200m wide (Kupfer, 1974). This in itself can form one type of breccia responsible for the appearance of exotic clasts in brecciated sediments. For example, the inclusion of often large blocks of basic volcanics originating from Callanna Group beds is a common feature of many diapiric bodies (*e.g.* Gum, 1987). As these volcanics would have occurred immediately above the postulated basal sequence of evaporites, it is resonable to conject that any upward salt doming would incorporate these volcanics. Such upward doming may also increase connate fluid pressures, which may be responsible for localized pneumatolitic deformation along less competent fluid-rich sedimentary beds.

If the sedimentary sequence is subjected to orogenic or epeirogenic stresses, the salt will be extremely mobile due to increasing pressure and temperature, and will preferentially intrude into planes of structural weakness such as fold hinges and fault planes. This mechanism has been suspected in providing a gliding or lubricating agent in several fold systems (Sonnenfeld, 1984), and is probably responsible for Stage 5 breccia which forms dykes and sills of flow-lineated clasts within a prominent matrix (often coarse carbonate) that passively intrudes the host strata. It is this type of breccia which is often described intruding along Delamerian faults and fold axes. The passive intrusive character may be due to high confining lithostatic pressure during Delamerian tectonism.

Carbonate isotopic data indicate that the coarse crystalline carbonate of the breccia matrix formed from groundwater precipitation, immediately after or during the Delamerian Orogeny. This was accompanied by carbonate veining and dyking.

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Chapter Two: Igneous Intrusives of the Adelaide Geosyncline: A Review.

> "In the Geosyncline, small intrusions of basic rock occurred, generally in structurally weak diapiric areas. More rarely, acid porphyry was intruded, *e.g.*, at Burra."
>
> Thomson (1969) discussing magmatism in the Adelaide Geosyncline during the Delamerian Orogeny (p.107).

2.1 Introduction.

In comparison with similar fold belts which often contain extensive intrusives of plutonic proportions (*e.g.* Lachlan Fold Belt, the Cordilleras, the Appalachians, the Urals), the Adelaide Geosyncline hosts relatively few and only small plutonic suites. Nevertheless, the intrusives of the Adelaide Geosyncline are of interest in regards to palaeo-basin formation, diapirism, volcanism and associated tectonics, and have been the subject of many investigations. This chapter summarizes the data available regarding their mineralogy, geochemistry and tectonic setting.

The main intrusive bodies to be discussed include (*cf.* Fig. 2.1 & Table 2.1):

(a) the Kanmantoo Trough and Padthaway Ridge granites;

(b) the mineralized granites of Anabama and Bendigo;

(c) basic intrusives occurring as dyke swarms and inclusions in diapiric bodies (including the diorites and albitites of the Willouran and Mt. Painter regions);

(d) granites within crystalline basement of the Mt. Painter region;

(e) an introduction to the intrusives of the Peake and Denison Ranges, and;

(f) Jurassic dolerites and kimberlites.

2.2 Granites of The Kanmantoo Trough and Padthaway Ridge.

The Kanmantoo Group intrusives have been the subject of many studies (*e.g.* White, 1966; White *et al.*, 1967; Milnes *et al.*, 1977; Fleming & White, 1984; Foden *et al.*, 1989; Turner *et al.*, *(in prep.)*. And in part due to their close proximity to the city of Adelaide, these granites have been, and are, the focus of many postgraduate research programs (*e.g.* Turner, *in prep.*; Mancktelow, 1979; Milnes, 1973; White, 1956). These scientists have recognized "pre-", "syn-" and "post-tectonic" suites of "S-", "I-" and "A-type" granites within the amphibolite-grade Cambrian metasediments. The metamorphic grade is often high enough (upper amphibolite facies) to encourage the development of anatectic migmatites (Fleming & White, 1984).

A complete review of these granites would be too voluminous to be incorporated into the text of this thesis. Instead, a thorough discussion of these intrusives; their petrography, geochemistry and tectonic implications, is presented as an appendix; "Tectonic Implications of Delamerian Magmatism in South Australia and Western Victoria" by J.D. Foden, S.P. Turner and R.S. Morrison (1989). In summary, both syn- and post-tectonic granites have been identified. The syn-tectonic granites and granodiorites formed in response to (compressional) Delamerian orogenic activity and involved partial melting of Kanmantoo Group metasediments. These intrusives, composed dominantly of SiO_2-rich granite and granodiorite, are commonly slightly foliated and contain abundant metasediment xenoliths. The plutons are also elongated, with the long axis parallel to the regional deformation trend (*e.g.* Palmer Granite). In contrast, the post-tectonic granites often form small isolated occurrences. Contact relations with the surrounding (amphibolite facies) metasediments are ubiquitously covered as these plutons are located to the immediate east and southeast of the Mount Lofty Ranges. The granites (*sensu stricto*) and porphyritic equivalents are massive, non-foliated, and contain cognate xenoliths. Their chemistries are similar to typical "A-type" plutons. These intrusives are highly fractionated, high level, trace element-enriched post-tectonic granites, formed from mantle-derived magma influxing into the upper crust (as indicated by the presence of the Black Hill gabbronorite pluton). They intruded during a brief period of crustal extension, which occurred in response to orogenic collapse and crustal lithostatic rebound, immediately following the cessation of compressional Delamerian tectonism.

2.3 The Granites of the Nackara Arc.

2.3.1 Introduction.

The largest and singularly most prominent plutons within the Adelaide Geosyncline are the intrusives of the Nackara Arc; the granites of Bendigo and Anabama. Although these granites are areally extensive, the outcrop exposures of the Anabama Granite are poor and very weathered, and most of the Bendigo Granite is only known from shallow subsurface drilling. The Anabama and Bendigo Granites are considered to occur along similar structural features to the granites of the Kanmantoo Group and are associated with Cambro-Ordovician Delamerian tectonism (Preiss, 1987).

With the exception of the Anabama Granite and the Bendigo Granite, intrusive bodies of the Nackara Arc are relatively small features. For example, a minor diorite body has been mapped by Berry *et al.* (1978) within basal Burra Group conglomerate approximately 60 km north of the Anabama Granite. It appears to be an extension of a prominent (5km long) diorite dyke intruding crystalline basement of the Willyama Inlier. Although not strictly within the Nackara Arc, another possibly cognate intrusive is an oval composite stock, approximately 200m-long and 100m-wide located further north within the Willyama Inlier. This pluton intrudes the metamorphic aureole of a Middle Proterozoic (?) granite batholith in the "Boolcoomatta Hills" (Segnit, 1949; *cf.* Table 2.1 *anal.* U & V). It was described as medium grained "albite syenite" and "essexite" composed of albite-quartz-magnetite-apatite-muscovite-chlorite-rutile and hornblende-oligoclase-biotite-epidote-magnetite-sphene-apatite respectively. Through the stock and surrounding metasediments intrudes a swarm of tormaline-bearing quartz-feldspar pegmatites. These igneous intrusives may not directly intrude Adelaidean sediments as their location is within the periferal crystalline basement, but their intrusion may have been synochronous with Adelaidean sedimentation and may pertain to the tectonic processes within the Adelaide Geosyncline. Rb-Sr geochronology by Flint & Webb (1980) on the *Tonga Hill soda-syenite*, believed to be the same body as that described by Segnit (1949), did not give conclusive results. The nearby *Poodla Hill adamellite* recorded a Delamerian age of 490 Ma with an unusual initial ratio of 0.795 (Flint & Webb, 1980).

2.3.2 The Anabama Granite.

The Anabama Granite, located approximately 50km south of Olary, is a roughly lenticular granite mass of sporadic outcroppings 65km long and 13km wide. The intrusion occurs in the eastern region of the Adelaide Geosyncline along the Nackara Arc, which is also known as the "Mt. Lofty-Olary arc". It is bounded to the south by the Anabama Fault zone, coinciding with the intersection of deep seated north-south basement features and northwest-southeast and northeast-southwest near-surface fractures (Gerdes, 1973). The Anabama Fault Zone is a complex of small scale faults providing a definitive structural margin of the Adelaide Geosyncline. It is an extension of the Redan Fault to the west (Thomson, 1969) and the Darling River Fracture Zone to the east (Scheibner, 1974), and probably provided some structural control on Adelaidean sedimentation.

To the south of the Anabama Fault zone in the vicinity of the Anabama Granite lies a linear sequence of metavolcanics; the Boucaut Volcanics. The exact stratigraphic position is uncertain, but Preiss (1987) reported the occurrence of several volcanic inliers within anticlinal cores that are stratigraphically beneath Rhynie and Aldgate Sandstone. Rb-Sr analyses (Webb, 1976) indicated a Cambrian age, but inferred radiogenic strontium loss during Delamerian metamorphism suggested an older true age, tentatively correlated to the Callanna Group Wooltana Volcanics (Preiss, 1987; Forbes, *in prep.*; Arnold, 1971; Edwards, 1971).

Small separate plutons intrude Adelaidean metasediments around the periphery of the main granite mass. The largest, a leucogranite, occurs 6km north-northwest of Anabama Hill. Others include biotite granite, pegmatite, biotite adamellite, and a biotite lamprophyre dyke similar to that which recorded a K-Ar age of 424-262 Ma in the Mt. Painter region (Forbes, *in prep.*; Webb & Louden, 1971).

The long axis of the Anabama Granite is roughly parallel to the regional strike of the Adelaidean strata, which consists of massive grey tillites of the Umberatana Group (Yudnamutana Subgroup). To a lesser extent it intrudes Burra Group (Belair Subgroup) phyllites, spotted and laminated schists, and metasediments belonging to the Wadnaminga Anticlinorium (Forbes, *in prep.*). With the exception of the contact metamorphic zone, a weak metamorphic biotite foliation within the granite is parallel to the regional strike (Blissett & Reid, 1973).

Detailed mapping of the granite by Mirams (1961) has shown that the granite, strongly altered in some outcrops, passively intrudes the surrounding Adelaidean metasediments. Granite contacts show a regional concordancy but are locally discordant. Sharp upturning of strata immediately adjacent the granite intrusion indicates minor doming associated with emplacement.

Blissett & Reid (1973) identified a narrow (200m wide) thermal metamorphism zone of almandine-amphibolite grade metasediments adjacent the granite intrusion. This is in contrast to the lower greenschist facies regional metamorphism found elsewhere in the region. Their detailed petrological studies indicate that the metamorphic grade decreases away from the pluton. The immediate contact of epidote hornfels grades to scapolite-bearing amphibolite or lower almandine-amphibolite grade before blending into the surrounding regional greenschist facies metamorphic grade.

The main lithologies are medium to coarse grained (1-2cm) equigranular biotite and minor hornblende granodiorite, a sub-porphyritic biotite adamellite with strongly zoned plagioclase, and other variants including tonalite, quartz diorite and biotite-hornblende diorite (?gabbro). Accessories include up to 5% sphene, zircon and apatite (Hellman & Fountain, 1982). Two generations of microgranite, and dacite porphyry have been recognized which appear to be fine grained equivalents of granodiorite and adamellite; one occurring penecontemporaneously and the other injecting into the main intrusive granite (Blissett & Reid, 1973). Dykes up to six metres wide of lamprophyre, quartz porphyry, diorite porphyry, dacite and rhyolite intrude the main granite mass (Mirams, 1961; Blissett & Reid, 1973).

In some intrusive lithologies, there exists a weak foliation of primary biotite, often replaced by chlorite, muscovite and/or epidote, roughly parallel with the regional fold orientation. Such foliation, in conjunction with the development of a prominent contact metamorphic halo, indicates syn-tectonic timing for emplacement.

Dykes of dacite and andesite porphyry show flow lineations (Forbes, *in prep.*) and may indicate that volcanic activity accompanied magmatism. Drill core recovered to a depth of 796m indicate that the earliest igneous phase is granodiorite into which intrudes biotite adamellite (Tonkin & Wilson, 1981).

Compston *et al.* (1966) dated the Anabama Granite by Rb-Sr as 473+/-3 Ma (intial $^{87}Sr/^{86}Sr$ ratio = 0.705). Steveson & Webb (1976) obtained radiometric ages of 468+/-62 Ma (initial $^{87}Sr/^{86}Sr$ ratio = 0.7074) and 477+/-84 Ma (initial $^{87}Sr/^{86}Sr$ ratio = 0.7073). These dates, in conjunction with 9 K-Ar dates ranging from 442 to 461 Ma, apparently confirms Miram's (1961) assumption that the granite is of early Palaeozoic age. Although most of the basement Willyama Complex have initial ratios in excess of 0.710, the Peryhumuck adamellite gneiss recorded values (0.7055), similar to that of the Anabama Granite (Flint & Webb, 1980), and may have provided some of the source material for the Anabama magma. However, the relatively low initial

$^{87}Sr/^{86}Sr$ ratio of the Anabama Granite is comparable with those obtained from Kanmantoo Group Delamerian syn-tectonic granites such as Palmer and Murray Bridge, indicating derivation from a similar deep-seated, more primitive source (Forbes, *in prep.*).

The discovery of anomalous Cu and Mo geochemical samples by Blissett & Mason (S.A. Dept. Mines and Energy, 1966) led to further work and the confirmation of Cu and Mo mineralization associated with hydrothermally altered granite by Asarco (Australia) Pty. Ltd. (Morris, 1981). Alteration is a progressive feature initiated by minor replacement of plagioclase by epidote and sericite, haematite replacement of orthoclase and chlorite replacement of biotite. More severe alteration involves carbonate, muscovite and quartz replacement. Greisens form rigid capped hills from the silicification and sericitization of the original biotite granite. Joint planes are commonly kaolinized and are thought to have provided conduit for hydrothermal fluids. El-Raghy (1980) described the two alterations events; the first causing potassic metasomatism up to 2km into the surrounding Adelaidean metasediments, the second forming "vents of a concealed porphyry system". Stokoe (1982) reported an early alteration phase involving quartz-pyrite-alkali feldspar veining followed by a later phase of quartz-pyrite-muscovite.

Blissett & Reid (1973) suggested that the shallow intrusion of the granitic body under low confining pressure during the Delamerian Orogeny resulted in volatile-induced brecciation and silicification of the upper portion of the intrusion possibly initiating hydrothermal alteration. Violent devolatilization is also evident by the formation of a "pebble dyke" and "megabreccia" of brecciated greisen in quartz-muscovite with abundant goethite veins during forcible transport of volatiles through zones of weakness in the cover rocks. El-Raghy (1980) described the presence of "breccia pipes" intruding into the main granite mass consisting of microgranodiorite clasts, suggesting that this material represents the deep-seated stock responsible for mineralization through a process of ascending pneumatolytic-hydrothermal residual volatile-rich magmatic fluids. The hydrothermal fluids were of low temperature origin (120-250°C) and of low salinity (14.9 wt.% NaCl) (Richards, 1980). The presence of a 3m wide dyke of unaltered dacite intruding into altered granodiorite (Hosking, 1969) indicates that magmatic activity continued after hydrothermal alteration.

Chemical analyses by Morris (1981) and Richards (1980) showed that progressive alteration results in progessive increase in SiO_2, K_2O, SO_3, Cu, Mo, Sn and Hg with a comparable decrease in Al_2O_3, MgO, CaO, Na_2O, TiO_2, MnO, P_2O_5, Sr and Zn (Table 2.3.2). Biotite adamellite has been recovered from drilling showing low grade Cu-Mo mineralization, probably representing the source material for mineralization (Stokoe, 1982).

Most authors believe that the style of alteration of the Anabama Granite represents that which is found in porphyry Cu-Mo deposits with progressive "shells" of differing styles of alteration. Tonkin & Wilson (1981) have assigned secondary biotite-alkali feldspar mineralization to the "potassic zone" and sericite alteration in porphyritic microdiorite to the "phyllic zone" of Lowell & Guilbert (1970) and Rose (1970). Similarily, Blissett & Reid (1973) suggested it is possible that greisen alteration may represent the phyllic zone. However, Richards (1980) emphasized that such concentric alteration shells are ill-defined, citing incomplete and missing alteration zones in the Anabama occurrence. Other than this debate on alteration, no further elucidation on petrogenesis of the Anabama Granite has been attempted.

2.3.3 The Bendigo Granite.

Similar intrusive bodies to the Anabama Granite have been located 84 km southwest, known as the *Bendigo Granite*. Two plutons (130 and 180 km^2) have been delineated by geophysical surveys and proven by subsequent drilling (Langsford, 1972a). The main granite mass, a grey biotite granodiorite and adamellite, intrudes metamorphosed Umberatana Group siltstones which form the Loch Winnoch Syncline (Forbes, *in prep.*). A contact metamorphic aureole exists up to 300m into the surrounding sediments composed of laminated hornfels with garnet-epidote skarns. Associated with the granite is a porphyry dyke swarm consisting of up to 3m wide andesites and dacites. Dykes have been found cross-cutting both the granodiorite and surrounding sediments 1.5km away from the main intrusion.

Like the Anabama Granite, the Bendigo Granite has been affected by hydrothermal metamorphism resulting in the formation of quartz-muscovite greisens surrounding quartz veins. Immediately adjacent the intrusions is a lens 100m by 300m of brecciated hornfels metasediments, probably caused by hydrothermal activity. The most common form of alteration is pervasive sericitization. With progressive alteration, biotite gives way to epidote and chlorite. Calcite and dolomite appear in strongly altered material. This process involves the removal of Ca, Mg and Na with the addition of H_2O and

CO_2. Copper porphyry-type mineralization of the granite has been recognized with the existance of an outer quartz-sericite-pyrite "phyllite zone" surrounding an inner sericite-carbonate-epidote "propylitic zone" (Langsford, 1972b).

Rb-Sr geochronology recorded an age of 464+/-84 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7069 (Webb, 1976). Both the date and initial ratio correspond strongly with that obtained for the Anabama Granite. Thus on the basis of isotope data, geochemistry, style of alteration and structural location, the Bendigo Granite appears to be an eastern equivalent of the Anabama Granite. Unfortunately, other than economic metals content, little is known of the major and trace element geochemistry of this granite body, thus inhibiting both petrogenetic analyses and detailed comparisons with the Anabama Granite.

2.4 Mount Lofty Ranges.

Magmatic activity during the Middle Jurassic has resulted in the extrusion of extensive tholeiitic basalts on Kangaroo Island (Milnes *et al.*, 1977; Milnes *et al.*, 1982). These rocks are comparable in age (170 Ma), initial $^{87}Sr/^{86}Sr$ ratios (0.711-0.712) and geochemistry to similar suites in Tasmania and Antarctica (Compston *et al.*, 1966; McDougall & Wellman, 1976), which have formed in response to the initial stages of continental rifting of Gondwanaland, eventuating in the separation of Australia from Antarctica.

Three swarms of dolerite dyke have been recognized on Kangaroo Island and in the southern Mt. Lofty Ranges (Parker *et al.*, *in prep.*). The Woodside dyke swarm in the vicinity of Mt. Barker and Palmer intrudes Kanmantoo Group and Upper Adelaidean metasediments. It is oriented roughly north-northeast, follows a major crustal lineament, and possibly coincides with the emplacement of the Black Hill norite body of Early Ordovician (*circ.* 487 Ma) age. The Yankalilla dyke swarm is restricted to the Early Proterozoic Myponga Inlier and is probably Middle Proterozoic in age. Minor metadolerite dykes, up to 35m wide have been reported from the southeast coast of Kangaroo Island, while dykes at Rosetta Head (Fleurieu Peninsula) were noted to intrude both the Kanmantoo Group metasediments and the Encounter Bay Granite (Parker *et al., in prep.*).

2.5 Intrusives Associated with Diapiric Breccia.

2.5.1 Introduction.

Areas of carbonate-cemented *diapiric* breccia commonly incorporate igneous bodies of variable sizes, shapes and lithologies, but usually of mafic affinity. Contact relationships are obscured by the breccia and usually poorly exposed, rendering any definitive conclusions to the intrusive-extrusive character difficult if not impossible. Nevertheless, the contact relationships are of paramount importance to distinguish between intrusive bodies and merely rafted remnant blocks from a lower stratigraphic horizon or from crystalline basement. Examples of zones of diapiric breccia with igneous bodies include the Blinman, Burr, Patawarta, Pinda, Mount Remarkable and the Oraparinna Diapirs, the Worumba Anticline, and in breccias of the Willouran Ranges and around the Mount Painter Inlier.

For many outcrops it is only possible to discriminate between volcanic and plutonic parentage. Mafic volcanic rafts may be from either the Callanna Group (*e.g.* Wooltana Volcanics) or Burra Group volcanics (*e.g.* amygdaloidal basalts in the Rhynie Sandstone). As the breccia is usually stratigraphically below the Cambrian, it is unlikely that the volcanic bodies would include Cambrian volcanics such as the Truro Volcanics or those of the Warburton or Arrowie Basins.

Plutonic rocks in these diapiric zones have a more ambiguous parentage. Gum (1987) conducted a study into the mafic bodies within these diapirs (*especially* the Enorama Diapir), and concluded that all examined were exhumed rafts of continental tholeiitic Callanna Group flood basalts; the coarser gabbroic bodies representing the slower-cooling remnants of thick flows or former feeder dykes to these flows. They are chemically and mineralogically comparable to the Cadlareena, Wooltana and Noranada Volcanics (Table 2.5; Gum, 1987).

2.5.2 Blinman and Oraparinna Region.

One of the most extensively examined diapirs in the Adelaide Geosyncline occurs at Blinman. Located 24km west of Parachilna, it is a roughly oval shaped structure averaging 10km in diameter. The slightly larger Oraparinna Diapir lies 36km south-southeast of Blinman Diapir.

Howchin (1907), in his expatiation on igneous rocks within the Blinman Diapir, identified the presence of

> "... the great volcanic field which was developed in Post-Cambrian time, chiefly at or near Blinman, forming the central part of the elevated dome. The country is riddled with basic dykes, which have a general east and west direction, but are not continuous for long distances, and are sometimes circular, which suggests that some of them may be volcanic necks".

Collected samples were later examined by Benson (1909) who identified "amygdaloidal melaphyres", "olivine-diabases, ophitic diabases free from olivine, granulitic-diabases, and gabbro-diabases" (*cf.* Table 2.1 *anal.* B). Further recollections of Howchin's (1922) wanderings of the Blinman area recorded "circular bosses (?chimneys)" and basic igneous dykes up to 120 feet wide intruding shales and dolomites, sometimes "underlain by a dark coloured (garnet) rock, which has undergone alteration by contact with an igneous dyke" and associated with "crush-breccias and crush-conglomerates in which the original bedding is entirely obliterated, or is present only in isolated fragments". West of Blinman, Howchin (1922) mentioned the presence of gneissic granite and granite as well as basic igneous dykes commenting

> "There is a curious, and not easily explained, relation between the igneous rock and the sedimentary deposits".

Mawson (1942) described the region as "the Oraparinna and the Blinman igneous centres", noting amygdaloidal melaphyres and gabbroid dolerite (*cf.* Table 2.1 *anal.* J) which

> "...have suffered mineral changes to a more or less degree; thus uralitization, saussuritization, epidotization and chloritization are regular features, while scapolite makes its appearance in some cases".

Detailed mapping by Howard (1951) and later by Coats (1964) delineated the presence of rafts of altered basalts (melaphyres of Benson, 1909) within the Blinman Diapir (*cf.* Table 2.1 *anal.* K & L). These basalts include amygdaloidal and non amygdaloidal varieties with pseudomorphs of antigorite, talc and magnetite after olivine. Groundmass is commonly recrystallized to an assemblage of albite, calcite, epidote, chlorite, oxides and actinolite with secondary amygdal fills composed of calcite and siderite. The non-amygdaloidal basalts are reported to occur conformably with halite pseudomorph-bearing sediment clasts within the diapir (Howard, 1951). The similarities of composition with altered basalts from the Oraparinna Diapir (Mawson, 1942) and the Wooltana Volcanics (Mawson, 1927) have been used as evidence for contemporaneous Willouran parentage (Coats, 1964).

The mafic intrusive suite of the Blinman Diapir can be subdivided into "doleritic gabbros", "olivine-free dolerites" and "olivine-bearing dolerites" depending on grain size and the presence of olivine pseudomorphs (Howard, 1951). The rocks have invariably endured an array of alteration forms including uralitization (replacement of pigeonite and augite by hornblende, actinolite and possible riebeckite), chloritisation and sausseritisation of plagioclase with alteration to zoisite, epidote and sericite.

Within the diapir, Coats (1964) has recognized "rapakivi type granite, granite porphyry, quartz feldspar porphyry, granodiorite and granite gneiss". The granitic material was interpreted to be probably the same age as the "older (pre-Willouran) granite suite" of Mount Painter, and probably mechanically emplaced to the present position through exhumation within the rising diapir. Preiss (1987) suggested that the granitic xenoclasts may be Gawler Craton material which has also been reported as schists and amphibolites in the Beltana and Arkaba diapirs.

The elongate Patawarta Diapir, located 16 km northeast of the Blinman Diapir, follows along the Narina Fault Zone (Coats, 1973). Associated with the diapir are amygdaloidal basalt and dolerite identical to those described in the Blinman Diapir. Hall (1984) has reported a localized contact metamorphic aureole showing an intrusive relationship between the Callanna Group sediments and the dolerite, and suggested that the dolerites were feeder dykes to Willouran volcanics. The dolerites are restricted to the diapir, do not intrude the surrounding Wilpena Group sediments and lack any contact metamorphic effect of the breccia, which has led Hall *et al.* (1986) to conclude that both the dolerite and amygdaloidal basalt form diapiric xenoclasts and predate diapiric activity (*cf.* Table 2.1 *anal.* M & N).

2.5.3 Worumba Anticline.

The geology of the Worumba Anticline, located 100km northeast of Pt. Augusta, has been recently researched and reviewed by Preiss (1985). Spry (1952a, 1952b) published the first regional map of the area and commented on the presence of dolerites and amygdaloidal basalts "restricted to the disturbed axial zone of the Worumba Anticline" or "crush breccia" in which he identified 61 separate mappable occurrences of igneous rock. The dolerites are commonly described as irregular oval plugs or stocks, with an original mineralogy consisting of augite and labradorite with accessary hornblende, ilmenite, apatite and quartz. Some samples have undergone uralitization and sausseritization, resulting in replacement of pyroxene by actinolite and replacement of labradorite by epidote, sericite and albite. In one sample that is veined by calcite [429A], biotite and riebeckite form an ophitic texture with albite. Although Spry (1952b) considered the dolerites to be intrusive into the surrounding breccia, he noted the lack of any contact metamorphic aureole. The amygdaloidal basalts are described in very similar terms as the dolerites. The amygdals are filled with calcite, the groundmass is devitrified consisting of albite, actinolite, epidote, chlorite, calcite and opaques, and primary mineralogy is largely destroyed by alteration (Spry, 1952b).

Further detailed mapping of the Worumba Anticline by Preiss (1985) identified chloritic dolomite marble surrounding a dolerite plug with a chilled margin, all of which forms a diapiric xenoclast indicating that although the dolerite is indeed intrusive, it and its surroundings have been emplaced into their present position by diapiric activity. Other dolerites were mapped intruding Niggly Gap Beds (Callanna Group). No intrusives were found intruding beds above the Callanna Group sequence. Preiss (1985) concluded that the dolerite intrusives may postdate the basalts and were altered and exposed prior to Sturtian tectonism, thus defining an age of emplacement between latest Willouran to earliest Sturtian.

A small plug of diorite was reported occurring in the Windowarta Diapir, located 34km east of the Worumba Anticline (Langsford, 1969). The intrusive/xenoclastic nature of this locality is presently unknown.

2.5.4 Northern Flinders Ranges.

Barnes (1972) described the occurrence of igneous rock in the largest diapir body in the Adelaide Geosyncline, the Burr Diapir, as "microdiorites and microandesites" with some coarser grained diorites and "microgabbros", with the largest single body measuring 700m by 240m. The diorites are plugs or dyke-like bodies and show intrusive relations within the "crush zone" sediments. The largest intrusion is surrounded by a zone of quartz-amphibole-chlorite-biotite-hornfels and calc-silicate rock considered to be a contact metamorphic aureole in the Skillogalee Dolomite. Most igneous masses, however, lack any contact metamorphic effect which Barnes (1972) attributed to be due to shallow depth of intrusion. Also found within the diapir are amygdaloidal basalts which may be the extrusive equivalent of the intrusive "microdiorite". These basalts are petrographically different to the Willouran Wooltana Volcanics of Crawford (1963) (Barnes, 1972).

The intrusive lithologies are composed of andesine-oligoclase with amphibole (?actinolite) or biotite which has ubiquitously replaced primary pyroxene or amphibole. Also present are secondary epidote, chlorite, sericite and scapolite with sphene and magnetite. The volcanics have undergone similar alteration with amygdals filled with biotite, carbonate or geothite. Barnes (1972) proposed that the mineral assemblage reflects hydrothermal alteration which took place soon after intrusion, postulated to be during the closing stages of the Duttonian Folding event.

Twenty kilometres northwest of the Burr Diapir lies the Lyndhurst Diapir, within which diorite and microdiorite are reported to intrude the diapir and in part cause copper mineralization (Wright & Binks, 1969). Within the Beltana Diapir, 66km southwest of the Burr Diapir, Leeson (1970) mentions the presence of two small plugs of scapolitized hornblende-quartz rock.

2.5.5 Southern Flinders Ranges.

Within the Melrose Diapir, located at the base of Mount Remarkable, Howchin (1916) noted the presence of discrete igneous bodies occurring within breccia. Theile (1916) identified the rocks as altered dolerites, quartz porphyries (including a quartz ceratophyre) and aplites (*cf.* Table 2.1 *anal.* O). The dolerite, including an olivine-bearing gabbroid dolerite, is composed of uralitized pyroxene and labradorite with secondary epidote and calcite. The acid porphyritic rocks were noted intruding the dolerite, and composed of feldspar phenocrysts with secondary chlorite replacing biotite, secondary albite and abundant calcite and calcite veinlets.

Near the Great Gladstone Diapir, located 38km north of the Melrose Diapir, Hiern (1965) described chloritized porphyritic microdiorite, both on the western flank of the diapir and intruding Umberatana Group sediments just north of the diapir.

The Mt. Grainger Diapir, located 30km northeast of Peterborough, is host to andesite dykes, amygdaloidal and trachytic basalts which show no contact metemorphic effect but are associated with quartz-tourmaline veining in nearby rocks (Wright, 1966). Original mineralogy of the andesite includes oligoclase-andesine, amphibole, pyroxene, biotite and magnetite which has been altered to tremolite, epidote, chlorite, muscovite, albite, carbonate, rutile and micaceous haematite.

Sixty kilometres northeast of Peterborough lies the Paratoo Diapir, in which occur plugs of medium to coarse grained dolerite, and around which exists a zone of thermally metamorphosed sediments consisting of fine grained hornfels (Hiern, 1965). Nixon (1965) described intermediate and acid igneous rocks which intrude both the Torrensian (Burra Group) strata and the dolomite clasts in the core of the diapir. The texture of the diorites are highly variable with phenocrysts of hornblende or feldspar set in a fine grained feldspathic or amphibole- (?actinolite-) rich groundmass with opaque minerals. Secondary green biotite and quartz is present along with epidote and chlorite. Chilled margins were noted along contact zones.

Nixon (1965) also reported the presence of granite within black carbonaceous shales, but was unable to determine it's relationship (possible tillite?).

In the Bulyninnie Crush Zone, located 28km east of the Mt. Grainger Diapir, Mirams (1960) mapped one plug of dolerite intruding Marinoan (?) sediments. However, Hiern (1965) identified several small plugs intruding diapiric breccia. Mount (1975) has identified amphibolites in the Thompson Gap Diapir, 14 km northwest of Quorn, as reworked fragments of former dolerite dykes and plugs, with possible volcanic and lamprophyic affinities.

2.5.6 The Arkaba Diapir.

Crawford (1957) noted the presence of basic intrusive rocks in dolomitic limestone associated with crocidolite mineralization 16km north-northeast of Hawker. The rock was identified as a diorite consisting of 60% andesine, 35% amphibole and 5% opaques with up to 20% sericitized feldspar. The amphibole is a pale green variety (?actinolite) partly replaced by blue glaucophane (?riebeckite).

Mount (1975) identified only one *in situ* metadolerite plug in Mount Desire Dyke, concluding that the remainder of igneous material in the Arkaba Diapir represents xenoclasts. The clasts, most of which are dolerites, range from diorite to gabbro in composition with andesine as the dominant plagioclase species. Also noted occurring are rare amygdaloidal intrusive dolerites, lamprophyres (including kerstantite) and fine grained mafic igneous rocks. Extrusive varieties are largely amygdaloidal basalts with some trachytes and metatrachytes. The shapes of the igneous masses are subangular with a sharp contact with the surrounding breccia and lacking either a chilled margin or contact metamorphic aureole. Alteration, which predates brecciation, is ubiquitous and often intense, producing secondary products including

> "saussurite, epidote, uralite, albite, chlorite, biotite, quartz, carbonate, haematite, limonite, goethite, leucoxene, clay, magnetite, antigorite, sericite, zoisite, clinozoisite, riebeckite, actinolite, specularite, sphene and malachite"

(Mount, 1975).

The size of the igneous bodies is generally smaller than that of the sedimentary breccia clasts. They do not occur outside the zone of brecciation. An amygdaloidal dolerite dyke intruding "rafts" of Willouran sediments indicates that at least one phase of igneous activity predates diapirism, perhaps related to Wooltana volcanism. Mount (1975) suggested that the *in situ* plug may be related to Delamerian Orogenic activity.

2.5.7 Northern Mount Lofty Ranges.

In the Robertstown Breccia Zone, north of Robertstown, mafic igneous bodies have been described in association with magnesio-riebeckite deposits (Wymond & Wilson, 1951; King, 1955: *cf.* Table 2.1 *anal.* U). Mount (1975) identified these bodies as metadolerite and rare gabbroid xenoclasts in the breccia consisting of tourmaline, biotite and feldspar with lamprophyric affinities. The extent and style of alteration is similar to that described for the Arkaba Diapir with joint planes filled by asbestos.

2.6 Spalding Inlier and Burra.

Syenite porphyries were described cross-cutting "obvious" bedding in the Burra copper mine. These are characterized by the presence of a quartz-tourmaline metasomatic alteration aureole. Dickinson (1942) suggested plutonism was responsible for copper mineralization. The mine is located at the contact between Burra Group Skillogalee Dolomite and diapiric breccia. The igneous material is situated entirely within the sedimentary strata (Nixon & Townend, 1966) which Scriven (1977) has re-interpreted to be tuffaceous volcanics, indicating extensive potassic metasomatism. Drexel & McCallum (1986) referred to "volcanic intrusions" (?) and postulated that copper mineralization may be related to Jurassic volcanism.

Unlike the Willouran xenoclast-bearing diapiric breccia structures, the Willouran (*River Wakefield Subgroup*) Spalding Inlier is bounded by thrust faults and has no brecciation. Intermediate to basic igneous rocks as dykes, sills or plugs including kersantite, dolerite, gabbro, microsyenite, diorite, andesite, dacite and quartz andesite intrude this inlier. As the igneous rocks are restricted to the inlier, they are thought to predate the depostion of surrounding Burra Group sediments. Alteration of these rocks is considered to be due to regional metamorphism to greenschist facies. This produced a secondary mineral assemblage of quartz-albite-epidote-biotite, although an amphibolite of the almandine-amphibolite facies was noted (Blissett, 1967). Forbes & Johnson (1966) reported hornfelsized and skarnified contact zones with calcareous beds of the River Wakefield Group including an epidote-cummingtonite contact metamorphic skarn with a sill-like gabbroic intrusion. Blissett (1967) suggested that intrusion of the gabbroic body during the Delamerian Orogeny resulted in secondary skarnification.

2.7 Mount Painter Region.

2.7.1 Intrusives within Crystalline Basement.

Crystalline basement rock is exposed in the Mount Painter region. Two major exposures account for the *Mount Babbage Inlier* and the *Mount Painter Inlier*. Intruding into the crystalline basement inliers are two generations of granite; the "Older Granite Suite" (Coats & Blissett, 1971) of which the *Yerila Granite* was dated by U-Pb to be 1551-1556 Ma (Johnson, 1980; Thornton, 1980), and the *Mudnawatana Granite* (Bowes, 1953) was dated by Compston *et al.* (1966) to be Delamerian or post-Delamerian in age (431+/-7 Ma). Very little work has been accomplished with regards to the Mudnawatana Granite.

Teale (1979) subdivided the Palaeozoic intrusives, or the "Younger Granite Suite" of Coats & Blissett (1971) into the *Mudnawatana Tonalite* of the northern Mount Babbage Inlier, and the *British Empire Granite* and the *Gordon Springs Granodiorite* of the southern Mount Painter Inlier on the basis of petrographical and geochemical differences.

The largest single pluton within crystalline basement, the British Empire Granite, is approximately 4km wide and 8km long, and composed of fine to medium grained muscovite-biotite granite. Teale (1979) described this intrusive as a non-foliated, post-Delamerian partially conformable sill dipping shallowly to the west. Teale (1979) also reported that the high SiO_2, peraluminous chemistry and high initial $^{87}Sr/^{86}Sr$ ratio for the British Empire Granite is analogous to "S-type" granites.

The Gordon Springs Granodiorite forms small stocks and dykes of fine grained grey biotite and/or hornblende granodiorite within the crystalline basement, located to the south of the British Empire Granite. Teale (1979) suggested that the presence of weak foliation within the granodiorite is indicative of pre-Delamerian intrusion. However, if the foliation is from primary biotite and parallel to the regional tectonic trend, as with the Anabama Granite, then the granite may alternatively be syn-tectonic. The chemistry and mineralogy of the Gordon Springs Granodiorite is indicative of "I-type" plutons (Teale, 1979).

The Mudnawatana Tonalite is a slightly foliated medium grained biotite tonalite forming a 4km long by 3km wide pluton within the northern Mount Babbage Inlier. Teale (1979) suggested this pluton is a pre-Delamerian "I-type", as indicated by its low initial $^{87}Sr/^{86}Sr$ ratio (0.7045+/-0.0012).

2.7.2 Intrusives within Adelaidean Sediments.

Sediments of the Burra and Callanna Groups were deposited upon the southern margins of the Mount Painter Inlier. It is within these sediments and their brecciated equivalents that occurs a variety of igneous bodies referred to as part of the "Younger Granite Suite" by Coats & Blissett (1971) (*cf.* Preiss, 1987 p.83). The igneous material is described as localized mafic and intermediate dykes and sills of uralitized dolerite and gabbro intruding basal Callanna Group Paralana Quartzite beds and Marinoan Wilpena Group strata. These rocks are dominated by hornblende and plagioclase (labradorite to andesine). Coats & Blissett (1971) suggested that the mafic intrusives represent two phases of magmatism; one associated with the extrusion of the Willouran Wooltana Volcanics, and the other later phase intruding in response to the onset of the Delamerian Orogeny.

Mawson & Dallwitz (1945) recounted the occurrence of "soda-rich leucogranite cupolas" in a zone south of the Mount Painter crystalline basement. These outcrop localities are referred to as "the Needles", "the Pinnacles", "Tourmaline Hill", "Sitting Bull" and "Giants Head", with the largest of thirty mapped bodies being approximately 200m in diameter (*cf.* Table 2.1 *anal.* R-T). These bodies are considered to be intrusive into the surrounding Callanna Group and Burra Group sediments (Preiss, 1987). The intrusives are enveloped in a contact metamorphic aureole hornfels which is sometimes with brecciated or distorted sediments (Collerson, 1984; Turner, 1976; Mawson & Dallwitz, 1945). Coats & Blissett (1971) suggested that the bodies are rafted remnants of Callanna Group intrusives, and proposed a Willouran age for emplacement. However, Collerson (1984) noted that this suite of apogranites intruded both Burra Group and Umberatana Group sediments indicating a later date for emplacement. Lottermoser (1987) and Teale & Lottermoser (1987) referred to the intrusives as Palaeozoic, but did not provide reasons (*cf.* Table 2.7.2).

Most rocks are fine to medium grained, but pegmatitic equivalents are present with crystals up to 10 cm in diameter. They are composed of albite-quartz-microcline-tourmaline-sphene-mica, occasionally including garnet-apatite-leucoxene-fluorite with abundant vughs forming a "spongy" or granular texture. The secondary replacement of alkali feldspar by albite and tourmaline, and the extensive thermal metamorphism of the immediate country rock to hornfels and marble, indicate extensive Na^{+}, B^{+3} and Cl^{-} metasomatism. The abundance of fluid inclusions (both liquid and gas) in aplites, pegmatites and the "spongy" masses attests to crystallization from volatile-rich magmatic fluids (Mawson & Dallwitz, 1945; Collerson, 1984).

Turner (1976) suggested that a linear formation of albite-bearing intrusive bodies with one uralitized metadolerite corresponds to a fault plane, inferring that emplacement was dominated by structural weaknesses in the underlying Adelaidean strata. Rb-Sr geochronology of an igneous intrusive (Armchair granite) into crystalline basement of the Mt. Painter Inlier recorded dates of 514 Ma and 531 Ma with initial $^{87}Sr/^{86}Sr$ ratios of 0.7203 and 0.7190 respectively, while leucocratic granites gave an age of 450 Ma (initial $^{87}Sr/^{86}Sr$ ratio = 0.7048) (Webb, 1976).

Fluid inclusion studies by Searson (1975) have placed the conditions of formation at a temperature range of 444°C to 553°C and a pressure range of 0.65 to 1.27 kbars, concluding that the bodies were rapidly and forcibly intruded at high crustal levels. Secondary inclusions exhibit two ranges of temperatures; 83-128°C and 374-404°C, with salinities approaching 20% NaCl. Thus shallow intrusion of the magma body was followed immediately by a period of saline hydrothermal activity. Further work by Lottermoser (1985; 1987) indicated maximum NaCl saturation of 60% in initial magmatic fluids greater than 537°C and pressures in excess of 1.1kbars. Albitization was due to hydrothermal activity in a partially crystallized magma with evidence for incipient fenetization and incompatible element transport (Collerson, 1984). Final F, B and CO_2 degassing resulted in internal hydraulic fracturing with subsequent tourmalinization and phlogopitization of both the granite and country rock. The geochemistry of these rocks from Teale & Lottermoser (1987) is presented in table 2.7.2 and shows them to be enriched in MnO, P_2O_5, Nb, Ta, Be, F and B. They are considered by Teale & Lottermoser (1987) to be A-type anorogenic granites.

Collerson (1984) noted the presence of a 75-100m diameter glimmeritic diatreme composed of chlorite after phlogopite, olivine and pyroxene cross-cutting hornfels immediately east of the Tourmaline Hill location. The chlorite chemistry and REE values for the diatreme, which postdates the granite, is similar to kimberlitic material and is probably mantle-derived (Collerson, 1984). Lottermoser (1985) suggested that violent emplacement of this body from mantle-derived fluids caused brecciation of the previously formed thermal alteration halo around the Tourmaline Hill Granite. Lottermoser (1988) expanded on this concept in describing the entire area, previously mapped as diapiric breccia, as a carbonatitic diatreme. However, his description of the breccia remained identical to other authors (*e.g.* Lemon, 1985 and Mount, 1975) who invoked an evaporite diapiric model for brecciation. Furthermore, his Rb-Sr date (418+/-2 Ma) for emplacement of the altered granitic bodies in the region was not substantiated, and may alternatively reflect the age of subsequent alteration. Altered granitic clasts in the breccia probably represent pre-Delamerian intrusives that have been incorporated into Delamerian-induced diapiric breccia remobilization (as indicated by the presence of deformed feldspars; Lottermoser, 1988).

North of the Pinnacles, intruding Callanna Group sediments, occurs a 700m lenticular body of pegmatite known as the "Arkaroola Pegmatite". This pink pegmatite is composed of tourmaline-bearing microcline-quartz with a grain size of 3 cm, and intrude the basal Callanna Group Paralana Quartzite and Wooltana Volcanics. Kleeman

(1946) acquired a U-Pb date of 400+/-50 Ma for samarskite from a pegmatite(?) intruding the crystalline basement, claiming the date to reflect a metamorphic event. Compston *et al.* (1966) recorded an Rb-Sr date of 460 Ma for the Arkaroola Pegmatite. Contact metamorphism around the main 0.24km^2 pegmatite mass has resulted in biotitization of the immediate sediments. Many similar bodies of pegmatite occur north of this locality in the Mount Painter Block, and are thought to be related (Turner, 1976).

2.8 Willouran Ranges.

In the Willouran Ranges, Murrell (1977) mapped what he considered to be crystalline basement exposures within Callanna Group sediments and their brecciated equivalents. These rocks are described as metasomatized gabbros and (monzo)syenites forming "scapolite-epidote-biotite rock", "albite-epidote-biotite rock", "albite-chlorite rock" and "albitites". Intruding the Callanna Group sediments and Murrell's (1977) so-called crystalline basement, but not the Burra Group, are dolerite and "soda-minette" lamprophyre dykes. In the area designated as the "Euromina Window", Murrell (1977) claimed that

> "the boundaries of the basement inlier are not well exposed but are approximately marked by an irregular zone of jaspilites and haematized conglomerates which either overlie or are associated with basement porphyries".

No further attempt is made to describe any contact relation or cite other evidence in support of these rocks being crystalline basement to the Callanna Group strata.

Parker (1983) mapped a section the Willouran Ranges in the vicinity of Rischbieth Well, located 25km southwest of Callanna Station. In this locality, Parker (1983) described the "Rischbieth

Structural Complex", of strongly deformed, distorted and brecciated Callanna Group strata which are "locally intruded by semi-circular, albitic, monzonite-syenite-diorite plugs". Subsequent drilling of one of these plugs has shown it to be equivalent to the Noranda Volcanics, consisting of interlocking plagioclase with intersertal amphibole (actinolite or riebeckite), epidote, quartz and sulphides (Farrand & Parker, 1986).

Detailed examination of albitite bodies by the author along the vicinity of the Bungarider fault has shown them to have radiating dykes and contain xenoliths of the surrounding sediments indicating that they are intrusive to the Willouran strata. Similarily, the gabbros, diorites and quartz diorites located at the northern end of the Mirra Creek within the Willouran Ranges (Fig. 2.8.1), intrude quartzites and carbonate, confirming the intrusive nature for these rocks. Drilling by Utah Development (1976) (Eurominna core, WD-33) into diapiric breccia transected through a 61m section of an altered gabbro-diorite body in Murrell's (1977) "*Euromina Window*" (or his so-called "crystalline basement") back into diapiric material. It has shown that the igneous body, characterized by an albitized margin, is unequivocally surrounded by brecciated and distorted Callanna Group sediments. The presence of abundant felsic veinlets at the top and bottom contacts suggests an intrusive relation analogous to intrusives in the Peake and Denison Ranges. The lack of a brecciated pluton margin indicates emplacement into previously mobilized diapiric material.

Much of Murrell's (1977) basement intrusive "porphyry" contains ripple marks and interbedded carbonates. This "porphyry" more closely resembles *Rook Tuff* (Willouran) volcanics which outcrop extensively north and northeast of the "Eurominna Window" locality, also identified by Preiss (1987). In fact, there is little evidence to indicate that any of the igneous and altered igneous material exposed in the Willouran Ranges is crystalline basement; a conclusion supported by B.F. Forbes (*pers. com.*) and Preiss (1987). Like exposures in the Peake and Denison Ranges and the Arkaroola region, the igneous rocks are intrusive to the Early Adelaidean sediments. It may be argued that the igneous material is exhumed crystalline basement. However, the lack of any siliceous granites or demonstrably metamorphosed crystalline cratonic material (*e.g.* foliated granites and schists as found in the Blinman diapir) excludes an Early to Middle Proterozoic source.

The majority of plutonic rocks are either gabbroic, dioritic or their altered equivalents (*e.g.* albitite). Of the gabbroic lithologies, the main mafic minerals are biotite and amphibole. Clinopyroxene (diopside-salite-augite, endiopside) was noted in some samples [8507-8] which have been invariably partially altered to chlorite. The primary turquoise amphibole is kaerstutite containing over 4 wt.% TiO_2; secondary pale-green replacement amphiboles are tremolite to actinolite. Kaersutite was noted to mantle clinopyroxene. Biotite occurs as both large, zoned, dark-brown (primary) and red-brown (secondary) flakes, with normally ~2 wt% TiO_2, but also some samples with over 6 wt.% TiO_2. Sphene and apatite are the most common accessory phase. Plagioclase is the dominant felsic mineral which has been albitized in altered samples. Unaltered gabbros [8508] have strongly zoned plagioclase with bytownite (An_{84}) cores and oligoclase (An_{24}) rims. Secondary minerals include scapolite, chlorite, albite and calcite. Epidote may be both primary and secondary. Minor oxides are almost exclusively ilmenite. Haematite appears as an alteration product. Extensively scapolitized and saussuritized gabbroic rocks (*e.g.* [8507]) still retain their original igneous texture. Relict subhedral amphibole and sphene are present although most other primary minerals have been superceded by pronounced secondary phases.

Felsic lithologies are often diorite or altered diorite; usually composed almost entirely of albite. Diorites [8800-1, 8517] have biotite, both primary brown and secondary red-brown, as the main mafic component. Secondary alteration products include scapolite, calcite, epidote and actinolite (?tremolite) which sometimes form pseudomorphs after ?pyroxene. Albite and minor alkali feldspar are the main felsic constituents with minor ilmenite and sericite. The major form of alteration is albitization. Some albitites [8503] have twisted crystals displaying prominent undulose extintion, as do quartz grains, indicating they have undergone (?regional) deformation. Albite commonly has chessboard twinning around margins of grains, and invariably involves replacement by secondary haematite and calcite.

The geochemistry of a suite of these intrusive bodies is presented in table 2.8. Most of the major oxide concentrations are comparable to the basic igneous volcanics of the Callanna Group. Of the trace elements, most readily noted are excessively high chlorine (up to 12,660ppm Cl), and high niobium (up to 125ppm Nb). The high chlorine content reflects the importance of scapolite as a secondary alteration product. Scapolitization has also been noted as a characteristic alteration mineral for the Wooltana Volcanics (Hilyard, 1986). However, the Wooltana Volcanics have very low Nb concentrations. Comparable high Nb has been recorded in the intrusives of the Arkaroola region (Teale & Lottermoser, 1987). Further discussion of the significance of the geochemistry will be reserved for later chapters.

2.9 Peake and Denison Ranges.

The 120km-long and 24km-wide Peake and Denison Ranges are composed of a series of Middle Proterozoic and Adelaidean inliers, located 200km northwest of the Willouran Ranges. A belt of plutonic rocks intrudes Callanna Group and Burra Group strata in the northern section of the largest inlier of the Peake and Denison Ranges; the Margaret Inlier. The largest pluton exceeds 3km in diameter, but most of the more than thirty separate plutons range from 0.5 to 1km in diameter (Morrison, 1986).

Brown (1894) and East (1889) mentioned the existence of a variety of intrusive igneous lithologies in the Peake and Denison Ranges, but it was not until Reyner's (1955) examination that a geological map was produced clearly defining the presence of intrusive material into Adelaidean strata. Of these, Reyner (1955) described the two largest plutons as medium to coarse grained red granite and smaller plugs, dykes and sills of albitite; all with clearly intrusive relations to the surrounding strata, but lacking contiguous thermal metamorphism with the exception of minor silicification. Also noted were large dykes and smaller irregular plugs and sills of basic intrusives predominantly composed of epidote, actinolite, oligoclase-andesine and magnetite.

Remapping of the Peake and Denison Ranges by Ambrose *et al.* (1981) has shown that the intrusives, named the *Bungadillina*

Monzonite, intrude Burra Group, and to a lesser extent, Callanna Group sediments. A portion of their map showing the north and central sections of the Margaret Inlier is presented in figure 2.9. They also were noted to occur within zones of diapiric breccia or distorted blocks of Burra Group sediments. These plutons were described as monzonites, syenites, albitites and minor granites composed of zoned plagioclase (An_{30-40}), which sometimes mantle alkali feldspar, quartz, augite, hornblende and biotite. Accessory minerals include sphene, epidote, garnet, magnetite and calcite (Turner, 1969). Other intrusive bodies include felsic spherulitic and dolerite dykes. The dolerite dykes are described as "long linear outcrops, which suggest a late-stage orogenic time of intrusion" (Ambrose *et al.*, 1981), composed of augite, olivine and plagioclase with uralitized equivalents (Turner, 1969). Also revealed was that much of Reyner's (1955) basic intrusives are in fact Callanna Group volcanics.

On the basis of K-Ar dating (six analyses of which recorded ages 500-470 Ma), Ambrose *et al.* (1981) concluded that the intrusives formed as the result of the Delamerian Orogeny. However, one ambiguous analysis recorded a date of 680 Ma, and a basic intrusive, thought to predate the emplacement of the Bungadillina Monzonite suite, recorded an age of 537 Ma.

The Peake and Denison Ranges are oriented parallel to the main north-northwest to south-southeast fault trend. Most of the major fold axes are also oriented in the same direction, as is the strike of most of the Adelaidean strata. Delamerian deformation has produced generally broad, open folds, becoming tighter to the eastern margin of the ranges. Parker (A.J.; *pers. comm.*) has observed that the area in the northern section of the Margaret Inlier as defined by the Bungadillina suite corresponds to a "structural ridge"; such that folds to the north of this ridge plunge to the north, and folds to the south plunge to the south. This feature is not apparent from the mapping of Ambrose *et. al.* (1981). However, it was noted in the course of detailed mapping in the vicinity of the Bungadillina suite that the main fold and strata orientation was not north-south, but *east-west*. Ambrose *et al.* (1981) has also identified other narrow east-west structural zones within the Margaret Inlier 15km east and 27km east southeast of Meyanungada Hill (*cf.* Fig. 2.9). All of these east-west structural zones are characterized by the presence of diapiric breccia, and one is characterized by the occurrence of doleritic intrusives.

This east-west "structural ridge" may be in response to the emplacement of the Bungadillina suite, or, as reported by Ambrose *et al.* (1981), from faulting along the *Karari Fault Zone*, which supposedly transects the Margaret Inlier at the same locality. However, these two structural explanations do not account for the east-west zones in the more southerly sections of the Margaret Inlier. It is not clear whether or not a second Delamerian deformation event produced these east-west zones. An alternative explanation is that these east-west structural zones occurred in response to pre-Delamerian diapiric activity which were subsequently remobilized during Delamerian tectonism. This would also account for the presence of diapiric breccia within these zones, and the apparent orientation (wide in the west and thin in the east), indicating direction of emplacement (from stratigraphic base to top).

2.10 Jurassic Dolerites and Kimberlites.

Small but numerous occurrences of kimberlite intrusions have been recorded in the vicinities of Orroroo and El Alamein in the northern Mount Lofty and southern Flinders Ranges (Turner & Parker, *in prep.*). Three kimberlite sills up to 2m thick have been noted intruding along a 25km belt of Adelaidean sediments (Tent Hill Fm.) of the Stuart Shelf (Stracke *et al.*, 1979). These kimberlites have been dated by K-Ar, Rb-Sr and U-Pb methods to be 170-172 Ma (Stracke *et al.*, 1979; Scott-Smith *et al.*, 1984; Black *et al.*, unpubl.). They belong to the ultra-potassic kimberlite suite, and are moderately enriched in incompatible elements (Ferguson, 1986).

East of Orroroo, kimberlites have been described consisting of irregularly shaped diatremes, the largest measuring 6.5ha, and dykes up to 2m wide intruding anticline hinges of Burra and Umberatana Groups sediments (Ferguson *et al.*, 1979). The kimberlites have crushed, shattered (up to 1.5m) or slickensided contacts with small contact metamorphic aureoles (10cm) (Colchester, 1972), and have been dated by Rb-Sr to 164-174 Ma. These kimberlites contain eclogite and granulite xenoliths with chrome pyrope, picroilmenite and chrome diopside xenocrysts. Scott-Smith *et al.* (1984) have classified the intrusives as a hypabyssal, calcite-phlogopite kimberlite, consisting of olivine megacrysts in a groundmass of carbonate, phlogopite, perovskite, olivine, spinel, apatite, clinopyroxene, serpentinite and monticellite. Some dykes were found to be diamondiferous, but none approaching economic grade (Scott-Smith *et al.*, 1984). Also described in the area is a 3-8m wide leucite lamproite dyke extending for nearly a kilometre (Colchester, 1982).

Tucker & Collerson (1972) have also recognized lamprophyric dykes up to 1m wide in the Walloway Diapir, located 18km northwest of Orroroo. Two types of lamprophyre were identified; one characterized by mica phenocrysts, the other by sepentinized olivine phenocrysts, with 50% to 80% carbonate in the groundmass. Minor constituents include chlorite, magnetite, ilmenite, chromite, apatite, zircon, perovskite and possible melilite. High trace element concentrations of Ce, La, Nb, Ba and Sr found in the lamprophyric rocks have been likened to primary magmatic carbonatites, but without the appropriate indicator minerals, they could not be classified as kimberlites (Tucker & Collerson, 1972). However, as the second of the two types of lamprophyres is petrographically similar to the Orroroo kimberlites, and as kimberlites have been reported by Stracke *et al.* (1979) and Ferguson & Sheraton (1979) occurring within 2 km of the Walloway location, Scott-Smith *et al.* (1984) have suggested they formed from the same magmatic event. Mount (1975) contended that the Orroroo kimberlites are xenoclasts which may have originally intruded a growing diapir, or alternatively been incorporated into the diapir from a sedimentary section.

The kimberlite occurrences have been petrogenetically classified on the basis of presence of mantle derived components. While some intrusions have kimberlitic garnets and diamonds obviously acquired from considerable depth in the mantle, others have had a shallower origin (Scott-Smith *et al.*, 1984). The age of kimberlitic activity corresponds to the initial fragmentation of Gondwanaland, but more complete comprehension of the tectonic configuration of the kimberlites and associated rocks requires further research.

2.11 Discussion.

From the preceding compendium on recorded igneous intrusive rocks in the Adelaide Geosyncline, certain characteristics are common to the majority of occurrences:

(1) Apart from the Bendigo and Anabama Granites, the igneous bodies form a volumetrically insignificant component of the entire Adelaide Geosyncline.

(2) Other than the post-tectonic granites of the Kanmantoo Trough, most of the igneous lithologies intruding Adelaidean sediments have been altered to some degree, usually through sodic, carbonate or alumina metasomatism. Some have been subject to scapolitization, and others are associated with Cu-Mo porphyry(?) mineralization.

(3) Apart from the Kanmantoo Group occurrences, plutonic bodies most commonly intrude Burra or Callanna Group strata, or are found in association with Callanna Group clasts in diapiric breccia.

(4) With the exception of the Anabama Granite, and some of the larger bodies of the Kanmantoo Group, the intrusives are small; seldom exceeding a kilometre in diameter.

(5) Structural deformation from Delamerian tectonism is largely limited to the syn-tectonic granites of the Kanmantoo Group, the granites intruding crystalline basement in the Mount Painter region, and the Anabama Granite. Deformation usually forms a weak mineral foliation parallel to the regional structure, but can range up to gneissic foliation as has developed within the Rathjen granitic gneiss (syn-tectonic granite; Kanmantoo Group).

The Bendigo and Anabama Granites can clearly be separated from other igneous occurrences. They intrude Umberatana Group sediments, have a prominent contact metamorphic aureole, and are host to copper mineralization accompanied by a style of alteration similar to porphyry-type Cu deposits. Their chemistry, mineralogy and structural setting associates them more closely to the Cambro-Ordovician granites of the Kanmantoo Group.

Of the igneous bodies that occur within areas of diapiric breccia, there continues to be controversy whether they are indeed intrusive or merely floating rafts exhumed from earlier stratigraphic positions. Lottermoser (1988) envisaged a post-Delamerian carbonatitic model for breccia formation and granite genesis in the Arkaroola region. In the Blinman Dome, the gneissic granite bodies are incontronvertibly crystalline basement that has been incorporated into a rising diapir. Gabbroic and dolerite bodies within the Blinman Dome and other diapiric bodies such as the Worumba Anticline have been the subject of scrutiny. The consensus of authors has it that many of the igneous bodies are either intrusive to the breccia or were originally intrusive to Geosyncline strata prior to breccia mobilization. Gum (1987) indicated that basaltic igneous bodies in the major diapirs are exhumed Willouran volcanics or coarse-grained equivalents (*i.e.* feeder dykes or cores of thick flows). Nevertheless, numerous authors have reported occurrences of dioritic bodies intrusive to their immediate strata. The precise stratigraphic allotment of these intrusives remains unresolved.

Kimberlitic intrusive bodies are again a clearly defined separate group identified by their gross mineralogical and geochemical differences. These Jurassic intrusives, like Jurassic basic dyke swarms, must be treated as a separate event in a very different but related environment: in particular, the rifting of Gondwanaland. Although the formation of a seafloor between eastern Antarctica and southern Australia was not completed until 53-55 Ma, the intrusion of dolerites and the extrusion of tholeiitic continental basalts as the result of an extensional rifting regime dates back to the Jurassic (Harrington *et al.*, 1973; Veevers & McElhinny, 1976).

The location and timing of igneous activity in the Adelaide Geosyncline appears to be largely controlled by crystalline basement tectonics. Callanna Group basic volcanism accompanied rapid stretching (? brittle fracturing) of the continental lithosphere and mantle upwelling; a common feature in the early development of sedimentary basins (*e.g.* Royden & Keen, 1980; McKenzie, 1978). After this initial period of volcanism, insufficient lithospheric extension during the growth of the Adelaide palaeo-basin probably prevented the development of a sufficiently high thermal gradient required for further magmatic activity, especially that which involves the melting of continental crust (Fyfe, 1987). Minor magmatism during Geosyncline sedimentation was localized, and probably fault-controlled.

Similarily, an insufficiently high geothermal gradient in the Adelaide Geosyncline (other than the Kanmantoo Trough, and immediately around and within the Mount Painter crystalline basement) during the Delamerian Orogeny discouraged the participation of prominent magmatism. In contrast, the high metamorphic grade reached during Delamerian metamorphism of the Kanmantoo Group sediments indicates that the geothermal gradient was high enough to promote widespread plutonism when coupled with a very hydrous source material (pelites) for melt production (Clemens & Vielzeuf, 1987). Resurgence of widespread magmatism in the Kanmantoo Trough occurred immediately after the Delamerian compressional phase in response to orogenic collapse and rising mantle-derived mafic plutons (Foden *et al.*, 1989).

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Chapter Three: Field Geology and Petrography of the Intrusives of the Peake and Denison Ranges.

"Eastward of Boorthanna, towards the higher portion of the ranges, there are large outcrops of diorite, intruded into quartzite, sandstone, and slate. These outcrops are not in defined dykes, but generally in large bosses and hills... Further towards the northern end of the Dennison* Range, besides diorite, there are hills of syenite, porphyry, and granite, containing much epidote."

H.Y.L. Brown reporting on the Peake and Denison Ranges for gold mineralization (1894).
* Spelling as recorded.

3.1 Introduction.

Unlike many occurrences of plutonic bodies within the Adelaide Geosyncline (especially those found within diapiric breccia), the intrusive relation of the Bungadillina suite in the Peake and Denison Ranges has never been contested. Since the first reported descriptions of the geology of the Peake and Denison Ranges, the intrusives in the northern section of the Margaret Inlier have always been known to clearly intrude the surrounding Adelaidean strata. In the proceeding chapter, the geology and petrography of this suite of rocks are presented. Maps presented in this chapter have been based on 1:10,000 scale colour aerial photographs. References to specific samples (*e.g.* [7501]) are recorded in the text, and the reader is encouraged to confer with petrographical and modal mineralogical tables accompanying this chapter and in Appendix A.

The intrusive lithologies of the Peake and Denison Ranges have been broadly subdivided into seven major groups including monzogabbros, syenogabbros, monzonites, syenites, quartz monzonites, quartz syenites and alkali syenites, with gabbroic lithologies having more than 35% modal mafic constiuents (*cf. Terminology and*

Classification). The modal mineral classification of 49 samples of the Bungadillina suite is presented in figure 3.1 and table 3.1. From this quantitative modal basis, and in conjunction with geochemical analyses (*cf.* Table 5.1), the remaining samples of the Bungadillina suite were visually classified. The entire petrographic report is presented in Appendix A.

Many of these rocks have invariably undergone some degree of sodic alteration. In the extreme case, this presents the eighth lithological group, albitites, which is composed of over 90% albite plagioclase (*e.g.* Plate 3.5 Penultimate to Bottom Right). Whole rock geochemical analyses aided in identifying significantly albitized samples ($Na_2O/Na_2O+K_2O>0.76$). In contrast, most plutons of the Kanmantoo Trough extending through to Anabama are coarse grained granites and granodiorites (*sensu stricto*), and most mafic bodies in diapiric breccias elsewhere in the Adelaide Geosyncline are best described as metadolerites and metabasalts.

The most prevalent lithologies of the Bungadillina suite, usually forming smaller plutons and sills, are medium grained hypidiomorphic equigranular monzonites, monzodiorites and syenites composed of varying amounts of alkali feldspar, plagioclase (oligoclase-labradorite) and mafic constituents with minor free quartz (*e.g.* Plates 3.2 Bottom Left; 3.1 Bottom Right). Mafic mineralogy includes euhedral to subhedral hornblende, biotite and/or clinopyroxene (diopside-salite). The mafic component can vary considerably within individual plutons from relatively mafic-free lithologies to monzogabbros and syenogabbros, often without any apparent inter-intruding relation. There often exists a continuum or gradational contact between contiguous lithologies of the Bungadillina suite. These ambiguous contacts have been presented as accurately as possible, although minor incursions have invariably been missed or misplaced.

A few small lobate plutons are composed almost entirely of monzogabbro or syenogabbro (~49-54 wt.% SiO_2). Although the mineralogy of these plutons does not change significantly, the coarser grained texture with large euhedral amphibole crystals immediately separates this lithologic group from simply mafic-rich monzonites and syenites (*e.g.* Plates 3.1 Top Left; 3.5 Bottom Left).

The largest pluton, found in the southeast region of the study area, is dominated by a coarse grained, euhedral to slightly porphyritic quartz syenite (Plate 3.5 Top Right). The relative abundance of free quartz and absence of mafic constituents makes this a readily identifiable separate lithology. The homogeneous quartz syenite and quartz monzonite of the two largest plutons of the study area form massive, prominent tors (*e.g.* Plate 3.1 Top Right), and the largest pluton itself provides the elevated topographic relief of the Mount Margaret Plateau.

Two major lithological groups which are mineralogically distinctive are the medium to coarse grained equigranular to strongly porphyrytic alkali syenite (Plates 3.1 Bottom Left; 3.5 Bottom Left), and the biotite lamprophyres (Plate 3.4 Centre Right). The alkali syenite group is characterized by the dominance of large laths (up to 5cm in length) of alkali feldspar which are often flow lineated. Few samples of alkali syenite were found to contain abundant euhedral garnet, aegirine-augite and fluorite. This lithology is not as volumetrically significant as other lithologies, but clear intrusive relations show that it postdates all other igneous lithologies with the exception of associated aplite and biotite lamprophyre (Plates 3.1 Bottom Left; 3.4 Centre Right).

Although not as voluminous as other lithologies, the biotite lamprophyres (~49 wt.% SiO_2) are yet a common intrusive usually occurring as small dykes or sills surrounding or intruding more felsic plutons. The distinguishing character of this seriate porphyritic lithology is the presence of pseudo-hexagonal "castellated" biotite phenocrysts. Using Streckeisen's (1979) classification scheme, the rock type would be called a *kersantite* or *minette* depending on the dominance of plagioclase or alkali feldspar respectively. As the modal difference is difficult to distinguish, the preferred reference is simply *biotite* lamprophyre, or alternatively; *calc-alkaline lamprophyre* (Rock, 1984). The appearance of lamprophyric dykes and sills is commonly associated with late-stage volatile enrichment of residual magma and is often found in many magmatic environments such as regional rifting regimes (e.g. Strong & Harris, 1974; Bedard, 1985), and in newly-stabilized orogenic, peripheral orogenic and island-arc settings (Rock, 1984).

The final group forms small, leucrocratic, medium to fine grained equigranular albitite bodies composed of over 90% albite plagioclase with minor quartz, chlorite and other alteration minerals (epidote, calcite and haematite) (Plate 3.5 Penultimate to Bottom Right). This rock type is not a primary lithology, but is the result of extensive sodic metasomatism which has altered the original igneous mineralogy without affecting the surrounding strata (Plate 3.2 Bottom Left). It should be emphasized that the majority of the

Bungadillina suite have experienced some degree of alteration including actinolitization, chloritization, haematitization and saussuritization of the mafic components, and sericitization, carbonatization and albitization of the felsic minerals. However, the albitites have been severely altered to the point where their original mineralogy is masked by alteration products, namely albite.

Accessory minerals of the Bungadillina suite includes sphene, apatite, magnetite and zircon, which are ubiquitous, euhedral, and in parts, especially magnetite and sphene, abundant.

Most of the smaller plutons have a very close spaced and abundant jointing pattern which probably formed in response to a relatively quick cooling history upon emplacement (*cf.* Plate 3.2 Bottom Left). Larger plutons have correspondingly wider spaced and less intense jointing pattern (Plate 3.1 Top Right), indicating the larger plutons had a slower cooling rate, prohibiting the development of close-spaced contraction fractures. Other than jointing, localized shearing and faulting, there are few structural features of the plutons of the Bungadillina suite to report on.

3.2 Northwestern Zone, Maps A and A'.

This section (Maps A and A') encompasses the second largest, most westerly pluton in the area of study, and a smaller oval-shaped pluton to its immediate northeast. These plutons form prominent tors (Plate 3.1 Top Right), and are locally referred to as "The Black Rocks". The largest pluton of this map area measures 3.6km by approximately 2km and features distinctive and variable lithologies forming a pronounced, zoned character. In contrast, the smaller, coarse grained quartz monzonite pluton to its immediate northeast (observed both in Maps A and B′), approximately 600m in diameter, is massive and homogeneous, lacking in any mineralogical or petrographical variations (*e.g.* Plate 3.3 Centre Right). The contact margin of the larger of the two plutons is relatively undisturbed with a slight buckling of the immediate strata (Fountain Spring Beds) to the north of the pluton. The southeast margin of the pluton comes into contact with buckled beds of siltstone and quartzite of probable Fountain Spring Beds or Mount Margaret Quartzite derivation, mapped as diapiric breccia. Preferential weathering of the diapiric breccia has resulted in poor exposure along this contact. Unlike other plutons, the intrusive bodies of this map sheet have not experienced extensive albitization. The most noticeable style of alteration takes the form of spherical clots of secondary epidote-calcite-chlorite, usually less than 6cm in diameter but some reaching up to 50cm. Preferential weathering around these zones has resulted in the deposition of abundant golf ball-sized green epidote nodules on the pluton's surface.

The core of the pluton features two separate syenogabbro zones. The southern gabbro zone (Map A′) is composed of 0.5mm euhedral clinopyroxene and biotite with strongly zoned plagioclase (labradorite cores to andesine rims) and orthoclase. Water-clear orthoclase crystals up to 4mm in diameter enclose euhedral feldspar, hornblende and clinopyroxene chadacrysts forming a patchy *ghost* porphyritic texture. Alteration includes patches of secondary epidote and actinolite, with actinolite commonly replacing biotite, and calcic replacing cores of zoned plagioclase crystals, which are also often sericitized [7523-5, 9574] (Plate 4.4.E). In contrast, the gabbroic zone in the northern sector of the pluton (Map A) is characterized by the inclusion of euhedral green hornblende crystals up to 4mm in diameter [7541, 9598] accompanying biotite, clinopyroxene and plagioclase, which are all enclosed by large ghost orthoclase crystals Plate 4.1.C & D). The contact zone with the surrounding monzonite shows a gradual reduction of the main mafic mineral components over a short distance of less than 2m [9595, 9597, 7540, 7538] (Plate 4.1.E & F). Immediately south of this syenogabbro is a small zone of fine grained diopside-bearing leucocratic monzonite porphyry [7539] carrying metasedimentary inclusions. It may represent late-stage volatile remobilization perhaps involving influx of meteoric or connate water into the pluton core [7200].

The pluton is also transected by a series of east-west trending porphyry dykes (Map A), the largest of which exceeds 4m in width and extends for over 1km, and one relatively small lamprophyre dyke towards the southern margin of the pluton (Map A'). Not all the dykes that intrude the pluton are the same. The largest dykes [9311, 9314] are alkali syenite porphyries with strongly zoned euhedral flow-lineated orthoclase laths and smaller 1mm euhedral green hornblende in fine grained groundmass. It is similar to a small albititized [7324] porphyry dyke in the northern section of the pluton which appears to have many of the petrographic features of the larger alkali syenite dykes (Plate 4.1.A & B). Small, extensively altered dykes have undergone epidote-chlorite replacement of mafic constituents and sericitization, albitization and carbonitization of the feldspars [9313, 7323]. As the lateral extent of such dykes is severely limited, the intrusion of these dykes may be associated with late-stage emplacement fractures (Castro, 1987).

The western margin of the pluton is composed of seriate porphyritic monzonite with strongly zoned feldspar phenocrysts up to 5mm in diameter. Mafic mineralogy varies from euhedral green hornblende, which has been partially [7526] to completely [7521] actinolitized, to partially chloritized biotite [7522]. In some localized zones, diopside becomes the sole mafic constituent [9599, 7532]. The monzonite of the northern section of the pluton (Map A) is composed of strongly zoned feldspars, diopside and biotite which has been partially to completely replaced by actinolite [7554-3]. The pluton's northwest margin (Map A) is characterized by monzogabbro [7534] which has a gradational contact with the adjacent monzodiorite [7535], and have hornblende and salite, and their actinolitized and sausseritized equivalents as the predominant ferromagnesian mineral species. These appear to intrude more felsic equivalents [7533], which may represent an original chilled margin to the pluton.

Along the northwest margin (Map A), the degree of zoning in feldspar crystals is controlled by the degree of feldspar alteration. The more altered and less mafic [7550] varieties are closer to the contact margin. Those with strongly zoned unaltered feldspars occur nearer the core [7552]. Both are composed of clinopyroxene and their actinolitized equivalents.

Further south [9588], biotite and actinolitized biotite and/or diopside are the dominant mafic constituents of a lithology which extends into a slightly more altered phase [9585] and a finer grained diopside bearing phase [9630] in Map A'. Green hornblende and salite are the prominent mafic constiuents further south [7549], reverting to a biotite-diopside assemblage closer to the southern syenogabbro body [9582-3], with the more altered equivalents [7520] showing actinolitization of both biotite and clinopyroxene (Map A′). A marginal leucocratic phase [9308] close to the contact is more porphyritic in texture with 1-2mm zoned feldspar phenocrysts with fine grained biotite, hornblende and clinopyroxene in a felsic fine grained groundmass.

Around the syenogabbro cores of the pluton [9580, 7542-4], the general lithology changes little except in becoming progressively more mafic (gradational contact), with the exception of a northeasterly trending linear megacrystic zone (Map A) with orthoclase megacrysts up to 4cm in diameter [7599]. This megacrystic porphyritic zone quickly grades into the surrounding equigranular texture. The cause of this megacrystic variation of the monzonite is uncertain, but may have resulted from a zone of volatile-enhanced crystal growth during *in situ* magma crystallization. This megacrystic variation, like most of the entire suite, contains the ubiquitous euhedral magnetite, sphene and apatite.

The smaller pluton to the northeast of Map A (also presented in Map B′) is a coarse grained quartz monzonite [9590-3]. This homogeneous massive lithology (Plate 3.3 Centre Right) is composed of strongly zoned orthoclase and plagioclase, with occasional sericitized cores or patches of muscovite. Perthitic feldspars up to 8mm in diameter form a seriate porphyritic texture with anhedral intersertal quartz. The main mafic mineral components are euhedral biotite and green hornblende which are in various stages of being replaced by actinolite and chlorite. Other forms of secondary alteration include interstitial carbonatization and patchy epidote. Accessories include the euhedral apatite, sphene, magnetite and the occasional zircon.

This body was noted to have been intruded by small aplitic to slightly porphyritic felsic dykes. These dykes probably represent the intrusion of late-stage residual felsic melt into contraction joints. They do not extend into the surrounding sediments. Also noted were occasional tabular gneissic xenoliths (Plate 3.3 Centre Right). Such xenoliths represent limited incorporation of Early to Middle Proterozoic crystalline basement material into the Bungadillina magma during magma transport.

3.3 Northern Zone, Maps B and B'.

3.3.1 Sill Swarm.

A major sill swarm is the most prominent feature of this map area. More than thirty sills have been recorded here, the longest of which is over 2.8km in length and 38m wide. The sills occupy a zone of interbedded siltstone and shale approximately 500m wide between two thick conformable sequences of massive Mount Margaret Quartzite (Plate 3.1 Right Centre). The southern extremity of the sill swarm pinches out with the shale and siltstone sequence (Plate 3.1 Bottom Right). Towards the northern extremity of the swarm (Map B), there are a series of felsic plutons, the largest approximately $800m^2$. Although the precise relationship between the sills and the plutons is debatable with regards to specific outcrops, field evidence indicates that in general the pluton intrusions postdate sill injection. This is most noticeable where a pluton truncates two prominent sills (Map B; adjacent sample site [7318]). Immediately north of this locality, the sills are apparently contorted by the force of the intruding pluton, also indicating that the sills predate the emplacement of the pluton.

The largest sill is a monzonite porphyry [7315] with hiatal porphyritic texture composed of euhedral 1-2mm green hornblende and feldspar phenocrysts in a fine grained felsic groundmass. The feldspar phenocrysts are moderately zoned, and the weakly zoned hornblende phenocrysts have incurred slight actinolitization and epidotization. In the northern extremity of this sill, the sill immediately east is composed of identical material [7318] with slightly smaller but strongly zoned hornblende phenocrysts (Plate 4.3.B). Towards the southern margin this sill splits into four separate sills 4-6m wide, but showing more extensive alteration with biotite pseudomorphs after euhedral green-brown hornblende (which is itself partially chloritized), and abundant calcite replacement in the felsic groundmass [7305-6] (Plate 4.4.C).

The three consecutive 4-6m wide sills westward [7303-4, 7312, 7316-7] show only slight alteration and groundmass size variation from the hornblende monzonite. They are accompanied by a small, finer grained doleritic eqivalent [7311].

East of the largest sill occurs a monzogabbro (2.8km long and 5 to 15m wide) sill which shows southerly progressive alteration. The northern extension of the monzogabbro [9007] consists of 1mm green hornblende and zoned feldspars in a fine grained felsic groundmass which has been subjected to minor actinolitization and epidotization (Plate 4.2.D). Further south [7314], hornblende shows evidence of biotite replacement, while calcite has replaced some of the coarser grained groundmass. Complete alteration to biotite, accompanied by more extensive carbonatization, occurs further south [7301]. The southern-most extremity [7300] features prominent chloritization, while lacking in a hiatal porphyritic texture. Similarly, in the southern section of a 3m wide sill to the immediate west of the monzogabbro, chloritized biotite and haematite have replaced euhedral hornblende and feldspar phenocrysts, which are themselves accompanied by a partially sericitized felsic groundmass. In the northern section of the sill, to the east, a small seriate porphyritic monzogabbro sill [7313] is composed of relatively unaltered slightly zoned green euhedral hornblende and plagioclase phenocrysts up to 3mm in diameter. Alteration of these sills appears to become more extensive southward, away from the main area of small pluton occurrences.

Intruding the central area of the sill swarm is a massive 12m diameter plug of quartz monzonite [7500], probably consanguineous with the larger quartz monzonite body to the west. Feldspar phenocrysts of this hiatal porphyry are zoned while biotite and minor chlorite form pseudomorphs of what was originally hornblende. Calcite occurs interstitially in the groundmass. A similar quartz monzonite plug [7501] 60m in diameter is intruded by one of the sills in the southern area of the swarm (Map B′). In contrast, this plug has abundant euhedral green and brown hornblende with slight actinolite alteration (Plate 4.4.A).

One of the most prominent and unique features of this sill swarm is its varied collection of xenoliths and xenocrysts. Included with accidental xenoliths of angular hornfelsed siltstone and shale incorporated from the contiguous sediments, are rounded to subrounded coarse grained monzogabbro, and smaller, finer grained and more angular dolerite xenoliths up to 0.3m in diameter [7700-2, 7503, 9007] (Plate 3.3 Top Left, Bottom Left and Bottom Right; Plate 4.2.C & H). These xenoliths are composed of hornblende, alkali feldspar, plagioclase (oligoclase-labradorite), magnetite, sphene and apatite which have been substantially altered to a composition of actinolite, alkali feldspar, albite, green and brown-green biotite, haematite and sericite. These rounded coarse grained mafic xenoliths (hornblendites) may represent ferromagnesian mineral-rich cumulates from the Bungadillina suite magma. The more angular doleritic xenoliths may represent re-incorporated chilled margins of earlier crystallized melt. Other xenoliths include subrounded tonalitic gneiss (Plate 3.3 Bottom Left), representing exhumed remnants of Early to Middle Proterozoic crystalline basement.

3.3.2 Plutons, Map B.

The majority of the plutons in this region are clustered around the northern section of the sill swarm, with the largest single body (other than the quartz monzonite referred to on Maps A and B') measuring approximately 900m². This pluton is a monzonite with subhedral zoned feldspar, and unlike the sills or other plutons in the immediate vicinity, has clinopyroxene (salite) as the main mafic component along with minor magnetite, sphene and apatite [9004-5, 7506]. A finer grained, more mafic zone towards the centre of this pluton is void of pyroxene in preference to green hornblende. The zone, in contrast to the surrounding monzonite, is considerably more altered with the presence of actinolite, biotite and epidote with abundant haematite (?) staining of the feldspars [7507].

To the immediate north intrudes a strongly porphyritic and slightly epidotized aegirine-augite-bearing alkali syenite with euhedral elongate orthoclase phenocryst laths up to 2cm in length [9003] (Plate 4.2.A). The alkali syenite outcrops away from any other pluton, but small dykes of the same material were noted intruding the monzonite in float around the margin of the pluton. Truncated dykes of alkali syenite were noted westward from this locality in a roughly linear (east-west) orientation, as opposed to the north-south orientation of the sills.

The most easterly plutons are composed of seriate monzonite porphyry with strongly zoned 1cm feldspar phenocrysts and smaller, slighly zoned clinopyroxene phenocrysts in a felsic groundmass [9002]. Alteration is evident in hiatal porphyrytic varieties, with albitization and actinolitization [7509, 9003] of the felsic and mafic constituents respectively. A small similarly altered monzonite body located 600m west has green hornblende in with the groundmass [7502]. The contact margin is well exposed in areas and shows a finer grained chilled margin, and with the immediate contact shales being sericitized and invaded by small quartz veins. A similar small pluton is exposed 450m west, but with abundant subhedral green hornblende as well as clinopyroxene and minor biotite [7508, 9001] (Plate 4.3.G). The pluton intrudes quartzite beds, the margin of which is riddled with abundant accidental quartzite xenoliths.

Towards the northwest terminus of the sill swarm intrudes a small set of monzonite to syenite plutons (with albitized equivalents), the largest of which is 300m by 100m. Of these, green subhedral hornblende is the main mafic component [7505] which has been progressively altered to actinolite [7504] (Plate 4.4.B) with minor clinopyroxene [9000]. The emplacement of these plutons has distorted adjacent less competent siltstone and shale strata causing them to wrap around the margins of the plutons. One small peripheral dyke

[9318] is a monzonite hiatal porphyry with minor biotite.

An elongate quartz monzonite pluton, very similar to others described in this map area, occurs as the northern-most plug studied. Like the other quartz monzonites, it is characterized by abundant euhedral brown-green hornblende with strongly zoned feldspars and interstitial quartz [7548]. This body has been partially intruded by an east-west trending alkali syenite dyke.

3.4 Central Zone, Maps C and D.

The relatively small map area represented by Map C is dominated by a sub-circular pluton (approximately 800m in diameter) accompanied by smaller lenticular plutons to its immediate south and southeast. These plutons contain features widely seen throughout the smaller plutons of the Bungadillina intrusive suite. To the northwest of the largest pluton of Map C, the contact is clearly with thick and relatively undisturbed Mount Margaret Quartzites. This contact is characterized by a metre wide zone of albitite extending from the contact into the pluton. To the southeast, the contact is with contorted and distorted (Stage 2 diapiric breccia; *cf. ch.* 1.5.3) siltstone and shale strata. Included are lenticular and truncated quartzite beds. The entire sequence is mapped as "diapiric breccia", but probably involves both Fountain Springs Beds and Mount Margaret Quartzite. To the immediate north is the southern end of a prominent north-south fault marked by a 3m wide, highly altered (kaolinized, sericitized and chloritized) leucocratic fault zone. Within the largest pluton occur lenticular quartzite xenoliths, the largest of which exceeds 100m in length. Smaller quartzite xenoliths were noted around the immediate vicinity of the contact margin. Monzonite porphyry sills 0.5-1m wide [9300-01] of limited extent were observed intruding the Mount Margaret Quartzite beds immediately east of the pluton, representing the southern extremity of the sills of Maps B and B′ (Plate 3.1 Bottom Right). These sills have undergone extensive carbonatization and chloritization of the former mafic components and sericitization of the feldspar phenocrysts.

The predominant igneous texture is holocrystalline hypidiomorphic equigranular to slightly seriate porphyritic with grain sizes seldom exceeding 1mm in diameter. The main body of the pluton is dominated by monzonite or quartz monzonite [9501, 9503, 9504, 9507]. Around the margins and extending into the core of the pluton are leucocratic equivalents which have been albitized, and to a lesser extent sericitized and haematitized [9502, 9508]. Small albitite dykes [7518] were found intruding the sediments immediately adjacent to the contacts. The southern and western region of all plutons in the area become mafic-rich with a progressive increase of ferromagnesian constiuents, predominantly amphibole, and to a lesser extent clinopyroxene (*i.e.* monzogabbro [9553]) and biotite [9506]. There is no indication that the more mafic phase predates or postdates the more felsic phase as contacts are gradational and do not display typical alteration or grain size variations as would be anticipated for igneous intrusions of demonstrably differing intrusive histories. Aplite dykes [9600] crosscut the pluton towards the margin, and some small patches of aplite identified as quartz monzonite [9601] occur within the pluton. Within the largest pluton occurs a clearly identifiable oval alteration zone 80m in diameter composed of strongly haematized monzonite [7527]. The cause of these iron-rich zones is unknown, but may be related to water-assisted mobilization of iron during the course of albitization.

It is interesting to note that the stratigraphic base of the pluton, with respect to the contiguous Mount Margaret Quartzite sequence (southern part of the pluton), is dominated by gabbroic lithologies, whereas the stratigraphic top (northern section of the pluton) is characterized by a margin of albitite. This style of intra-plutonic differentiation is also present for the largest pluton of the Bungadillina suite (Maps F′, G and I).

The smaller of the two linear plutons to the south of Map C is vertically zoned such that the lowest exposed lithology on the eastern and western margin of the pluton consists of monzogabbro which grades upwards through monzonite, and is peaked by leucocratic albitite with a brecciated contact margin. Brecciated leucocratic albitite margins are a common feature in many of the smaller plutons in the Peake and Denison Ranges, indicating localized fracturing of the chilled margin of a partially consolidated pluton during the course of emplacement.

The 250m long pluton to the southeast of Map C forms a small steep-sided hill. It is also lithologically stratified. This pluton is vertically zoned from monzogabbro [9553] at the base of the outcrop through monzonite [9624] with the summit of the outcrop characterized by leucocratic albitite [9623]. Again the plutons are surrounded by distorted and varied sedimentary beds (Stage 2 diapiric breccia). Although albitization and albitite brecciation of the plutons occur along the contact, there is no apparent alteration or contact metamorphic imprint in the immediate sediments (*cf*. Plate 3.2 Bottom Left).

The most mafic lithologies of the largest pluton [9100, 9505] in Map C are generally holocrystalline hypidiomorphic granular, composed of euhedral slightly zoned hornblende crystals up to 2mm in diameter which are partially or totally replaced by actinolite and accompanied by subhedral clinopyroxene (diopside - salite). The felsic constituents are slightly zoned and lightly sericitized orthoclase and plagioclase with secondary calcite and epidote. A finer grained variant [9506] is best described as a biotite porphyry with 1mm biotite books in a fine grained felsic groundmass. This is similar to the most mafic lithology of the peripheral pluton to the immediate southeast [9553] which is composed predominantly of subhedral chloritized biotite and fine grained biotite-rich xenoliths, but with equigranular feldspars. More felsic monzonites contain minor actinolite [9502] and quartz monzonites with chloritized biotite [9501]. Graphic texture has been noted occurring in one area [7528]. Progressive albitization is characterized by the haematitization of magnetite [7527], carbonatization of the felsic minerals, and extensive chloritization of the mafic constituents; often accompanied by secondary muscovite [9400, 9502-3, 9506-8]. Haematite and chlorite often form pseudomorphs after primary hornblende [9601].

The pluton of Map D, approximately 1km long and 0.5km wide, is composed largely of albitized hornblende monzonite. The eastern contact is with distorted and brecciated siltstones and mudstones, whilst the southern contact is with massive quartzites. One large carbonate xenolith 30m in diameter was noted at the northeast corner of the pluton. The carbonate probably originated from the nearby (Burra Group) Skillogalee Dolomite. The eastern section of the pluton displays large angular (brecciated?) actinolitized hornblende monzogabbro xenoliths up to 3m in diameter [9703], which are encompassed within albitite [9543-5]. These monzogabbro xenoliths may represent a ferromagnesian mineral-rich cumulate phase incorporated into an intruding felsic magma.

3.5 Southeastern Plutons, Map E.

The two largest plutons present in this map area are relatively uniform in texture and mineralogy which vary from hornblende or minor biotite monzonite [9547, 9549, 9558] to albitite [9548, 9550, 9552] with partially albitized examples [9551]. Although the more leucocratic zones of albitite can be readily identified in outcrop, there appears to be little order to its distribution. The plutons intrude distorted and disrupted siltstone, quartzite and carbonate beds, which often include zones of diapiric (Stage 4) breccia. It is within this breccia that an unusual 18m wide mafic (biotite lamprophyre?) plug [7510] appears to have intruded the surrounding diapiric breccia. Although no contact alteration halo is present in the surrounding diapiric breccia, the igneous body has a chilled margin. This relationship may represent either a small rafted plug that had not been itself brecciated due to its massive nature, or plug emplacement postdates (Stage 4) diapiric brecciation.

In between the two monzonite-albitite plutons intrudes a 50m diameter plug of coarse grained alkali syenite [9562], composed of 2-4cm long interlocking laths of orthoclase, and representing the most easterly known occurrence of this lithology. Smaller dykes of this material intrude eastward towards the eastern margin of the map area.

The 350m long oval monzogabbro body to the east of the map area [7516] features extensive veining and mantling of strongly albitized and carbonatized monzonite towards each extremity (fronticepiece). The network veining effect suggests a late-stage filter-pressing of residual magma from the crystallizing mafic body which has been truncated at its contact by diapiric (Stage 4) breccia. The southwestern contact of this mafic-rich body is with relatively undeformed shales, whilst the northeastern contact is with diapiric breccia, indicating that the weakest plane for igneous intrusion into the sedimentary sequence was also that for diapiric brecciation.

The only defined intrusion of Bungadillina material into Callanna Group volcanics occurs in the southern portion of this map area. Here, a 30m wide dyke [9561] intrudes a sequence of basaltic Cadlareena Volcanics, which in turn overlies the basal Younghusband Conglomerate and underlies the Burra Group sediments.

3.6 South-Central Plutons and Sills, Maps F and F'.

These map areas are dominated to the northwest (Map F) by two elongate and discordant syenogabbro [7511, 9520, 9524, 9540, 9541, 9542] and monzogabbro [9565-70, 9901] plutons. For the most part these plutons are massive and homogeneous, and as they preferentially weather more readily than felsic equivalents, they form topographic lows, the plains of which are covered with magnetite sand. The lithology is composed of equant euhedral crystals of amphibole 1cm in diameter within finer grained feldspar-biotite-magnetite (Plates 3.1 Top Left and 3.2 Top Left; 4.2.B & F). The rims of these mafic plutons are often albitized and brecciated (Plate 3.2 Bottom Right). Clinopyroxene-bearing zones within the dominantly hornblende-biotite gabbros was noted only in two small localities [9570, 9625]. A 0.2-0.5m wide zone of mafic-rich xenoliths was noted in one of the two gabbroic plutons, and may represent re-incorporated ferromagnesian mineral-rich cumulate (Plate 3.5 Penultimate to Top Right). Other xenoliths include rounded cricket ball-sized hornblende monzonite [9701] and unusual rounded albite-calcite rock which may represent recrystallized carbonate [9707]. The presence of monzonite xenoliths indicates that the mafic monzonites may predate these gabbroic lithologies. Intruding the gabbro are dykes of both biotite lamprophyre [9627] to the north and alkali syenite to the south [7547] (*cf.* Plates 3.2 Top Left; 3.4 Top Right, Centre Right and Bottom Right).

There is evidence of multiple mafic intrusion with slightly more felsic syenogabbro intruding a more mafic host (Plate 3.5 Bottom Right) in a smaller pluton in Map F [7513, 9525, 9353]. This pluton is completely surrounded by an albitite margin, and is intruded by a 2m wide alkali syenite dyke [9303] which is an extension of a larger alkali syenite body [7320].

Between the two largest gabbroic bodies lies a coarse grained to megacrystic alkali syenite (Map F) which has been albitized to various extents. The pristine lithology is dominated by large strongly zoned and barium-bearing orthoclase laths, strongly zoned andradite garnet, aegirine-mantled aegirine-augite to diopside pyroxene, biotite and fluorite (Plate 4.3.E & F) [9563]. In progressively more altered variants, the pyroxene dissappears and garnet is pseudomorphed by magnetite [7546]. In the most altered examples, the entire lithology is eclipsed by albite and carbonate [7515]. The strongest characteristic of this alkali syenite is its elongate and aligned orthoclase laths (*e.g.* Plate 3.1 Bottom Left). This feature is readily identified in other exposures, and although the garnet, pyroxene and fluorite may be absent, it is mapped as the same lithology.

The monzonite plutons of this map area (Map F) are homogeneous and equigranular, other than minor gabbroic or albitite margins [9526, 9528, 9530-3]. Their textures and mineralogies are like other monzonites previously described. In contrast, the northern section has homogeneous leucocratic albitite plutons [9523-4, 9608, 9614, 9512], one of which has a monzogabbroic southern margin [9521]. A smaller elongate pluton between these two albitite bodies is noted for a clinopyroxene-rich syenogabbro zone [9524] within monzogabbro [9513-4]. The syenogabbro may represent a mafic-rich cumulate of the monzogabbro.

The southeast of the easterly map area (Map F′) is dominated by the northern part of the largest single pluton in the Margaret Inlier. The pluton in this locality is a massive, equigranular homogeneous coarse grained quartz syenite [9021-3] which comes into direct intrusive contact with a clinopyroxene-bearing syenogabbro at its northern margin [9011-4]. Within the pluton, green selvages up to a metre in length were identified as being pyroxenite xenoliths composed solely of diopside [9706] (Plate 3.5 Penultimate to Top Left). These xenoliths may represent the re-incorporated concentrate of an earlier fractionated component (cumulate). The possibility of formation of mineral cumulates within the pluton is also indicated by possible primary crystal layering in the quartz syenite (Plate 3.5 Top Right).

To the immediate northwest of quartz syenite pluton exists a myriad of tabular intrusive bodies and small plutons (Map F′). Where precise intrusive relations can be measured, invariably the more felsic lithologies intrude the more mafic (Plate 3.4 Top Left, Top Right, Bottom Right) with the exception of biotite lamprophyres which intrude monzonites [7327, 9327, 7559] (Plates 3.4 Centre Right, 4.2.E). Variations of the mafic content within single bodies is also demonstrated within one folded sill [7330-3], suggesting a heterogenous magma during emplacement.

The tabular intrusives usually form sills following the general east-northeast to west-southwest bedding direction. The previously mentioned folded sill provides one of the most compelling evidence for pre-deformation intrusion of the suite. The sill can be followed around the nose of a steeply dipping anticline. The southern limb intrudes the thick, more competent Mount Margaret Quartzites, while the northern limb intrudes less competent but conformable siltstones and shales. The less competent beds have been more strongly influenced by both Delamerian folding and diapiric activity, and have been shown on Maps F and F′ as diapiric breccia. This accentuates both the difficulty and error in mapping diapiric breccia. The structures and lithologies present in diapiric breccia can only be shown on very small scale maps, but if mapped on a general basis, confusion can arise when assigning essentially a structural feature (diapiric breccia) to a predominantly lithological map. The precise timing of this east-west orientation of the bedding and associated folding is not known.

In most cases, the gabbroic plutons in this area form small discrete bodies [9010] or as associated phases in slightly larger and more felsic plutons [7567]. Minor albitite bodies [7561, 9632] are present, as well as largely homogeneous small monzonite plutons [7563, 9024, 9800].

3.7 The Southern Pluton, Map G.

The largest pluton of the Margaret Inlier consists predominantly of massive, homogeneous coarse grained quartz syenite [9021-6] and syenite [7556, 7569-70]. The precise boundary between the two general lithologies is difficult to determine as the textures are identical and the changes in quartz content are subtle. Within the syenite occur zones of clinopyroxene-bearing syenogabbro, most notably along its southwestern margin [7557-8, 7568] (Plate 4.3.C). Like other gabbroic lithologies of the Bungadillina suite, this is composed of euhedral 1cm hornblende and biotite crystals with slightly smaller diopside-salite and zoned feldspar. The lack of sharp contacts indicate that the emplacement of the syenite occurred soon after the syenogabbro. As with the northern section of this pluton, pyroxenite xenoliths, albeit altered to actinolite, are present [7704]. Intruding through the syenite are dykes of coarse grained alkali syenite containing minor aegirine-augite [7326]. Late-stage hydrothermal pink asbestos veins, up to 20cm wide were noted intruding the quartz syenite in the vicinity of sample [7569]. This pluton largely intrudes Mount Margaret Quartzite without significant deformation to the immediate surrounding strata. However the far eastern margin (adjacent [7704]) has undergone pronounced contact metamorphism (Plate 3.5 Penultimate to Bottom Left), and is the only example found in the study area.

Also noted to the west of the pluton were small sills of syenite [7325] and biotite lamprophyre intruding Mount Margaret Quartzite beds (Map g).

3.8 Northeastern Area, Map H.

This area is dominated by small plutons and sills composed of medium grained equigranular leucocratic albitite [9633-5], often stained red due to haematization. The host of intrusions are lightly folded and faulted siltstone and sandstone which show no indication of contact metamorphism and no distortion due to intrusive emplacement, other than localized shearing on the eastern margin of one pluton [9634]. Only in the northern extension of the northeastern pluton has a relatively unaltered equivalent of the albitized lithologies [9016-7]. The 140m diameter eastern-most pluton was originally thought to be an altered gneiss due to its strongly layered characteristics (Plate 3.5 Top Left). This feature, however, may in fact be a primary igneous layering, and in accordance with the mineralogy, albeit extensively altered, this pluton may be a monzogabbro [9901].

3.9 Southeastern Area, Map I.

The eastern side of the largest southern pluton [9050-1] displayed on this map area is of the same massive coarse grained texture as found elsewhere in the pluton, but is extensively albitized (Plate 4.4.G). Inaccessibility and difficulty in distinguishing between significantly altered and unaltered samples in the field made detailed mapping prohibitive. However, the distinct contrast between the eastern (Map I) and the western (Map G) margins of the pluton is analogous to a zoned pluton, such that the ferromagnesian mineral-rich cumulate forms at the stratigraphic base (western side) and the altered felsic material forms the stratigraphic top of the pluton (eastern side) (*cf. ch.* 3.4, Map C).

The southern-most pluton of this map area is noted by having clinopyroxene syenogabbro [7575] intruded by syenite [7567] (Plate 3.5 Bottom Left). The syenogabbro is distinctive from other amphibole-bearing bodies by having euhedral and finely zoned hornblende mantling actinolite (rather than *vice versa* as found in all other coexsisting hornblende-actinolite) and abundant free quartz (Plates 4.1.G & H, 4.3.A). This syenogabbro may also represent a mafic-rich cumulate rock. Other plutons in the vicinity are alternatively composed of hornblende mantling salite [7577] (Plate 4.3.D) and plagioclase mantling alkali feldspar [7338]. A northwest monzonite-monzogabbro pluton [7580] is intruded by monzonite dykes [7337] which itself is intruded by biotite lamprophyre.

Many smaller plutons occurring in the southeast of the map area were found to have truncated sills in contact with diapiric breccia. Contacts with contiguous sediments are usually passive (Plate 3.2 Centre Right). The relationship of the albitite dykes [7338] in the northwest of the map area to other intrusive bodies is unknown. The small plutons to the far northwest of Map I were not examined in this study. Their lithologies and boundaries were extrapolated from field notes of Ambrose *et al.* (1981).

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Chapter Four: Mineralogy of the Intrusives of the Peake and Denison Ranges.

> "Megascopically the basic rock appears to be a dark green, medium grained rock composed of a yellow green mineral, a dark green mineral, and plagioclase, with some magnetite and haematite."
>
> Reyner (1955) describing the mineralogy of a mafic intrusive in the Peake and Denison Ranges.

4.1 Introduction.

This chapter describes and discusses the mineralogy of the intrusives of the Peake and Denison Ranges using both petrographical and chemical data. Chemical analyses of mineral suites were conducted utilizing a JEOL 733 microprobe analyser connected to a KEVEX 7000 Series energy dispersive system from polished rock sample surfaces at the Electron Optical Centre, the University of Adelaide. Analytical conditions include a 15Kv accelerating voltage and 3nA electron beam current. Calibration of the KEVEX EDS system was based on oxide and pure copper standards (Griffin, 1979).

4.2 Oxides.

The oxides include the mineral groups encompassing the *spinel series*, the *ilmenite series*, the *pseudobrookite series* and *TiO_2 polymorphs*. Oxides of the spinel group can be separated into end-member components of magnetite ($Fe^{+2}Fe^{+3}{}_2O_4$), jacobsite ($MnFe^{+3}{}_2O_4$), magnesioferrite ($MgFe^{+3}{}_2O_4$), hercynite ($Fe^{+2}Al_2O_4$), ulvospinel ($Fe^{+2}{}_2TiO_4$) and chromite ($Fe^{+2}{}_2Cr_2O_4$), while the ilmenite series can be expressed in terms of the end-member components of ilmenite ($FeTiO_3$), haematite (Fe_2O_3), corundum (Al_2O_3), geikielite ($MgTiO_3$) and pyrophanite ($MnTiO_3$). Microprobe analyses of the oxides are presented in Appendix K. Ferric iron recalculations are based on stoichiometric constraints such that analyses have been recalculated allowing for a four cation total from six oxygens. Excessive cations have been accommodated by convertion to appropriate quantities of ferric and ferrous iron. Excessive Fe^{2+} in spinel probably represents erroneous microprobe analyses, which are nevertheless dutifully recorded as wustite (FeO) in Appendix K. Similarly, excessive titanium in ilmenite is rare and again probably indicates poor mineral analysis.

Oxides are a minor component in igneous rocks, but are invaluable in their ability to record the physical conditions of crystallization. Magnetite is a ubiquitous and almost sole oxide in the intrusives of the Peake and Denison Ranges, forming small, euhedral and usually compositionally homogeneous grains (*e.g.* Plate 4.1.E-H). In some lithologies it is a major component. Weathered gabbroic terrains are often covered by residual magnetite sands. Such bodies have been found to be partially responsible for distintive aeromagnetic anomalies outlined and drilled by Stockdale Pty. Ltd. to the immediate west of exposed plutons in the Peake and Denison Ranges (Jarvis & Newell, 1985). Minor oxide components in the intrusives include ilmenite, haematite, anatase, pyrophanite, perovskite and chromite. Jarvis & Newell (1985) have reported picroilmentite (geikielite) and chromite from gravel samples in the vicinity. Minor sulphides such as pyrite, chalcopyrite, galena and sphalerite have been found as tiny inclusions in euhedral magnetite grains.

Magnesium is a very minor component in the oxides of the Peake and Denison Ranges, never exceeding 0.64 wt.% MgO. Likewise, aluminium content does not exceed 0.35 wt.% Al_2O_3 with the exception of the one chromite grain encountered (4.3 wt.% Al_2O_3). In contrast, manganese is sometimes a major component in both ilmenite and magnetite within some samples. The syenogabbro [7575] of Map I recorded up to 2.71 wt.% MnO in ilmenite while having whole-rock MnO of only 0.17 wt.%. It is one of the few rocks to contain ilmenite as the sole oxide. The sills of Maps B and B′ have ilmenite with up to 15.44 wt.% MnO [7311] and up to 3.54 wt.% MnO in magnetite [7301], while recording less than 0.14 wt.% MnO in whole-rock analyses. Neumann (1974) stated that ilmenites in peralkaline suites have the highest concentrations of manganese (7-30 wt.% MnO). Another sample known to contain ilmenite is the albitized syenite [9630] from the zoned pluton of Maps A and A′, while the syenogabbro of Map F [9542] recorded titanohaematite. The sills (Maps B and B′) are the only plutons in the Bungadillina suite to contain co-existing magnetite and ilmenite.

Euhedral magnetite and minor ilmenite crystals in the intrusives of the Peake and Denison are considered to be primary magmatic constituents. Oxidation of magnetite is most commonly exemplified by the formation of haematite immediately along fractures and margins of magnetite grains. Partial haematization is considered to represent partial or incomplete oxidation. More strongly altered lithologies, such as albitites, have anhedral interstitial haematite completely replacing other oxides and iron-bearing mineral phases (*e.g.* Plate 4.2.H).

Anatase or rutile, usually as almost pure TiO_2, often occurs as an alteration product of sphene in close association with calcite, and to a lesser extent as an alteration product of ilmenite. Sphene is also found to alter to ilmenite. Such reactions are the result of oxidation and can be expressed as:

$$4 \text{ ilmenite} + O_2 = 2 \text{ haematite} + 4 \text{ anatase/rutile}$$

$$2 \text{ sphene} + 2\ CO_2 = 2 \text{ calcite} + 2 \text{ quartz} + 2 \text{ anatase/rutile}$$

$$6 \text{ sphene} + 2 \text{ magnetite} + 6\ CO_2 + 2\ O_2 = 6 \text{ ilmenite} + 6 \text{ calcite} + 6 \text{ quartz}$$

In low grade metamorphic mineral assemblages, the alteration of rutile-ilmenite or ilmenite-magnetite (depending on Ti/Ti+Fe) to rutile+haematite is due to increasing fO_2 (Rumble, 1982). Alternatively, Yang (1987) has demonstrated that ilmenite and titanomagnetite are unstable in the presence of carbon dioxide. During low grade metamorphism, for example (<270°C @ 1 kb), ilmenite will alter to siderite-haematite-anatase with only a few hundred bars partial pressure of CO_2.

The intrusives of the Peake and Denison Ranges commonly have small euhedral magnetite crystals enclosed in all other major mineral phases, indicating the mineral crystallized very early from the melt. Apatite and zircon often form inclusions in magnetite, and magnetite usually crystallizes prior to sphene. Thus as a primary crystallizing phase, the oxides impress a fundamental influence on (a) progressive crystallizing trends, (b) subsequent crystallizing mineralogy, and, if extracted or concentrated, (c) bulk composition of the resultant rock.

The intrusives, other than the sills of Maps B and B′, represent a suite dominated by magnetite-sphene, and are largely ilmenite-absent. Verhoogen (1962) demonstrated that low oxygen fugacity (fO_2) encourages titanium incorporation into oxides, while higher temperatures and low silica activity ($aSiO_2$) will encourage Ti into pyroxene. Conditions of high oxygen fugacity, high silica activity and low temperature will promote the co-exisistence of magnetite-sphene in preference to diopside-ilmenite or magnetite-perovskite (Verhoogen, 1962; Haggerty, 1982a & b). In contrast, the unusual co-existence of perovskite with sphene in one sample [9542] suggests high temperatures coupled with low silica activity ($aSiO_2$) that will decompose sphene to quartz + perovskite. Coexisting sphene and perovskite has been previously reported only from strongly undersaturated volcanics (Carmichael & Nicolls, 1967; Smith, 1970). As this is definitely not the situation with the syenogabbro [9542], the occurrence of perovskite may alternatively be xenocrystic as is the case with chromite. Ishihara (1977) has suggested that high oxygen fugacity magnetite-bearing magmas are generated from lower crustal and upper mantle regions, whilst lower oxygen fugacity ilmenite-bearing magmas formed from, or mixed with, organic carbon-bearing crustal rocks.

Coexisting magnetite-ilmenite was noted in only three samples, all of which are from the sill swarm of Maps B and B′ [7301, 7303, 7311]. Of these, only one [7301] was capable of utilizing oxygen fugacity - temperature measurements from magnetite-ilmenite pairs (Buddington & Lindsley, 1964), recording approximate crystallization temperatures of 600°C, 730°C and 760°C with fO_2 of 10^{-20} atm., 10^{-17} atm. and $10^{-16.7}$ atm. respectively. These temperatures and oxygen fugacity calculations correspond closely to the experimental FMQ buffer curve (Wones & Gilbert, 1982). The conditions calculated from the first pair are considered to be erroneous as the analyses contain excessive quantities of MnO (more than 5% jacobsite component in magnetite and over 11% pyrophanite component in the ilmenite)

(Haggerty, 1982). The presence of ilmenite in the sill swarm rather than magnetite as in most of the other intrusive bodies indicates that these rocks crystallized under conditions of considerably lower fO_2.

The titanohaematite-bearing syenogabbro [7575] (Map I) would have had slightly lower fO_2 conditions that discouraged coexistence with magnetite. The alkali syenite [9563] (Map F) contains very few oxides, but has an extraordinarily high ferrous iron concentrations (maladministered analyses?) suggesting crystallization conditions of relatively low fO_2.

A chromite grain mantled by Cr-magnetite was found in the sills of Map B′ [7303]. The sub-rounded Cr-rich core, clearly distinguishable from the euhedral rim, recorded 59 wt.% Cr_2O_3. The rim was composed of 2.26 wt.% Cr_2O_3. Both aluminium and magnesium are in very low abundances (Cr value (Cr/Al+Cr) = 0.90; Mg value (Mg/Mg+Fe) = 0.02). In contrast, the monzonite from which the chromite grain was noted has very low whole-rock Cr values (15ppm), as do most all intermediate and felsic intrusives of the Peake and Denison Ranges.

The occurrence of chromite is restricted almost exclusively to mafic and ultramafic suites, as Cr_2O_3 spinel has the ability to partition into early-formed spinels at elevated pressures and temperatures (Muan, 1975). Evans & Wright (1972) have demonstrated that chromite loses Cr in favour of Fe and Ti with decreasing temperature. Dick & Bullen (1984) noted that the Cr value of chromian spinel quickly increases with the degree of partial melting from a mantle source. Similarly, the Mg value corresponds to the relative proportion of olivine and chromite in the rock. Thus falling temperatures accompanied by the removal of chromite (and possibly also olivine) in the sample [7303], has responded by re-equilibration of this particular chromite grain to a condition of severe Mg-depletion. This chromite occurrence can only be considered to be a relict xenocryst from a primitive, perhaps parental source, which has partially re-eqilibrated within its present environment as evident from the Cr-rich magnetite rim (Carmichael *et al.*, 1974). High Cr values and low Mg values are comparable to intrusive "mantle diapirs" of Newfoundland (Malpas & Strong, 1975), while Dick & Bullen (1984) likened such chromian spinels to arc-related volcanic and intrusive peridotites.

Thus the early formed oxides (largely magnetite) in the Bungadillina suite indicate initial crystallization conditions of high oxygen fugacity generated in the lower crust or upper mantle. Subsequent concentration of magnetite may have been an important cumulate phase. High MnO-bearing ilmentite in the sills (Maps B and B′) indicates a peralkaline source, crystallizing under conditions of slightly lower oxygen fugacity, perhaps involving a greater crustal component in the melt for their genesis. The presence of mantled chromite represents relict mantle-derived xenocrysts, indicating the presece of a mantle component for the derivation of the Bungadillina suite magma. Oxide alteration to haematite-rutile is in keeping with low grade metamorphism under oxidizing conditions.

4.3 Sphene.

Like the oxides, sphene is a ubiquitous, locally abundant, and the dominant titanium-bearing accessory mineral in the intrusives of the Peake and Denison Ranges. It commonly forms euhedral crystals up to 1mm in length, crystallizing about the same time as magnetite as it occurs as an inclusion and mantling phase of magnetite in different intrusive bodies (*e.g.* Plate 4.3.A & F). In hydrous mafic compositions, sphene has been recognized to be stable from 10-18 kbars up to 1020°C, forming a refractory phase with magnetite, apatite and zircon for up to 60% partial melting (Hellman & Green, 1979). Occasionally sphene is noted to replace pyroxene [9598] and biotite [9582], often altering to ilmenite-carbonate [9004] or magnetite-carbonate-anatase/rutile [9023] assemblages. Small anatase inclusions often form in sphene grains, and magmatic ilmenite is often coated by sphene [7303, 9594, 7568]. Sphene electron microprobe analyses are recorded in Appendix L. Electron microprobe analyses showing the presence of Cr_2O_3 and V_2O_5 are considered to be actually indicating rare earth elements (REE) as both vanadium and chromium would preferentially be incorporated into spinel which has higher partition coefficients for these elements (Green & Pearson, 1986).

The cores of zoned sphene crystals contain appreciable quantites of REE and aluminium at the expense of titanium. Rims have relatively pure $CaTiSiO_4$ compositions. As sphene crystallizes early, the early incorporation of light REE into sphene reflects the mineral's high partition coefficients for these elements and indicates the early extraction of light REE from the melt. In contrast, Sawka *et al.* (1984) ascribed light REE enrichment to crystal-melt separation prior to the crystallization of the accessory phases. The intrusives of the Peake and Denison Ranges show general enrichment of Ti, Ce and Nd with decreasing SiO_2 indicating a) the early formation of sphene, and b) the early incorporation of light REE into sphene, and c) the accumulation of sphene in with more mafic phases (Fig. 4.3.A & B).

Sphene that has exsolved ilmenite has slightly higher silica and calcium, less titanium. Few sphene crystals show irregular patchy texture, defining REE-enriched areas suggesting some minor subsolidus redistribution. Most analyses contain less than 2% wt.% Al_2O_3 with one exception which is associated with biotite (6.30%) interpreted as secondary metasomatic sphene (Tulloch, 1979).

The alteration of sphene produces small anatase/rutile crystals in association with apatite, carbonate and Fe-oxide, indicating incomplete retrogressive decomposition, probably while in contact with a phosphatic volatile component as indicated by the ubiquitous presence of apatite. Changing P-T-X_{CO_2} conditions of the alteration conditions can result in the recrystallization of sphene as a secondary replacement mineral.

4.4 Garnets.

Garnets, as a primary igneous mineral, are found in only one lithology in the eastern half of Map F in the Peake and Denison Ranges: alkali syenite [9563, 7514, 7546-7]. The only other occurrence [7301] is as a chlorite-garnet xenolith, probably representing chlorite-garnet schist derived from Early Proterozic basement material, the Peake Metamorphics. The garnets of the alkali syenite body are reddish-brown concentrically zoned euhedral crystals up to 1mm in diameter coexisting with clinopyroxene (salite - aegirine-augite) [9563] (Plate 4.3.E & F), whilst those of the xenolith form homogeneous subhedral grains, their extremities outlined by chlorite. Progressive sodic metasomatism in alkali syenite is accompanied by the appearance of green amphibole [7546, 7547] and the immediate retrogression of garnet, which is completely absent in the most altered alkali syenite sample [9562] (Plate 4.4.F). Complete electron microprobe analyses of the garnets are recorded in Appendix J with estimation of ferric iron calculated from stoichiometric constraints.

The garnets analysed from the xenolith [7301] belong to the *pyralspite* group ($X_3Al_2Si_3O_{12}$ where X=Fe^{2+},Mg,Mn), the igneous garnets from the *ugrandite* group ($Ca_3X_2Si_3O_{12}$ where X=Ca,Al,Fe^{3+},Cr,Ti). Of the ugrandite group, the igneous garnets are andradite [$Ca_3(Fe^{3+},Ti)_2Si_3O_{12}$] with both melanite (1-8 wt.% TiO_2) and schorlomite (>8wt.% TiO_2) varieties (Fig 4.4.A & B). Larger examples of these zoned garnets have small Ti-rich cores (10.75% TiO_2) grading to Ti-depleted and Fe-rich towards crystal margins (Fig.4.4.A). In contrast, the whole-rock titanium content of the Ti-garnet-bearing phase [9563] is relatively low (0.44 wt.% TiO_2). The garnets from the xenolith are almandine ($Fe^{2+}{}_3Al_2Si_3O_{12}$) with substantial andradite, spessartine and pyrope components (Fig. 4.4.B).

Garnets of the alkali syenite intrusion are depleted in chromium (<0.16 wt.% Cr_2O_3) manganese (<0.64 wt.% MnO) and vanadium (<0.44 wt.% V_2O_3). The aluminium content of garnet inclusions in pyroxene are much higher in Al (up to 14.38 wt.% Al_2O_3) at the expense of Fe and Ti than others (up to 5.13 wt.% Al_2O_3) which crystallized after or during that of pyroxene. Inclusions of aegirine-augite are found within melanite and schorlomite. Titaniferous andradite crystallization was in part inequilibrium with the crystallization of Na-rich clinopyroxene. The phase relations in the system $CaSiO_3$-$CaMgSi_2O_6$-Fe_2O_3 investigated by Huckenholz *et al.* (1969) indicates the potential for ferric iron substitution between diopside and andradite when in equilibrium with haematite below 1150°C. The necessary abundance of Fe^{3+} required for this reaction is reflected in the whole-rock [9563] geochemistry ($Fe_2O_3/FeO > 1$).

Grossular garnet inclusions in pyroxene may be considered to be an alteration product, but the presence of acmite-rich pyroxene inclusions in garnet is in keeping with the observation that acmite is stable at low oxygen fugacities and high pressures (Gilbert, 1969). Experiments on the join between diopside and ferri-Tschermak's molecule (Huckenholz *et al.*, 1969) have demonstrated that that the subsolidus assemblage of clinopyroxene$_{ss}$+haematite+andradite is stable at more than 35 wt.% $CaFe^{3+}{}_2SiO_6$ at 1000°C. In relations along the diopside-andradite join (Huckenholz *et al.*, 1969), garnet compositions between And_{40} and And_{49} and clinopyroxene are the stable phases with wollastonite. Experimental analyses indicated that progressive increase of Na in diopside will decrease the temperature of crystallization such that crystallization of sodic pyroxene will be in equilibrium with the crystallization of andradite.

The occurrence of Ti-andradite garnets in igneous rocks is restricted to strongly alkaline igneous rocks such as nepheline-syenite, carbonatite, ijolite and phonolite (Deer *et al.*, 1982). The crystallization of schorlomite cores with melanite rims indicates initial crystallization in conditions of very low oxygen fugacity (Virgo *et al.*, 1976a). In contrast, Gustafson (1974) demonstrated that pure andradite is stable only at higher fO_2 values between the quartz-magnetite-fayalite (QFM) and iron-magnetite (IM) buffers. Low fO_2 has also been postulated for the alkali syenite [9563] from oxide analyses. The low absolute intrinsic oxygen fugacity values for Ti-andradite at 1 atmosphere approach the lower limits likely for magmas derived from upper mantle magma chambers (Virgo *et al.*, 1976b). The progressive depletion of garnet from alkali syenite may reflect sharply changing magmatic conditions. Increasing oxygen fugacity during intrusion, accompanied by sodic metasomatism, may revert melanite-schorlomite to sphene-ferrohastingsite (A. Purvis, *pers. com*). Thus the rare occurrence of andradite, like chromite, may represent relict upper mantle-derived crystals, which in the course of magma transport and emplacement in conditions of higher oxygen fugacity, have been resorbed from most of the alkali syenite occurrences. Furthermore, the restriction of these garnets to the late-stage alkali syenite of the Bungadillina suite, suggests that the alkali syenite formed from upper mantle-derived material of low oxygen fugacity.

4.5 Pyroxenes.

4.5.1 Introduction - Pyroxenes.

The pyroxenes in the intrusive of the Peake and Denison Ranges are not as prevalent as the amphiboles or biotite, but are a major distinguishing constituent in many of the lithologies such as the zoned pluton of Maps A and A′, alkali syenites and small gabbroic bodies of Maps F and F′, and some of the more mafic phases of the largest pluton of the intrusive suite (Map G). The calcic pyroxenes are commonly small homogeneous euhedral crystals less than 1mm in diameter (Plate 4.1.C-H). Few of the larger crystals display prominent concentric zoning (both normal and oscillatory; Plate 4.3.C & D), and can occur as inclusions in both hornblende and biotite. Uralitization, or the process of alteration of pyroxene to amphibole, is evident in the partial recrystallization of actinolite along rims and crystal cleavage planes. There are no Ca-poor pyroxenes, neither as individual crystals nor as exsolution products, in any of the intrusive bodies. It appears that there exists insufficient enstatite-ferrosilite components within the Ca-rich clinopyroxene chemistry to warrant exsolution of a separate orthorhombic Ca-poor phase.

The Ca-rich pyroxenes form two distinct groups; the diopside-hedenbergite group which forms a complete solid series between the two end-members ($CaMgSi_2O_6$ - $CaFe^{2+}Si_2O_6$), and the sodium- and ferric iron-rich variety of aegirine-augite ($(Na,Ca)(Fe,Mg)[Si_2O_6]$). With the exception of sodium-rich pyroxenes in syenites [7326] and alkali syenites [9563], the pyroxene compositions amongst all pyroxene-bearing lithologies is remarkably consistent, suggesting consanguinity between the various plutons. In igneous rocks, the diopside-salite pyroxenes commonly crystallize from alkali basaltic magmas or in more strongly alkaline rocks (Deer *et al.*, 1978). Aegirine-augite is found in two samples; an alkali syenite [9563] and a pyroxenite xenolith [9706]. This mineral is characteristic of alkaline igneous rocks (*e.g.* Deer *et al.*, 1978). Appendix C provides a complete documentation of 283 independent electron microprobe analyses from 26 separate samples. Ferric-ferrous iron has been recalculated on the basis of stoichiometric constraints allowing for six oxygens and four cations per unit formula. Pyroxene classification quadrilateral for the Bungadillina suite is shown in figure 4.5.1.

4.5.2 Pyroxene Zoning.

The pyroxenes range in chemistry from $Di_{96}Hd_4$ to $Di_{48}Hd_{52}$ and display three types of zoning in individual crystals; (1) euhedral concentric zoning such that chemical variations correspond to crystal face growth, (2) anhedral or patchy zoning with irregular boundaries, and (3) the mantling of one pyroxene upon another most noticeable with aegirine-augite [9563] (Plate 4.3.E & F). Zoning typically records fluctuations between Fe, Al and Mg concentrations. Normal concentric zoning is from diopsidic augite cores to salite margins. In the pyroxenes of the Peake and Denison Ranges, cores are commonly diopsidic, forming concentric oscillatory zones towards the margin. Zoning is usually characterized by gradual Fe and Al enrichment followed by a sharp decline corresponding to an equivalent increase in Mg. This type of zoning commonly features large unzoned cores, with only the margin showing fine oscillations, indicating initial equilibrium crystallization. Irregular patchy or mottled zoning may show similar chemical variarions between Fe- and Mg-rich zones. Figure 4.5.2 displays the oscillatory nature of euhedral zoning with respect to Al and Mg/Mg+Fe, which is common in finely zoned pyroxenes. In contrast to many similarly zoned clinopyroxenes, TiO_2 is not a salient component which seldom exceeds 0.60 wt.%. The gradual decrease of Mg towards the outer margin of individual zones corresponds to the anticipated trend with respect to decreasing temperature (Schairer & Yoder, 1962). Similarly, the Ca-Tschermakite component $CaAl_2SiO_6$ varies sympathetically with Mg and decreases with decreasing temperature, which is observed with most zoning trends (Herzberg & Chapman, 1976). The aluminium content, however, will be readily influenced by variations in silica activity such that a decrease in $aSiO_2$ will lead to an increase in the $CaAl_2SiO_6$ content of pyroxene for a given plagioclase composition (Carmichael *et al.*, 1970).

Oxygen fugacity is initially controlled by co-precipitating magnetite, a common euhedral and homogeneous inclusion in pyroxenes. Although there is no immediate petrographic indication that oscillating fO_2 was a contributing factor to pyroxene zoning, the intimate association of the hydrous mineral phases of hornblende and biotite suggests the partial pressure of water played an imperative role in crystal formation. Fluctuating aH_2O may be an appropriate mechanism to encourage the development of oscillatory zoning in pyroxenes. Alternatively, Deer *et al.* (1978) have attributed fine oscillatory zoning (<20um) due to slower growing (100 or 010) crystal faces to incorporate more Al than the faster (111) face. Thus in melts with crystals growing fast enough to prevent equilibrium, the initial high Al content of a growing crystal would gradually deplete before temporary cessation of growth. This hiatus is marked by an optically and chemically sharp boundary. Crystallization of high Al pyroxene would then continue when sufficient Al is retrieved from the melt. The fine regularity of oscillations argues against fluctuating magmatic conditions in the form of large-scale magmatic convection or introduction of new magma, as such changes would severely disrupt crystallization patterns in co-existing phases. Thus zoning appears to be either a function of Al-regulating crystal-liquid equilibria associated with alumina saturation in both the liquid and crystallizing phases, or fluctuating activity of water.

The mantling of aegirine-augite upon salite is recorded in the Ti-garnet-bearing alkali syenite [9563] (Plate 4.3.F). There is a distinct compositional boundary between aegirine-augite and salite identified by a colour change from pale green to dark green. These pyroxenes have high acmite component ($NaFe^{3+}Si_2O_6$), and correspond to high whole-rock Mg/Mg+Fe (0.4) (Fig. 4.5.3.D). Zoning commonly features diopside core grading to salite towards the rim, and mantled by aegirine-augite. This relation has also been reported for the most differentiated alkaline rocks in the Shonkin Sag laccolith and is comparable to the common salite > ferrosalite > aegirine sequence encountered in basic alkaline suites (Deer *et al.*, 1978).

Patchy zoning in clinopyroxenes largely involves the separation of Fe-rich salite and Mg-rich diopside into irregular but homogeneous areas with chemically sharp boundaries. The variations cannot be viewed optically but are readily distinguished utilizing the electron microprobe. Minor enrichment of Na and Al also corresponds to zones with higher Fe (Figs. 4.5.3 & 4.5.6.A, C & E). Pyroxene-bearing rocks generally contain pyroxenes with *either* patchy *or* concentric zoning. Thus the occurrence of patchy zoning appears to be due to localized alteration of individual rocks rather than regional metamorphism. Patchy texture in plagioclase has been accounted for by resorption due to drastic magmatic changes such as eruption to high crustal levels. This sudden lithostatic pressure reduction under anhydrous conditions can cause plagioclase corrosion, resorption and recrystallization (Smith, 1974). In pyroxenes, however, even in this scenario, some rudimentary form of concentric zoning would prevail. Alternatively, it was noted that samples which have prominent euhedral zoning do not contain secondary epidote (*e.g.* [7326, 7556-8]), and those with patchy zoning have invariably undergone some degree of epidotization. The formation of epidote will involve the redistribution of Fe and Al amongst the primary mineral constituents. Accordingly, the instigation of this patchy texture, as the response to localized epidote alteration, is not an unreasonable conjecture.

4.5.3 Pyroxene Chemistry.

The pyroxenes of the intrusives of the Peake and Denison Ranges are all Ca-rich clinopyroxenes varying from salite to diopside in composition, with minor incursions into the fields of augite, ferrosalite, endiopside and aegirine-augite (Figs. 4.5.3.D & 4.5.4). Variations between coexisting pyroxene compositions, with the exception of aegirine-augite which contains relatively high concentrations of Fe, reflect minor fluctuations in Fe, Mg, Al and Ca concentrations (Figs. 4.5.4 & 4.5.6.A, C & E). Their general chemistry approximates 700-500°C crystallization temperature of Lindsley's & Andersen's (1983) graphical two-pyroxene geothermometer. Chemical variations within aegirine-augite [9653] in comparison with typical salite-bearing lithologies demonstrate that the depletion of Mg for Fe corresponds to an equivalent increase in Na content (Fig. 4.5.3). Similar Na-enrichment trends are present in the alkali syenite dyke intruding the largest southern pluton [7326] and a pyroxenite xenolith northeast of the dyke locality [9706], suggesting that the xenolith is a cumulate from a more evolved Na- and Fe-rich magma. In contrast, the most Mg-rich diopsidic pyroxenes are from the western zoned pluton of Maps A and A'.

Iron-magnesium ratios of pyroxenes mirror the Mg/Fe conditions in the liquid from which they have crystallized. In the Peake and Denison Ranges, the range of Mg values for all pyroxenes is remarkably similar regardless of the whole-rock Mg/Mg+Fe ratios, suggesting consanguinous crystallization. As their is little correlation between the whole-rock and pyroxene Mg/Mg+Fe ratios, pyroxene crystallization probably occurred in conditions considerably divorced (upper mantle to lower crustal?) from their final whole-rock associations (Fig. 4.5.5). The exception is the aegirine-augite-bearing alkali syenite (Fig. 4.5.5; [9563F]), which has had its Mg ratio modified by increasing Na in the pyroxenes. The high calculated ferric iron component in some pyroxenes suggests that the oxidizing conditions of crystallization may have artificially increased the pyroxene Mg/Mg+Fe ratio relative to the melt, and encouraged the crystallization of magnetite. Alternatively, pyroxene crystallization may have been initiated in conditions far removed from those of final emplacement, where melt and pyroxene Mg-Fe ratios were more compatible. Huckenholz *et al.* (1969) recognized up to 33% $CaFe_2^{3+}SiO_6$ at 1175°C and 1 atm. in calcic pyroxenes can crystallize from melts of high oxygen fugacity.

The chemical variations of the pyroxenes are also evident in the minor components of Al and Mn (Fig. 4.5.6). The greatest range of aluminium, up to 6 wt.% Al_2O_3, is found in the pyroxenes of the small gabbroic bodies in Map F [9570, 9520]. This feature is also apparent for the zoned pluton of Maps A and A′, suggesting consanguinity for pyroxenes between the two bodies. In contrast, pyroxene aluminium content of the xenolith [9706] and syenogabbro from Map I [7575] is very low (<0.34 wt.% Al_2O_3). These low values reflect the paucity of whole-rock aluminium as both [9706] (pyroxenite xenolith) and [7575] (mafic cumulate) have whole-rock concentration less than 5 wt% Al_2O_3. Most lithologies have pyroxenes with moderate quantities of aluminium, usually in the range of 0.5 to 3 wt.% Al_2O_3.

The highest titanium contents are recorded from [9570] with up to 1.33 wt.% TiO_2, while most pyroxenes have less than 0.30 wt.%

TiO_2. Titanium exchanges for ferric iron in calcic pyroxenes and is often coupled with aluminium (Sack & Carmichael, 1984). The aluminium content of pyroxene is strongly pressure dependent such that in the garnet-lherzolite field, the aluminium content decreases with increasing pressure at a constant temperature (Herzberg, 1978). Less variation is present in concentrations of manganese (Fig. 4.5.6.B, D & F). All pyroxenes record low Mn values with the exception of the alkali syenite dyke [7326] in the southern pluton (Map G) which has MnO exceeding 3 wt.%.

The clinopyroxenes of the intrusives of the Peake and Denison Ranges are characterized by high Ca, Mg/Mg+Fe and Fe^{3+}, low Ti, Al and Cr, and variable quantities of Na and Mn. Peridotite diopsides from high grade subcontinental metamorphics are notably enriched in Na relative to Cr (Kornprobst, 1981), whereas alkali basalts are typically more augitic, have 2-5 wt.% Al_2O_3 and over 0.2 wt.% Cr_2O_3 (*e.g.* Duda & Schmincke, 1985). Clinopyroxenes which have crystallized from primitive mantle material to form residual peridotites and harzburgites often have low Ti and Al relative to those from a fractionated source (*e.g.* Coish & Rogers, 1987; Ishiwatari, 1985; Medaris, 1984), but have higher Cr values than those of the Peake and Denison Ranges. Early fractionation of chromian spinel from a primitive magma may be responsible for the depletion of Cr from the melt, thus leading to the subsequent crystallization of chromium-depleted calcic pyroxenes.

The Bungadillina suite pyroxenes appear to have crystallized from a single (alkali basalt?) parental melt in lower crustal to upper mantle conditions. Alkali enrichment in some of the melt (namely forming the felsic-rich alkali syenite) resulted in the crystallization of aegirine-augite. Oscillatory crystal zoning was either due to fluctuating aH_2O or due to crystallographic constraints. Patchy zoning involved low grade localized alteration, possibly in response to epidotization.

4.6 Amphiboles.

4.6.1 Introduction.

Amphiboles are the most widespread and diversified mafic component in the intrusive rocks in the Peake and Denison Ranges. They occur as both a primary magmatic mineral and a secondary alteration product. For the purposes of this discourse, the term *hornblende* is used in a general sense denoting a magmatic derivation. More specific nomenclature as prescribed by the International Mineralogical Association on amphibole classification (Leake, 1978) will be referred to when required.

For the more than 250 individual amphibole analyses included in this work from the intrusives of the Peake and Denison Ranges, all except two belong to the calcic amphibole group (Fig. 4.6.1). The variation of these compositions is extensive; displaying a range from magnesian hastingsite and ferroan pargasite to actinolite. The two analyses that are not included in the calcic amphiboles are both best described as cummingtonite. Electron microprobe analyses of the amphiboles is based on a stoichiometric structure of 23 oxygens (to accommodate the volatile component). Both ionic configurations and the ferric-ferrous iron distributions were calculated utilizing a FORTRAN programme for amphiboles devised by Spear & Kimball (1984). A complete listing of amphibole analyses and their respective recalculation methods is presented in Appendix D.

The amphiboles most commonly occur as euhedral or subhedral phenocrysts and chadacrysts (*e.g.* Plate 4.1.C & D). Hornblende is a minor component in the more siliceous lithologies, and entirely absent from extensively albitized intrusives. It is most pronounced in monzonites, syenites and their gabbroic equivalents. More acicular forms often display flow lineation (Plate 4.2.B & D). Euhedral clinopyroxene and magnetite crystals are often enclosed in or mantled by larger hornblende grains (Plate 4.3.D), while biotite can be found both as an amphibole inclusion or as an amphibole pseudomorph (Plate 4.4.C & D).

The coexistance of hornblende and actinolite in many samples makes it imperative to identify and separate primary igneous amphiboles from secondary alteration or metamorphic amphiboles. The very sharp boundary between contiguous hornblende-actinolite indicates low pressure and low temperature alteration (Grapes & Graham, 1978). The unusual presence of cummingtonite may either represent a metamorphic xenocryst or a similarily altered orthopyroxene (Mongkoltip & Ashworth, 1986). Primary magmatic hornblende is often characterized by prominent concentric zoning (*e.g.* Plate 4.3.B), while secondary actinolite is often associated with the alteration mineral assemblage of calcite-epidote-albite-chlorite (*e.g.* Plate 4.4.E). Actinolite may be the sole mafic constituent in more severely altered lithologies (*cf.* Appendix A).

4.6.2 Amphibole Zoning.

Amphiboles of the intrusives of the Peake and Denison Ranges exhibit chemical variations within individual crystals in three different modes: (a) concentric zonation from core to rim, (b) irregular patchy variations most readily noted from electron microprobe imagery (similar to that in pyroxenes), and (c) coexisting hornblende-actinolite. Compositional changes which have caused euhedral concentric zonating can be attributed to fluctuating magmatic conditions during crystallization, whereas *actinolitization* is considered to be due to secondary alteration.

There is no evidence to suggest that zoning by irregular contiguous phases (b) in hornblende is controlled by crystal structure as there are no regularly spaced exsolution lamellae or correlation to crystal cleavage. The two coexisting phases show dominantly Fe-Mg and Al-Si substitution with minor effects on the alkali element concentration (Figs. 4.6.2.E & F, 4.6.3.E & F). Magnesium-iron and Si-Al exchanges are in the ratio of approximately 1:1, although reverse relations were noted for few coexisiting phases. The chemical variations of amphiboles which have coexisting hornblende-actinolite show similar trends to those with irregular or patchy variation, but more extreme compositional differences (Figs. 4.6.2.G & H, 4.6.3.G & H).

Magmatic amphiboles showing regular concentric zoning have oscillating chemical compositons from core to rim with slight changes in the Fe, Ti, Al and Si contents (Figs. 4.6.2.A & B, 4.6.3.A & B). *Major* chemical changes correspond to coexisting actinolite which commonly mantles zoned hornblende (Plate 4.4.A & B). Concentric euhedral zoning is a common feature of igneous hornblendes, but usually with Mg-rich cores to Fe-rich rims (Deer *et al.*, 1963). Some individual crystals display continuous oscillatory zoning from core to middle followed by continuous oscillatory zoning from middle to rim, but in a different orientation. This indicates a change in the conditions of crystallization, perhaps as partial resorption during crystal growth. These variations may be due to fluctuating fO_2 during crystallization as there are no chemical variations that can be specified to temperature or pressure changes, and without the controlling buffer of crystallizing magnetite, the fO_2 will be more free to vary. However, like the oscillatory zoning of clinopyroxene, the regularity of these fine oscillations cannot be completely accounted for by such drastic fluctuations in the magmatic environment, and may be better explained by crystalline intra-facial crystal-liquid inequlibrium (as with clinopyroxene).

Green (1982) noted disequilibrium relations between xenocrystic pargasitic hornblende and magnesio-hornblende from British Columbian andesites, suggesting progressive crystallization conditions within a compositionally zoned, but mixing magma chamber. Under such conditions, the evolution of *patchy* zoning in Bungadillina hornblendes may also involve crystallization in a zoned and mixing magma chamber. Likewise, the formation of concentric zoning may be in response to crystallization in similar conditions, but without magma mixing.

4.6.3 Amphibole Chemistry.

The correlation of amphibole *Mg value* ($Mg/Mg+Fe^{2+}$) to whole rock chemistry is presented in figure 4.6.4. The broad range of amphibole values indicates, much like pyroxenes, that amphibole chemistry was equivocally determined by associated whole-rock chemistry. Cawthorn (1976) noted the correlation of the whole-rock Mg value with temperature, such that Mg value decreases with decreasing temperature and is associated with progressive crystal fractionation. A vague increase in amphibole Mg/Mg+Fe corresponds to whole-rock decrease from 0.7 to 0.6, suggests some degree of *in situ* amphibole fractionation in the western zoned pluton of Maps A and A', with the quartz monzonite [9593] showing the highest degree of fractionation.

Other variations in the chemical compositions of hornblende analyses have been found to reflect, albeit imprecisely, different lithologies within the Bungadillina intrusive suite. The aluminium contents of the sills and small plutons of Map B are generally higher (up to 13.34 wt.% Al_2O_3) and the sodium generally lower (less than 2.28 wt.% Na_2O) than other amphiboles as depicted in figure 4.6.5.E & F. In contrast, amphiboles from a dyke in the largest southern pluton show the highest Na content (up to 3.06 wt.% Na_2O) [7326]. Amphiboles from the zoned pluton of Map A have moderate sodium contents (Fig. 4.6.5.E). Alkali syenite and the syenogabbro of Map I [7575] plot within a restricted zone which is incorporated into the field of the zoned pluton (Fig. 4.6.5.E & F). These trends appear to be little effected by either patchy irregular zoning (Fig. 4.6.5.G) or actinolitization (Fig. 4.6.5.H). The corresponding composition of amphiboles from smaller unassociated bodies may reflect a similar magmatic source. For example, some amphiboles [7513, 9520, 9542] more closely resemble those from the sills of Maps B and B', whilst the broad scatter for the amphiboles of Map I [7575] correspond to those of the zoned pluton of Maps A and A'.

The amphiboles of the intrusives of the Peake and Denison Ranges are characterized by consistently low titanium (<2.61 wt.% TiO_2) in contrast to mantle-derived amphiboles which have over 4 wt.%

TiO_2 (*e.g.* Dautria *et al.*, 1987). The broad chemical groups outlined using Al and Na of the amphiboles are also repeated by comparing Ti and total alkalis (Fig. 4.6.5.A & D). Most amphiboles from the zoned pluton of Maps A and A′ have less titanium, corresponding to the amphibole compositions from the syenogabbro of Map I [7575], whereas the amphiboles from the sills and plutons of Maps B and B′ form a distinctive group from those of the largest southern pluton (Map G).

Titanium and total alkalis (Fig. 4.6.5.A & D) show a general positive linear correlation. Cawthorn (1976) suggested that both TiO_2 and Na_2O decrease with increasing pressure. Thus pressure variations appear to have more influence on amphibole composition variations than temperature fluctuations as indicated by Mg values. Unlike the Mg value, there is no consistency between the titanium content in amphiboles and the corresponding whole-rock titanium content, although Cawthorn (1976) suggested that amphiboles crystallizing under crustal pressures are typically low in titanium.

Amphiboles are a major mafic mineral component in calcic and intermediate intrusive rocks, noted to be the first silicate mineral crystallizing on the liquidus in experimental systems from 2-10 kbars (Helz, 1973). For more felsic compositions, amphiboles are more prevalent in peralkaline granites and syenites than calc-alkaline or peraluminous systems. The composition of crystallizing hornblende is dependent on the intensive parameters of temperature, pressure, fO_2, X_{H_2O} and bulk composition. At elevated temperatures with constant pressure and fO_2, hornblende is more abundant and stable in intermediate than granitic rocks, as is hornbende in the intrusives of the Peake and Denison Ranges. In some rock compositions, hornblende is less stable at higher fO_2 (HM buffer). Conditions of high fO_2 are indicated for the intrusives of the Peake and Denison Ranges from magnetite. However, magnetite appears to have crystallized earlier than amphibole. The prevalence of amphiboles with Fe^{3+}>Al indicates that crystallization of some amphiboles were influenced by conditions of high oxygen fugacity (Wones & Gilbert, 1982). A-site occupancy in amphiboles increases with temperature. The range of alkali contents for these amphiboles indicates some A-site variations, although both Na and K are not necessarily restricted to A-site occupancy. Al^{IV} increases with increasing temperature at constant crystallizing variables, while titanium content is lower in hornblendes crystallizing from higher fO_2. Igneous amphiboles have generally low Al^{VI} contents with $Al^{IV}/Al^{VI}>=3.3$ (Fleet & Barnet, 1978), a situation generally more applicable to many hornblende analyses from the Bungadillina intrusives.

4.6.4 Coexisting Calcic Amphiboles: Hornblende-Actinolite.

The presence of coexisting calcic amphiboles, hornblende and actinolite (*i.e.* tremolite-ferrotremolite), is well documented from low and medium pressure regional metamorphic terrains and contact metamorphic rocks, notably in metabasites during *prograde* metamorphism (Miyashiro, 1968; *ibid* 1973; Cooper & Lovering, 1970; Brady, 1974; Tagiri, 1977; Grapes & Graham, 1978; Hynes, 1982; Arai & Hirai, 1985). In the greenschist metamorphic facies, hornblende is metastable relative to the assemblage of actinolite with albite-chlorite-epidote +/- quartz-sphene-calcite; a common assemblage in the altered intrusive rocks of the Peake and Denison Ranges. With increased pressures and temperatures, actinolite continues to form at the expense of these phases until the middle amphibolite facies when hornblende-andesine is the stable assemblage (Ernst, 1968). *Retrograde* metamorphism is recognized as responsible for causing actinolitization in mafic intrusives. This results in an incomplete subsolidus disequilibrium reaction through progressive hydration during magma cooling (Vejnar, 1975; Ujike, 1982; Otten, 1984; Mongkoltip & Ashworth, 1986). Partial replacement of hornblende by actinolite is thought to represent an arrested stage of progressive actinolitization (Grapes, 1975; Grapes & Graham, 1978; Ghose, 1982).

The occurrence of actinolite with hornblende is an outstanding feature of the amphiboles of the Bungadillina suite. Actinolite can be the sole amphibole, characterized by patchy, fibrous masses in the more strongly altered samples. Actinolite coexisting with hornblende commonly occurs as a mantling phase. Actinolite, as well as chlorite, also replaces biotite (Plate 4.4.D). Actinolitization of hornblende appears to have been more advanced along microfractures and cleavage, suggesting intracrystalline structural controls inflenced mineral alteration. Actinolitization is accompanied by decrepitation of the original crystal form. Complete alteration commonly forms anhedral actinolite crystal aggregates (Plate 4.4.E).

Complex amphiboles are expected to revert to two or more simpler amphibole phases under equilibrium conditions, but are slowed by low temperature cation diffusion rates. The separation of amphibole phases forms miscibility gaps between coexisting amphibole pairs, commonly as cummingtonite-actinolite, cummingtonite-hornblende and hornblende-actinolite. The lack of cummingtonite in the Bungadillina suite reflects the lack of orthopyroxene from which it commonly alters (Mongkoltip & Ashworth, 1986). Conditions that encourage immiscibility are when the M4 site is filled with large cations, when the A-site is occupied in one and empty in the other, or when the M4 site is occupied by differing cation species (Ghose, 1982). The transition of actinolite to hornblende essentially involves the substitution of Al for Si with postulated reactions such as (Grapes & Graham, 1978):

(1)
$$\underset{\text{albite}}{NaAlSi_3O_8} + \underset{\text{actinolite}}{Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2}$$
$$=$$
$$\underset{\text{edenite}}{NaCa_2(Mg,Fe)_5AlSi_7O_{22}(OH)_2} + \underset{\text{quartz}}{4\ SiO_2}$$

(2)
$$\underset{\text{actinoite}}{Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2} + \underset{\text{chlorite}}{14\ (Mg,Fe)_5Al_2Si_3O_{10}(OH)_8} +$$
$$\underset{\text{epidote}}{24\ Ca_2Al_3Si_3O_{12}(OH)} + \underset{\text{quartz}}{28\ SiO_2}$$
$$=$$
$$\underset{\text{tschermakite}}{25\ Ca_2(Mg,Fe)_3Al_4Si_6O_{22}(OH)_2} + 44\ H_2O$$

The most widely noted evidence for the presence of a miscibility gap or compositional discontinuity between tremolite-actinolite and hornblende are sharp optical and chemical boundaries between co-existing amphiboles, and the lack of separate *and* co-existing crystals of both hornblende and actinolite. These are features consistent with the altered mafic intrusives of the Peake and Denison Ranges.

In the syenogabbro of Map I [7575], noted for it's low alumina content (4.78 wt.% Al_2O_3), and considered to represent a cumulate phase, hornblende is found clearly mantling homogeneous euhedral actinolite cores by means of a series of very fine concentric hornblende rims, analogous to a magmatic origin (Plate 4.3.A). The very low total Al_2O_3 of the rock indicates that the actinolitized mineral was not originally hornblende but may have been another Al-poor amphibole (other actinolitized samples are not depleted in alumina). Alternatively, the actinolite may have been Ca-poor pyroxene. However, as diopside already coexists with the mineral assemblage and shows little sign of alteration, uralitization of Ca-poor pyroxene may not have occurred.

The rare occurrence of hornblende-mantled actinolite [7575] (in rocks that commonly reflect the opposite arrangement) indicates that the formation of hornblende was a primary igneous reaction postdating initial actinolitization. Actinolitization may have occurred at elevated pressures and temperatures; conditions which discourage the development of a pronounced miscibility gap. Examination of coexisting hornblende-actinolite in various metamorphic environments by Misch & Rice (1975) demonstrated that above 600°C at 5kbars there is no compositional discontinuity between coexisting hornblende and actinolite. Conditions below that would form a well-defined miscibility gap.

Most examples of progessive actinolitization of the mafic phases in the intrusives of the Peake and Denison Ranges formed in response to low grade metamorphism. Examples of incomplete actinolitization or the complete absence of actinolite argues against widespread regional metamorphism as the prime cause. Actinolitization may have been initiated by metasomatic conditions upon intrusion and were later modified by regional metamorphism. The occurrence of apparently primary hornblende mantling euhedral actinolite grains in one sample [7575] suggests a complex history of formation at elevated pressures (>1kbar) and temperatures (>600°C).

4.6.5 Amphibole Compositions, Geothermometry and Geobarometry.

Primary igneous amphibole compositions have been demonstrated to vary with bulk rock composition, pressure, temperature, oxygen fugacity and silica activity (Wones, 1981; Wones & Gilbert, 1982). The monzogabbros and syenogabbros of the Peake and Denison Ranges differ from gabbros (*sensu stricto*) by having hornblende as the dominant mafic mineral component, even though their respective bulk rock chemistries may be similar. However, basalts and gabbros are commonly water undersaturated, inhibiting the formation of amphiboles. A basaltic magma would crystallize to more than 50% amphibole if it contained enough water to satisfy amphibole stoichiometry (about 2 wt.%) (Wones & Gilbert, 1982).

It is well known that the Ti content in hornblende increases with increasing temperature of formation (Helz, 1973; Raase, 1974; Spear, 1981). The Ti content of hornblende can be used as a rough geothermometer if the oxygen fugacity is close to the QFM buffer and there is sufficient Ti in the rock for hornblende stoichiometry (i.e. coexisting ilmenite present). This relation (Helz, 1973) is presented as:

$$T>970^{\circ}C - T(^{\circ}C) = 273Ti+877 \text{ or } T<970^{\circ}C - T(^{\circ}C) = 1204Ti+545$$

where Ti is in the number of cations per unit formula (23 oxygens). In the intrusives of the Peake and Denison Ranges, sphene is the most common Ti bearing phase. Ilmenite and anatase are only minor constituents, usually associated with sphene alteration. Application of Helz's (1973) geothermometer recorded *maximum* temperatures from 704°C [9593] to 923°C [9630]. These hornblendes, however, have crystallized in conditions of high oxygen fugacity (towards the MH buffer). Increasing the fO_2 from the QFM buffer to the MH buffer strongly lowers the Ti content of hornblende (Helz, 1973; Otten, 1984). In the case of basaltic rocks which have high Ti contents, the oxygen fugacity will have less effect on the Ti content in hornblende. In contrast, the intrusive rocks of the Peake and Denison Ranges commonly have less than 1 wt.% TiO_2 making them much more susceptible to fO_2 conditions, and resulting in probably misleading geothermometric estimates.

Recent studies in calcic amphibole compositions from calc-alkaline plutons have shown a positive correlation between depth of emplacement and Al content. The original empirical relationship proposed by Hammarstrom & Zen (1986)

$$P(+/-3\ \text{kbar}) = -3.92+5.03Al_T$$

has been slightly modified by Hollister *et al.* (1987) to

$$P(+/-1\ \text{kbar}) = -4.76+5.64Al_T$$

where P is in kilobars and Al_T is the total Al content of hornblende. For the successful application of this simple geobarometer, Hollister *et al.* (1987) have specified that certain restrictions must be imposed including: (a) an assemblage of quartz - plagioclase - biotite - orthoclase - sphene - magnetite, (b) analyses of hornblende rim compositions only; pressure above ~2kbar, (c) coexisting plagioclase compositions in the range of ~An_{25} and An_{35}.

The appropriate application of such a geobarometer on the intrusives of the Peake and Denison Ranges is restricted to only a few lithologies with regards to the aforementioned guidelines, and even then the problem of patchy subsolidus amphibole exsolution and coexistence with actinolite may give questionable results. Nontheless, it provides a useful tool for comparison with other geothermometric and geobarometric calculations.

Only six analysed samples were found to be suitable for the hornblende geobarometer, and of these, one sample from the southern pluton of Maps G & I [9023] and a gabbro from Map F [9570] recorded negative results. Consistent results were acquired from the sills of Maps B and B′ [7301, 7311] of 7.2-8.2 kbars, which is in contrast to a pluton in the same vicinity [7513] of 0.9-1.6 kbars (the results being too low for formula confidence). Pressures recorded in the hornblendes from the zoned western pluton of Map A [9598] and from relatively unaltered material in the southern pluton of Map G [7558] range from 6.3-8.6 kbars and 5.3-7.0 kbars respectively.

The tentative pressures and temperatures of crystallization acquired from selected hornblendes from the intrusives of the Peake and Denison Ranges crystallization are somewhat removed from that of final emplacement. The high pressures recorded from the sills of Maps B and B′ indicate a depth of crystallization in the range of 24km. Fe-Ti oxide geothermometry from one of the sills [7301] indicates a maximum temperature of crystallization of 760°C. Yoder & Tilley (1962) have demonstrated that this co-existing scenario cannot exist as it is above the melting conditions for water-saturated basalt. However, it probably indicates that crystallization of Fe-Ti oxides and hornblende occurred under different conditions. Water-saturated granites would form under conditions of lower pressures (around 6kbars=~18km depth) and lower temperatures (600-700°C) (Luth *et al.*, 1964).

4.7 Biotite.

The most common mafic mineral in the suite of igneous intrusives in the Peake and Denison Ranges is biotite, usually occurring as 1-2mm subhedral to euhedral slightly zoned books. In biotite lamprophyres, it a characteristic sole mineral, forming a trachytic texture in a fine grained felsic groundmass (Plate 4.2.E). Biotite commonly crystallizes soon after that of hornblende, but occasionally forms inclusions in euhedral amphibole crystals. Chadacrysts of sphene, apatite, magnetite, clinopyroxene and occasionally zircon are found within biotite crystals.

On occasion, biotite is the major mafic component, frequently crystallizing in preference to hornblende or replacing amphibole altogether. In such cases, biotite forms pseudomorphs of fine grained patchy network of crystals (Plate 4.4.C & D). The replacement of amphibole with biotite is not a secondary alteration product as there is no associated potassic anomaly. Biotite replacement of amphibole is thus expressing Bowen's reaction series with decreasing pressure and temperature during crystallization, accompanied by increasing partial pressure of water.

In most granites, the low activity of alkali feldspar and silica (until late in the crystallization sequence) prevents the growth of biotite in preference to amphibole. Melts with moderate potassium concentration and low aH_2O will crystallize biotite prior to amphibole (Wones & Gilbert, 1982). What may occur if an anhydrous magma with early crystallizing amphibole is then suddenly inundated with groundwater as it intrudes, say, a wet sedimentary pile? The influx of water from the wall rocks would decrease the temperature of crystallization and amphibole would become metastable with increasing aH_2O in favour of biotite. The crystallization of biotite would then ensue at the expense of amphibole (amphibole + liquid = biotite);

hence the partial to complete replacement of the earlier formed igneous amphibole by igneous biotite (Wenner & Speer, 1986). Alternatively, biotite replacement of amphibole can be subsolidus re-equilibration without the addition of fluids. In the Peake and Denison Ranges, however, the lack of calcite, epidote, chlorite and quartz accompanying biotite pseudomorphs argues against subsolidus replacement (Speer, 1987).

Alteration can affect biotite one of two ways; recrystallization to chlorite or less frequently to actinolite. In lithologies that have undergone albitization, biotite is absent. The potassium that was in the crystal lattice was liberated as part of extensive Na-for-K metasomatic substitution in exchange for chlorite. Chlorite is often seen partially replacing biotite (Plate 4.4.D). Alternatively, actinolite is also noted to partially replace biotite. Ferry (1979) investigated the chloritization of biotite in conjunction with overall sericitization and saussuritization of a biotite granite. The reaction can be expressed as:

$$\text{biotite} + H_2O + H^+ + Ca^{2+} + Fe^{2+} + Mg^{2+} + Mn^{2+} = \text{chlorite} + \text{sphene} + H_2SiO_4 + K^+ + Na^+$$

Biotite compositions of the Bungadillina suite range from annite_{72} to annite_{26}. Only analyses from syenogabbro [9525, 9541] (Map F) and one analysis from alkali syenite [9563] (Map F) recorded Mg/Mg+Fe ratios high enough to be classified as phologopite (Fig. 4.7.1). The titanium content is relatively low, never exceeding 4.65 wt.% TiO_2. The chemistry of biotite, like amphibole, was noted to reflect different intrusive bodies in the intrusive suite (Fig. 4.7.1). The most readily distinguishable were biotite analyses from alkali syenite [9563] with almost all recording annite$_{72-65}$, the exception being an altered inclusion. The other end of the spectrum is dominated by Mg-rich biotite from small gabbroic bodies of Map F [9525, 9541]. The biotites from the zoned pluton of Maps A and A′ are generally enriched in titanium relative to all other groups (Fig. 4.7.1.D), whereas aluminium is enriched in biotites from the sills of Maps B and B′ (Fig. 4.7.1.C). Unlike the wide range of chemical variations for the amphiboles from the zoned pluton of Maps A and A′, the biotites have restricted compositions, whereas those of the sills and plutons have a much broader compositional range, commonly corresponding to biotites from the largest southern pluton of Map G [7557-8, 7568, 7570].

Like amphiboles, the Mg value of biotites should reflect the Mg value for the melt from which they are crystallizing. Figure 4.7.2 demonstrates that, unlike the vague connection for amphiboles and the non-connection for the pyroxenes, the biotites have two distinctive groups of increasing Mg values of biotite with an equivalent increase of Mg values of the corresponding whole-rock, one group of which is notably represented by the zoned pluton of Maps A and A′. The sample with the highest Mg values is a syenogabbro [7541] while the lowest are monzonites [7542, 9595]. The wide range of values for the alkali syenite [9563] may reflect a different crystallization history. However, the consanguinity suggests some degree of *in situ* biotite crystallization, controlled by whole-rock composition.

Schreurs (1985) demonstrated that biotite composition can correspond to specific metamorphic environments. Low to intermediate grade granulite facies biotites have Ti>0.45 atoms per unit formula and Al^{IV}<0.55. These are compositional conditions met by the biotites of the zoned pluton of Maps A and A'. The compositions of other biotites suggest crystallization in lower pressures and temperatures.

4.8 Feldspars.

4.8.1 Introduction.

The feldspar group of minerals [$(K,Na)AlSi_3O_8$ - $CaAl_2Si_2O_8$] presents the single-most abundant and variable felsic mineral in the intrusive suite of the Peake and Denison Ranges, appearing as early- to late-stage primary igneous forms and as secondary alteration products. The prominence of this mineral is exemplified by the presence of *albitite* bodies, composed almost entirely of albite feldspar; the ultimate end-product of *albitization*. Most of the intrusives are composed of weakly to strongly zoned subhedral plagioclase ranging from labradorite to albite. Zoned alkali feldspar is relatively uncommon. Strongly zoned plagioclase crystals with Ca-rich cores (in excess of An_{50}) are often extensively altered, replaced by a composite of calcite, sericite and albite. Like some zoned amphiboles, these cores may be characterized by an irregular boundary separating the altered core from a euhedrally zoned rim indicating partial resorption due to some large-scale change in magmatic conditions prior to complete crystallization. This is considered a hydrous reaction attributed to the metastable nature of early crystallized high pressure and high temperature calcic plagioclase in ultimately low pressure and low temperature conditions.

Alkali feldspar, mostly occurring as orthoclase but occasionally as microcline, is usually a late-stage interstitial phase which can crystallize as a coarse-grained mosaic giving the rock a *ghost-poikiolitic* texture (*e.g.* Plate 4.2.B). In alkali syenites, however, orthoclase occurs as large euhedral crystals, forming demonstrably zoned barium-bearing phenocrysts. Unlike minimum-melt silica-rich granites, there are few examples of either perthitic or graphic textures in the feldspars. Those rocks that do display such textures are invariably quartz monzonites or small quartz-rich felsic dykes (*e.g.* albitites).

The mantling of minerals, both mafic and felsic, is an occasional feature, forming thin serrated rims of water-clear albite. Like the rimming of primary mafic constituents with actinolite, it is considered to be due to progressive secondary alteration (Plate 4.2.A), although magmatic mantling may have been present in a few samples (Plate 4.3.H). The present texture and composition of the feldspars is considerably dependent on the extent of alteration, most notably in the recrystallization of albite, calcite and sericite. Alkali feldspar which has been replaced with albite commonly does not display the characteristic multiple twinning of albite (*e.g.* Plate 4.4.H), instead retaining the simple twinning of its precursor. Chess-board twinning, often regarded as the hallmark of albite metasomatism, is restricted to albitites. Fine-grained groundmass feldspar is often speckled with sericite and calcite.

The chemical variations of the feldspars; as exemplified by their zoning, the variations in coexisting pairs and nature of alteration, were examined utilizing in excess of 280 microprobe analyses, presented in Appendicies E (alkali feldspar) and F (plagioclase).

4.8.2 Zoning.

Zoning is the most prevalent feature of the feldspars in the intrusives of the Peake and Denison Ranges, readily identifed optically and easily analysed by electron microprobe. Both plagioclase phenocrysts and granular plagioclase groundmass may be zoned, whereas alkali feldspar is only zoned as a phenocryst phase (*e.g.* Plates 4.1.A, 4.3.G). Unzoned cores of plagioclase (An_{40-60}) are often coated with a relatively thin rim of more sodic plagioclase (An_{5-15}) (*e.g.* Plates 4.3.B, 4.4.C), or more rarely, are mantled by alkali feldspar. Cores may also be partially saussuritized; replaced by quartz, epidote and calcite, the latter of which is commonly expressed as small anhedral inclusions. Epidote inclusions in zoned plagioclase crystals have been observed to have a thin albite rim. Clinopyroxene, apatite and magnetite are also common inclusions in cores of zoned plagioclase crystals. Sphene inclusions concentrate along the relict core margins where it is engulfed in more sodic marginal plagioclase. Fluorite inclusions have been noted in zoned alkali feldspars from alkali syenite [9563] (Plate 4.4.F).

A more rigorous examination of the zoning details often reveals the presence of a complex oscillatory zonation pattern characterized by an irregular saw-tooth core-rim composition pattern (*e.g.* Fig. 4.8.1.B, I & K). Both normal- and reverse-oscillations have been recorded in the plagioclase crystals, with the maximum Ca compositions not at the immediate core, but directly adjacent a generally unzoned core (*e.g.* Fig. 4.8.1.B & O). Growth from a liquid with decreasing temperature cannot readily account for such features. There is no reason why unzoned or at least simply zoned crystals cannot form directly from the melt. Conditions at the crystal surface in natural systems, must be complex, and zoning could have resulted from diseqilibrium, supersaturation, variations in hydrostatic or volatile pressures (Smith, 1974).

Prominent oscillatory zoning in alkali feldspar phenocrysts often features euhedral Ba-rich zones on both the crystal margins and in the middle immediately following the core zone. These zones were recognized by anomalous TiO_2 readings from electron microprobe analyses which also correspond to barium. Normal crystallization develops progressively richer Ba feldspar towards the margin. Long & Luth (1986) noted the concentration of Ba in the centre of zoned alkali feldspar phenocrysts, and accounted for this phenomenon (of increasing, followed by decreasing, concentrations of crystallizing Ba) by a number of factors, including changing partition coefficient, concentration or growth rate. They demonstrated reverse Ba zoning can be resolved from crystallization of alkali feldspar, quartz, plagioclase and mafics in an igneous system.

Crystallization of feldspar from a magma will reflect the physio-chemical properties of its immediate environment including pressures, temperatures, compositions, fugacities and activities. A fractionating magma experiences an ever-changing environment which will be recorded by the zones in crystal phases within it. Thus early-crystallizing calcic plagioclase, as opposed to alkali feldspar, was probably from a Ca-rich melt crystallizing at high pressures and temperatures. If transported closer to the surface, to conditions of lower pressure, the crystal would be metastable with respect to its new environment and may be resorbed, altered, or recrystallized to a more stable form of feldspar.

Alkali feldspars, when zoned, have fine oscillatory zoning (*e.g.* Fig. 4.8.2.B, C & D). Unzoned and anhedral alkali feldspar phenocrysts, poikiolitically enclosing other zoned mineral species in many lithologies, have very pure orthoclase compositions, which suggests these feldspars have undergone secondary subsolidus re-equilibration (*e.g.* Fig. 4.8.2.A & E). On the other hand, fine oscillatory zonation must be accounted for by other means. Fine oscillations are probably due to diffusion-associated variations in crystal growth, crystal surface contamination by another coexisting phase, or fluctuating volatile contents in conjunction with the rate of crystallization between being volatile-bearing and anhydrous (Smith, 1974). Coarse oscillations are more in tune with a major change in the physio-chemical conditions of the environment as may be found, for example, in a convecting magma chamber.

4.8.3 Feldspar Geothermometry.

The presence of coexisting alkali and plagioclase feldspars in the many intrusive rocks in the Peake and Denison Ranges has permitted the use of feldspar geothermometry to evaluate the physical parameters of crystallization. Given stable equilibrium conditions, the composition of coexisting feldspars is a function of pressure and temperature. Barth (*e.g.* 1962) proposed semi-empirical feldspar thermometric relations which have since been calibrated on the basis of experimental and thermodynamic data to quantify the feldspar exchange reactions. Of the plethora of work accomplished on this theme, four have been utilized in the calculations tabulated in Table 4.8.3 summarizing analysed feldspar pairs in selected samples of the Bungadillina suite. Analyses were conducted on an electron microprobe utilizing a defocused beam across immediate alkali feldspar-plagioclase boundaries. Two different mineral relations were targeted; inclusions in zoned hosts and coexisting rims. Often the plagioclase inclusions in zoned alkali feldspars has compositions comparable to the rims of the zoned plagioclase. Most of the low temperatures recorded (300°C-400°C) are similar to those commonly found in hydrothermal crystallizing feldspars (*e.g.* McDowell, 1986), attesting to subsolidus K^+ mobility in relatively K-depleted lithologies. Figure 4.8.3 displays the restricted alkali feldspar compositions near the *orthoclase* apex of the feldspar triangle. In contrast, plagioclase retains more calcic compositional variations, especially within cores of zoned crystals. Slow diffusion rates have probably restricted Ca depletions from plagioclase cores during subsolidus re-equilibration processes. Later forming sodic plagioclase and alkali feldspar, however, were more readily re-equilibrated during late-stage crystallization and/or albitization. Temperatures acquired, that resemble magmatic conditions (669°C max.), are invariably from alkali syenite which has retained much of its original potassium content, probably as the result of earlier crystallization of alkali feldspar.

4.9 Epidote Group.

4.9.1 Epidote and Clinozoisite.

Epidote is a ubiquitous secondary alteration mineral in the intrusives of the Peake and Denison Ranges, rarely occurring as a primary igneous product, but often in conjuntion with calcite and albite as a homogeneous and relatively pure alteration product. In the zoned pluton of Maps A and A', epidote forms subspherical alteration patches or nodules up to 1m in diameter in association with albite, calcite, chlorite, actinolite and sphene. Such nodules have also been described in mafic lavas in New South Wales (Smith, 1968) forming as the result of burial metamorphism. They occur in association with prehnite, quartz, actinolite and calcite and are attributed to the migration of calcium originating from the breakdown of (a) calcic plagioclase to albite and (b) clinopyroxene to chlorite. These minerals recrystallize with epidote in structurally favourable zones such as intersecting fractures. In contrast, Harrigan & MacLean (1976) suggested a more complicated evolution for epidote alteration patches (up to 0.5m in diameter) in gabbro dykes, with formation due to autometasomatism from circulating magmatic fluids or hot meteoric water 'pumped' through the rocks. The timing of alteration, however, is difficult to accurately determine (Smith, 1977).

The chemical data for epidotes from 32 microprobe analyses is tabulated in Appendix I. The most common form of the epidote group minerals is epidote [$Ca_2(Fe^{3+},Al)Al_2O.OH.Si_2O_7.SiO_4$]. The theoretical pistacite end-member, $Ca_2FeAl_2Si_3O_{12}(OH)$, is Ps=[$100Fe^{3+}/(Fe^{3+}+Al)$]. None of the 32 epidote electron microprobe analyses exceeding Ps_{38} and few less than Ps_{20}.

The core of a zoned clinozoisite [$Ca_2Al_2O.AlOH.Si_2O_7.SiO_4$] crystal was analysed with $Ps_{6.4}$ grading to an iron-rich rim. Although the reverse relation is more common in low-grade metamorphic terrains, Al-rich cores and Fe-rich margins have been described resulting in progressive chemical variations in the metasomatizing fluid (Kitamura, 1975). Epidote associated with the alteration of feldspar is commonly more depleted in iron with Ps_{11-17}, whilst that composed of the highest ferric iron component (Ps_{40}) formed at the expense of clinopyroxene. Such iron-rich epidote has been noted within biotite and chloritized biotite of a granite altered at approximately 300-350°C and P_{H_2O}<2kbars (Tulloch, 1979).

Investigations into synthesized epidote stability with varying oxygen fugacity and temperature has found that the ferric iron content increases with increasing fO_2 (Liou, 1973). Epidote is a common mineral forming in hydrothermal systems such as the Salton Sea geothermal system in California (Keith *et al.*, 1968). In sub-greenschist metamorphic conditions (*circa* 200-250°C) in volcanics of British Columbia, epidote forms together with chlorite, prehnite, albite and calcite, replacing olivine, plagioclase and groundmass while preserving phenocrysts of pyroxene, hornblende and spinel (Beddoe-Stephens, 1981). Unlike the plutons of the Peake and Denison Ranges, epidotization of the diorites of Al Hadah, Saudi Arabia, formed veins and fracture coatings in response to a progressive influx of Ca^{2+}-rich fluids during pluton cooling and contraction. This resulted in the transformation of calcic plagioclase-hornblende-biotite-quartz to epidote-hornblende-actinolite-albite-(quartz) (Marzouki *et al.*, 1979).

In the Peake and Denison Ranges, the common association of calcite with epidote affirms that epidotization requires the addition of CaO. High activity of CO_2 favours the formation of epidote over pumpellyite. The absence of prehnite and pumpellyite restricts the conditions of metamorphism to the lower greenschist facies. For example, the reactions of prehnite+epidote+quartz = epidote+calcite and prehnite+chlorite+epidote = pumpellyite+quartz limits the conditions of metamorphism to pressures of less than 2.5 kbars and temperature range of 320-360°C (Nitsch, 1972). The consistant ferric iron content amongst most all epidote analyses corresponds to formation under consistant conditions of oxygen fugacity.

4.9.2 Allanite.

Rarely occurring is the REE-rich member of the epidote group, allanite. Allanite is readily recognizable in electron microprobe analyses from high REE (recorded in electron microprobe analyses as anomalous vanadium) and manganese (up to 1.25 wt.% MnO) contents, forming independently from other epidote minerals. Where allanite occurs, it usually has a REE-rich halo of micro-veinlets surrounding the main mineral which may be anastomosing cracks of metamict varieties. Allanite is a common, accessory, late-stage phase in felsic igneous intrusives, often concentrated in pegmatites. Allanite also occurrs as a hydrothermal and alkaline metasomatic product, with hydrothermally derived allanite showing lower Ce/Y ratios than igneous allanite (Deer *et al.*, 1986). This distinction was inconclusive for the intrusives of the Peake and Denison Ranges. Allanite was noted in only a few samples as a very minor phase, and reflects the lack of whole-rock rare earth elements in the intrusives of the Peake and Denison Ranges in general.

4.10 Chlorite.

Chlorite $[(Mg,Al,Fe)_{12}(Si,Al)_8O_{20}.OH_{16}]$ is a secondary alteration product primarily of the mafic constituents of the intrusives of the Peake and Denison Ranges. It is commonly found in association with most secondary species. In more thoroughly altered rocks such as the albitites, chlorite can be the sole mafic constituent, completely replacing, in particular, biotite. The chemistry of the 22 microprobe analyses (Appendix H) classifies the chlorite as ripidolite, pycnochlorite and/or diabantite (Hey, 1954; Fig.4.10.1). Two analyses are anomalously iron-rich with 41-43 wt.% FeO which are thought to have been acquired through close association with allanite and vein epidote.

Recent studies (Eggleton & Banfield, 1985) on the alteration of biotite to chlorite in granites have demonstrated the hydrothermal reaction (330-340°C) can be expressed as:

$$1 \text{ biotite} + 0.21 \text{ anorthite} + 1.64\ H_2O + 0.08\ O_2 =$$
$$0.46 \text{ chlorite} + 0.11 \text{ sphene} + 0.10 \text{ epidote} + 0.56 \text{ muscovite} + 0.63 \text{ quartz} + 0.02 \text{ magnetite} + 1.46\ K^+$$

A similar reaction has been completed for igneous biotites at temperatures at approximately 200°C by Parry & Downey (1982). This style of alteration is accompanied by sericitization of calcic plagioclase (as found in zoned cores), including the addition of Ca^{2+}, H_2O and H^+ at the expense of K^+. In the Bungadillina suite, chlorite appears to have formed under similar conditions.

4.11 Synopsis.

From the preceding discussion, the following mineralogical characteristics can be concluded for the Bungadillina suite.

(1) The intrusives are composed of similar mineral suites largely involving hornblende, biotite, clinopyroxene, plagioclase and alkali feldspar. Only alkali syenite was noted to contain demonstrably different minerals: sodic pyroxene and titaniferous garnet.

(2) Magnetite is an early crystallizing phase indicating initial conditions of high fO_2, whereas ilmenite is restricted to the sills of

Maps B and B′ and may reflect lower fO_2 conditions. Co-existing magnetite-ilmenite pairs in the sills (Maps B and B′) record fO_2 at 10^{-20} to $10^{-16.7}$ atmospheres and temperatures up to 760 °C.

(3) Sphene is the major titanium-bearing mineral phase. Its coexistence with magnetite indicates high $aSiO_2$, and the early concentration of LREE into sphene largely controls whole-rock LREE concentrations.

(4) The presence of xenocrystic chromite indicates a mantle influence in parental source derivation.

(5) Melanite and schorlomite garnets in alkali syenite suggest late-stage crystallization from upper mantle conditions of very low fO_2.

(6) An anhydrous parental melt is indicated by early crystallization of an anhydrous mineral assemblage including: diopside-salite accompanied by calcic plagioclase, magnetite and sphene.

(7) The intimate relationship between of the hydrous mafic phases of hornblende and biotite suggests some fluctuation of aH_2O occurred during their later crystallization.

(8) Diopside-salite compositions are similar to those which have formed from primitive mantle material, but the lack of chromium in these pyroxenes suggests early fractionation of Cr- (and Ni-) bearing mineral phases.

(9) The salite-aegirine-augite pyroxenes of the alkali syenite are common to rocks of peralkaline affinity.

(10) The Mg value of pyroxenes has no relation to the whole-rock composition suggesting crystallization in conditions divorced from their present lithological location, whereas amphibole shows a slight correlation, and biotite, especially from the zoned pluton of Maps A and A′, shows a strong correlation indicating relatively *in situ*

crystallization.

(11) Low titanium contents in amphiboles may be in response to crystallization in conditions of high fO_2.

(12) Amphibole geothermometry and geobarometry recorded crystallization conditions ranging from 704° to 923° and 7.2kbars to 8.2kbars.

(13) The highest temperature for coexisting feldspars was calculated to be in the order of 669°C. The majority of pairs, especially late-crystallizing orthoclase, have undergone subsolidus re-equilibration and record low (hydrothermal) temperatures.

(14) The secondary mineral assemblage of epidote, calcite, actinolite, chlorite and haematite is in keeping with the localized effects of low-grade hydrothermal alteration.

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Chapter Five: Geochemistry of the Intrusive Rocks of The Peake and Denison Ranges.

> "The perceptive writings of H.H. Read (1948 in 1957) have conditioned us into accepting that there are 'granites and granites'. Perhaps, in view of the geochemical evidence presented here, it would be more appropriate to admit that there are 'granites, granites and still more granites'."
>
> Preface, *Origin of Batholiths - Geochemical Evidence*, Atherton & Tarney (1979).

5.1 Introduction.

In order to obtain a representative suite of the chemistry of igneous intrusives in the Peake and Denison Ranges, 132 samples were subjected to major and trace element whole-rock geochemical analyses, the complete tabulation of which is recorded in Appendix B and a summary of which is presented in Table 5.1. Preparation of a sample involved acquisition of an appropriate quantity (depending on grain size), removal of the immediate weathered portion, crushing, and separation into an appropriate fraction and grinding. Major element analyses include 11 oxides, all of which were analysed by (fused disc) XRF with the exception of Na_2O (atomic absorption) and ferric iron (titration). The volatile constituents of sulphur, water and carbon were not separately analysed and are thus amalgamated into "H_2O^+". The concentrations of fourteen trace elements were determined by (pressed pellet) XRF, and fluorine was analysed by specific ion electrode. Of these samples, 77 duplicates were analyes to test the accuracy of XRF determination. Little, if any, discrepancy was noted. Thus for all [9000]-series samples, the recorded analytical values represent the average of two separate analyses. Analytical conditions for all aforementioned routines are duely compiled in Nesbitt *et al.* (1980).

Sr isotope determinations were accomplished using a Thompson CSF-206C mass spectrometer at the Department of Geology and Geophysics, the University of Adelaide. Detailed Rb analyses were accomplished utilizing detailed XRF analyses (Nesbitt *et al.*, 1980).

For 46 samples, an additional four trace elements (La, Sn, Ta & W), including five trace elements (Ce, Ga, Nb, Y & Zr) which were also determined at Adelaide University, were independently analysed from different samples of the same outcropping by Comlabs Pty. Ltd. (Perth, W.A.). These figures are separately presented in Appendix B1. The *Comlabs* analyses are not used as evidence in any arguments in this text as the author had no control over analytical methodology. Nonetheless, the data are included for comparative purposes, which the reader is warmly invited to review, courtesy of Union Oil Development Corporation. In general, it was found that the Comlabs Pty. Ltd. analytical resolution for these trace elements was insufficient for detailed petrochemical purposes. This lack of resolution is especially evident in comparison with identical analyses by the University of Adelaide.

There are probably several injections of magma involved with emplacement of the entire Bungadillina suite (*cf. ch.* 3.3). To accommodate such intra-suite variables, the following variation diagrams were constructed to discriminate possible lithologically independent rock types (*i.e.* biotite lamprophyre and alkali syenite), chronologically different suites (*i.e.* zoned pluton of Map A and sill swarm of Map B) and geographically separate bodies (*i.e.* south pluton of Map G-I). With this mode of grouping, it is then possible to successfully order small, scattered and seemingly autonomous occurrences into larger, more definable arrays.

As discussed in previous chapters, many of the rocks have been invariably altered through albitization, epidotization or carbonatization. Alteration, as in the case of albitization, requires exchange of primary, magmatically derived K for secondary Na. For the successful application of geochemical technique, it is essential to separate chemical characteristics produced by primary crystallization from those which have been the result of secondary altering processes (*e.g.* metasomatism). To these ends, there are two methods available; (a) petrographic study of secondary alteration products, and (b) geochemical identification of specific metasomatic elements. Although petrographic analysis has the ability to distinguish distinctive mineralogical relations between primary and secondary assemblages, such as the secondary replacement of hornblende by actinolite, it cannot provide as quantitative a vehicle for measurement as geochemisty. Thus this chapter has a two-fold purpose: to quantify the processes involved with primary igneous petrogenesis and to distinguish the effects of secondary metasomatism.

5.2 Major Element Geochemistry - Classification.

The variety of lithologies in the intrusive suite of the Peake and Denison Ranges is reflected in their respective chemistries. SiO_2 ranges from 47-75 wt.% and Al_2O_3 from 4-21 wt.%, with the majority of samples being intermediate in composition (52-66 wt.% SiO_2). Samples range from those which are silica undersaturated to those which are silica oversaturated. Although the normative figures are not presented in table 5.1, they contain between 15% normative quartz to 12% normative nepheline (*cf.* Appendix A; Fig. 5.2.1.C).

Miyashiro's (1978) classification scheme identifies the rocks of the Bungadillina suite as alkalic (Fig. 5.2.2.A), while Shand's (1927) classification scheme shows the intrusive suite to straddle the metaluminous field along the peralkaline margin (Fig. 5.2.1.A). The consistant 1:1 ratio between alumina and total alkalies also defines Shand's (1927) little-used *sub-aluminous* field (Al=Na+K). The Bungadillina suite shows minor incursion into both the peralkaline and peraluminous fields in this classification scheme. The suite, however, is regarded as distinctly non-peraluminous as only eight samples record normative corundum. Similarly, only two samples recorded normative acmite; the hallmark of peralkaline rocks.

Attempts to classify the Bungadillina suite by means of schemes based on the primary magmatic concentration of the alkali elements may be potentially misleading due to the effects of secondary sodic metasomatism. Thus it is imperative to distinguish those samples that have been subjected to substantial alkali alteration from relatively unaffected equivalents. For example, the broad spectrum of Na_2O+K_2O (Fig. 5.2.2.A) compositions prevents accurate classification utilizing Peacock's (1931) alkali-lime index, but can be principally considered to be alkali-calcic in character (Morrison, 1986). Figure 5.2.1.B illustrates the extent of sodic metasomatism. Strongly altered samples have Na_2O/K_2O+Na_2O greater than 0.76. This value is not fixed, but is considered the upper limit of a range expressing incomplete Na for K substitution commencing from about 0.64, which approximates an apparent compositional gap. The most siliceous samples are also strongly metasomatized indicating some degree of silica enrichment with sodic alteration. Nonetheless, some samples with as little as 50 wt.% SiO_2 have undergone substantial sodium enrichment indicating that silica concentration is not the only factor bearing on the processes of albitization. Similar lines of albitization discrimination can be successfully applied using the *igneous spectrum* of Hughes (1972) (Fig. 5.2.2.C). The field of altered igneous rocks (A) successfully delineates albitized samples ($Na_2O/Na_2O+K_2O>0.76$), with an apparent compositional gap between the altered and unaltered fields (Fig. 5.2.2.B). Morrison & Foden (1989) have also identified, by congruous geochemical means, albitized samples of the zoned pluton of Maps A and A'.

The recognition of altered samples is important when classifying the Bungadillina suite utilizing AFM diagrams (Fig. 5.2.1.B). Most of the unaltered samples plot broadly within the fields defined by typical alkaline and calc-alkaline trends. Morrison & Foden (1989) described a much more defined trend, between alkaline and calc-alkaline fields, for samples predominantly from the zoned pluton of Maps A and A'. Significantly altered samples deviate from these trends by plotting towards the total alkali (A) apex, as albitization has resulted in the preferential enrichment of sodium, in part at the expense of iron (the *F* apex).

Albitization is equally noted in the clustering of altered samples around the normative albite apex in the normative quartz-albite-orthoclase-nepheline double quadrilateral (Fig. 5.2.1.C). This diagram demonstrates that, like SiO_2 content, there is no discriminating lithology for albitization in either quartz-normative or nepheline-normative rocks. The significance of quartz-nepheline normative coexistence will be further described in proceeding chapters. In both the AFM and normative mineralogy diagrams, the anomalous sample [7575] which plots towards the iron and quartz apices respectively, is an actinolite-rich syenogabbro; a probable cumulate rock with less than 5 wt.% Al_2O_3.

5.3 Major Element Geochemistry - Variations.

The most conspicuous lithology of the intrusives of the Peake and Denison Ranges comprises the albitites and similarly altered rocks as discussed in the previous section (5.2). The most definitive major elements of the altered lithologies are the alkalis which are unique in having very high Na_2O (5.31-10.69 wt.%; Fig. 5.3.1.E) and very low K_2O values (0.24-2.15 wt.%; Fig. 5.3.1.F). Geochemical analyses of the range of samples indicate the presence of a specific "compositional gap", suggesting that alteration was a comprehensive process, forming geologically distinct alteration zones, as noted with, for example, the albitized margins of gabbroic plutons. This feature, however, may alternatively reflect sampling technique in which few *partially* altered lithologies were sampled. The ranges of the alkali concentrations are in part due to incomplete sodic metasomatism with the division between altered and unaltered samples somewhat arbitrary. Corresponding SiO_2 range from 50.39 wt.% from an altered syenogabbro [9011] (Map F') in the northern margin of the largest pluton in the Bungadillina suite to 71.15 wt.% from a secondary albitized zone [9625] within a small syenogabbro pluton (Map F).

Many of the albitized rocks also exhibit depleted iron, both ferric and ferrous, in comparison to relatively unaltered samples (Fig. 5.3.1.C & D). Although there is considerable range of iron values ranging from 0.10-8.58 wt.% Fe_2O_3 ([9608]: small albitite pluton, Map F; [9520]: pyroxene-bearing syenogabbro zone of small monzogabbro pluton, Map F) and 0.04-4.55 wt.% FeO [9608 & 9011], most register less than 2 wt.% combined Fe_2O_3 and FeO.

In comparison of unaltered samples with those that have been albitized, similar trends are accompanied by a reasonable scatter, as demonstrated by CaO, Al_2O_3, MnO, MgO and P_2O_5 (Figs. 5.3.1.A & B, 5.3.2.A, B & D). TiO_2, however, exibits slight enrichment to the trend, ranging from 0.10 [7515] to 1.39 wt.% [9011] (Fig. 5.3.2.C). Both fluorine and chlorine concentrations are similar to the unaltered F trend and Cl scatter with only one sample [9523] above 1000 ppm F (1820 ppm) and four samples above 500 ppm Cl (Figs. 5.3.2.E & F).

In contrast to the potassium-deficient albitites and other albitized rocks, the alkali syenites are characterized by high concentrations of K_2O (up to 10.93 wt.%) (Fig. 5.3.1.F) and relatively low Na_2O (1.70-4.70 wt.%), forming a unique lithological group. To compensate for the extraordinarily high total alkali content of the alkali syenites, CaO, FeO, MnO, MgO, TiO_2 and P_2O_5 are slightly less than the average for unaltered samples (*cf.* Table 5.1). All others are much the same with the exception of chlorine which is relatively high with five samples in excess of 480 ppm Cl.

Similar to the alkali syenites, the two analysed biotite lamprophyre dykes [9327 & 9627] have high chlorine (975-760 ppm), similar fluorine (460-340 ppm) and relatively low concentrations of CaO (7.56-5.71 wt.%), FeO (3.50-3.90 wt.%) and MnO (0.07-0.04 wt.%). But unlike the alkali syenites, the lamprophyres have moderate Na_2O+K_2O (8.58-8.85 wt.%), and low ferric iron. The alkali ratio, Na_2O/K_2O+Na_2O, is similar to that of unaltered monzonites and monzogabbros. With respect to other major oxides, TiO_2, P_2O_5, MgO and Al_2O_3 concentrations in the lamprophyres are congruous with contents of typical unaltered Bungadillina intrusives relative to silica (49.86-50.58 wt.% SiO_2).

The second largest of the Bungadillina suite, the westerly pluton of Maps A ans A′, is composed of an extensive intrusive suite ranging from syenogabbro and monzogabbro to monzonite and (albitized) quartz monzonite (also from the small adjacent quartz monzonite plug; *cf.* Maps A or B′, as described by Morrison & Foden (1989)). The suite forms a broadly linear trend for all major oxides against silica. Silica ranges from 48.55 to 61.43 wt.%. In the variation of Al_2O_3 against CaO, there exists a distinct inflection from a positive to a negative trend at 5-6 wt.% CaO (Fig. 5.3.3.F). Morrison & Foden (1989) suggested the inflection represents calcic plagioclase-controlled fractionation in magmas with less than 5 wt.% CaO, and hornblende-pyroxene fractionation control at higher CaO contents. Small late-stage dykes intruding the pluton [9311 & 9314] are the most siliceous for unaltered samples of this suite with approximately 63% SiO_2 and represent the felsic end-member of the various chemical trends (Fig. 5.3.3).

The syenite, quartz syenite and syenogabbro, comprising the largest pluton of the Peake and Denison Ranges (Maps F′, G & I), portray a separate intrusive suite to that of the zoned pluton of Maps A and A′. Both the silica-depleted (>53 wt.% SiO_2) and silica-rich end-members (62-64 wt.% SiO_2) have higher K_2O than the pluton of Maps A and A′ (Fig. 5.3.4.D). These end-members are also similar to the alkali syenites, which are also reflected in similar high total alkali contents. The gabbroic northern margin of this pluton (Map F′) appears to be altered with less than 1% K_2O and Na_2O/Na_2O+K_2O less than 0.15 for a silica range of 50-56 wt.% [9011-2]. Al_2O_3, CaO, FeO, MgO, TiO_2, P_2O_5 and Cl all have concentrations and trends like those trend of the zoned pluton of Map A (Fig. 5.3.4.H, 5.3.5.B & D, 5.3.6.B). However, Fe_2O_3, MnO and F are slightly enriched in this pluton.

The small homogeneous quartz monzonite plug of Maps A or B′ is chemically similar to the quartz syenite of the largest pluton (Maps F′, G and I) in all major elements except potassium. Although Na_2O contents are similar, the slightly more siliceous (63-67 wt.% SiO_2) quartz monzonite [9590-3] has lower K_2O. The lower potassium of the quartz monzonite is a chemical characteristic more compatible with the silica-rich end-member of the zoned pluton (Maps A and A′) trend (Fig. 5.3.3). Alternatively, the low potassium content may correspond to incomplete albitization.

The sill swarm of Maps B and B′ provides slightly differing chemical trends in comparison to either those of either the largest pluton (Maps F, G & I) or the zoned pluton (Maps A and A′). Sodium, CaO and Al_2O_3 contents for these monzonites, monzodiorites and gabbroic equivalents are slightly less in concentration, but displaying compatible trends in comparison with other intrusives (Fig. 5.3.4.A, E & G). Iron, MnO, TiO_2 and MgO contents of the sills are slightly greater for the equivalent range in silica (52-62 wt.% SiO_2) (Figs. 5.3.5.A & C, 5.3.6.A), while chemical variations for the other major elements are generally indistinguishable from the trend developed from the zoned pluton.

The small plutons of Map B, occurring intimately with the sills, form another regionally cohesive group. Their chemistries display a broad range of values for silica (55.79-66.85 wt.% SiO_2) as well as other major oxides. Some samples record quite high ferric and ferrous iron (up to 4.11 wt.% and 3.31 wt.% respectively [9007]). The geochemical trends are similar to that of the sills of the area, with minor potassic enrichment at the expense of sodium and aluminium. In contrast to the variety of concentrations for chlorine in the sills, the plutons of Map B have uniformly low values (100-195 ppm).

Gabbroic xenoliths [7702, 7704] recovered from some sills were sufficiently large to separate and analyse. Silica contents are uniformly low (51.31 & 56.77 wt.% SiO_2), but aluminium varies widely (5.66 & 13.15 wt.% Al_2O_3) and fluorine is very high (1380 & 4640 ppm) although no fluorite was (optically) present. The low aluminium (as well as Cl and P_2O_5) content of one xenolith [7704] is compensated by a corresponding enrichment in CaO, FeO, MgO and MnO, as this xenolith is dominated by Al-depleted amphibole (actinolite). A similar chemical relation is seen with an actinolite-rich syenogabbro [7575] of Map I which has similar chemical characteristics to the xenolith [7704] by having only 4.78 wt.% Al_2O_3 but, in contrast, is extremely enriched in titanium (1.94 wt.% TiO_2) and phosphorous (1.63 wt.% P_2O_5). The less siliceous, TiO_2 and Na_2O-depleted xenolith [7702] is markedly enriched in P_2O_5, MnO and F. The unusual chemistry of these gabbroic xenoliths and that of the syenogabbro [7575] is more like that of a mineral cumulate than that of a basaltic magma. Many of the samples may also reflect chemistries of mineral cumulates, and not correspond to a parental homogeneous magma.

5.4 Trace Element Geochemistry - Alteration.

As with major elements, it is essential to readily identify those samples which have endured secondary geochemical mobilization; alteration. In the Bungadillina suite, alteration most commonly takes the form of albitization. In the trace elements, albitization has resulted in depletion of the large ion lithophile elements (LIL) of K, Ba, Rb and, to a more selective extent, Sr (Figs. 5.4.1.A, C & E). Albitization has more strongly affected Rb and Ba with samples not exceeding 76 and 832 ppm, and most less than 30 and 400 ppm respectively. Strontium has a much more scattered plot with most samples less than 500 ppm, but with fourteen samples recording in excess of 500 ppm Sr. The process of albitization has apparently replaced alkali feldspar and calcic plagioclase by albite. As well as mobilizing the calcium and potassium contents of these minerals, albitization has also released the Ba, Rb and Sr contents of these minerals. Strontium, which would have been preferentially retained in primary calcic plagioclase, would have at least been partially salvaged by albite, hornblende and apatite during alteration.

Most all other trace elements have been little affected by albitization and plot concordantly along with relatively unaltered samples. Gallium, Ce, Nb, Zr & V (Figs. 5.4.2.H, F, C, A & B), and Cr & Ni (Figs. 5.4.1.B & D) show little modification, either enrichment or depletion, as the result of albitization. Low Sc and V contents in the albitized samples correspond to the general trend towards silica enrichment due to the progressive eviction of Sc- and V-bearing components of hornblende and magnetite during albitization (Fig. 5.4.2.D & F). On a broad basis, it can be argued that albitization has resulted in slight Nd enrichment of at least some samples. Yttrium is the only element which consistently shows a 5-10 ppm enrichment in albitized samples in comparison to unaltered samples with similar SiO_2 contents (Fig. 5.4.2.G).

5.5 Trace Element Geochemistry - Variations.

Zirconium concentrations range from 80 to 200ppm, with only slight enrichment towards more siliceous lithologies (Fig. 5.4.2.A). Three samples; a syenite [7557], an albitite [7515] and a xenolith [7704] have unusually high Zr for the Bungadillina suite (201, 268 and 350 ppm respectively), perhaps as the result of zircon accumulation in these phases. Niobium experiences similarly little variation with concentrations ranging from 3.7 [7575] to 13.9 ppm [9313] (Fig. 5.4.2.C). However, it may be argued that Nb experiences a slight early enrichment with respect to silica, but the degree of enrichment (<5ppm) is negligible.

The light rare earth elements (REE) of Ce and Nd have broadly similar concentrations and slight decreasing concentrations with increasing silica (Figs. 5.4.2.E & F). Albitized samples [9545 & 9012] define the range for both elements with 5-146 ppm for Ce and 1-75 ppm for Nd. Alkali syenites represent the only group showing slight enrichment in these elements in comparison with the broad trends produced by most other lithologies, perhaps indicative of late-stage volatile enrichment. Few of the more mafic albitized samples show any enrichment (*cf.* Table 5.1). Preferential concentration (cumulate phase?) of light REE-enriched sphene is believed to be in part responsible for higher Ce and Nd contents in more mafic lithologies (*cf. ch.* 4.3).

The transition elements scandium and vanadium are much more enriched in more mafic rocks, record more coherent geochemical trends, and appear to be little effected by sodic alteration (Figs. 5.4.2.B & D). Vanadium concentration is in general ten times greater than that of Sc. The actinolite-rich rock [7575] contains the highest vanadium content (589 ppm) while SiO_2-rich albitites [9543 & 9625] recorded the lowest (<25 ppm). A mafic-rich albitite [9514] has the highest Sc content (65 ppm), and again the silica-rich albitites contains the lowest (<5 ppm). There was only minor relative enrichment of scandium in lithologies containing a high concentration of mafic constituents such as the lamprophyres and xenoliths, while alkali syenites retained average to slightly depleted concentrations.

Chromium and nickel, in most cases, have very low concentration, except in the most mafic samples. Chromium seldom exceeds 30 ppm for samples with SiO_2 greater than 60 wt.% and Ni does not exceed 20 ppm for the same range of silica (Fig. 5.4.1.B & D). One lamprophyre in particular [9630] has the very high Cr (275 ppm) and Ni (69 ppm), and a mafic-rich member of the zoned pluton of Map A recorded 201 ppm Cr and 74 ppm Ni. High values of these elements are thought to be in part due to xenocrystic Cr-rich oxides (chromite) and residual Ni-rich silicates (olivine?) (*cf. ch.* 4.2).

Like the major oxides, the trace element trends for the sills of Maps B & B′ and the southern pluton of Maps F′, G & I display slight variations from the trends noted for the western zoned pluton of Maps A and A′ (Morrison & Foden, 1989). Like FeO and MgO, the sills have slightly more enriched Sc and V trends than the zoned pluton (Fig. 5.3.5.E & G), whereas the southern pluton adheres more closely, albeit with a greater scatter, to the western pluton trend (Fig. 5.3.5.F & H).

The broad distribution for the high field strength trace elements of Zr, Y and Nb for the sills and southern pluton corresponds to the trend dictated by the zoned pluton of Maps A & A′ (Fig. 5.3.6.C-H). If any contrasting variations could be identified, then the sills may have slightly lower concentrations, on average, to the zoned pluton, whereas the southern pluton is slightly more enriched.

5.6 Isotope Geochemistry.

5.6.1 Potassium - Argon.

Ambrose *et al.* (1981) conducted a limited K-Ar geochronological investigation of the intrusives of the Peake and Denison Ranges, concluding that the suite is Delamerian in age. Two hornblende samples from the massive quartz monzonite of the largest southern pluton and from the pluton in the northeast section of Map A recorded very consistant ages ranging from 492-502 Ma. In contrast, the western zoned pluton of Maps A & A′ was responsible for two contrasting dates of 679 and 469 Ma from biotite and hornblende respectively. A final (total rock) date from a dolerite dyke gave an age of 537 Ma, but Ambrose *et al.* (1981) suggested that this date represents an older intrusive phase. These dates for the Bungadillina suite are slightly but notably older than K-Ar whole-rock dates for Delamerian granites in the Kanmantoo Trough and the Padthaway ridge which average around 460 Ma (Webb, 1976; Milnes *et al.*, 1977). Milnes *et al.* (1977) suggested that this date (460 Ma) corresponds to the age estimated for waning of metamorphic conditions of the Delamerian Orogeny.

Experimental work on the relative ^{40}Ar retentivity of biotite and exolved amphibole (hornblende-cummingtonite) has shown that the biotite will give an older age as the exsolution microstructure of the amphibole aids in the escape of radiogenic ^{40}Ar from the crystal lattice (Harrison & Fitzgerald, 1986). Many of the amphiboles in the intrusives of the Peake and Denison Ranges often have a complex exsolution of hornblende-actinolite, suggesting these amphiboles have undergone a similar style of radiogenic loss, thus ruining their use for geochronology. Similarly, Seidemann (1988) has demonstrated that K-Ar values show increasing scatter for increasing hydrothermal alteration and decreasing potassium content (of Jurassic basalt flows), suggesting that small amounts of excess radiogenic ^{40}Ar are present which record artificially older ages.

As previous K-Ar geochronology has proven at best ambiguous and at worst misleading, further geochronological work, both whole-rock Rb-Sr and zircon U-Pb, was undertaken to attempt to refine the age for emplacement of the igneous suite.

5.6.2 Rubidium - Strontium.

The examination of Rb-Sr isotope systematics was conducted to more closely define the age of intrusion and initial $^{87}Sr/^{86}Sr$ ratios of the plutons in the Peake and Denison Ranges. Whole rock analyses were made in preference to analyses of mineral separates in the assumption that whole rock samples would more likely act as a closed system. The analyses are summarized in table 5.7. Measurements on three albitized rocks and two carbonates were also undertaken to examine the effects of alteration. Analyses were concentrated in three major areas; largest southern pluton (Maps G & H), the zoned western pluton (Maps A & A') and the sill swarm (Maps B & B').

From inspection of data points on figure 5.6.2, it is apparent that the scatter is too severe for accurate geochronological use. The MSWD would be excessively large, and there is no valid Rb-Sr isochron. Without an acceptable line, there cannot be any reliable information regarding initial $^{87}Sr/^{86}Sr$ ratios. Contamination by extrenuous sources, sodic metasomatism, preferential contamination or poor sample preparation and analysis may all or in part have been responsible for poor Rb-Sr isotope results.

The effects of carbonate contamination was investigated by examining the Rb-Sr isotope systematics of two carbonate samples [7597-8] from calcite veining in Adelaidean strata, and carbonate matrix from diapiric breccia. Calcite microveinlets, noticeable in more altered samples of the Bungadillina suite, may have originated from groundwater and represent a potential source for contamination. The carbonates are severely depleted in Rb relative to Sr, plotted along the $^{87}Sr/^{86}Sr$ axis. Contamination of igneous rocks by the carbonate would thus shift samples towards the $^{87}Sr/^{86}Sr$ axis, and provide another cause for the wide array of whole-rock Rb-Sr isotopes.

5.6.3 Uranium - Lead.

In conjunction with the South Australia Department of Mines and Energy, a U-Pb zircon date was obtained with the assistance of C.M. Fanning at Amdel Laboratories. The rock was collected by the author from the zoned western pluton [9583], from which the zircons were extracted, separated and grouped according to size and magnetic succeptibility, then forwarded to Amdel for preparation and measurement. The resultant date of 525+/-37 Ma (Fanning, 1987) for zircon crystallization (Fig. 5.6.3) has been derived from a far too discordant isochron with a far too great MSWD (150) to render any meaningful age. An isochron with such a demonstrable lead-loss (evident from large cracked zircons and small sized zircons used for analyses) probably has a younger true age than indicated (G. Dunning, Mem. Univ. NFLD; *pers. comm.*). However, Morrison & Foden (1989) have used this unreliable date to support erroneous Rb-Sr geochronology.

5.6.4 Carbon and Oxygen Isotope Geochemistry.

In the igneous rocks of the Peake and Denison Ranges, carbon is accommodated in calcite, which occurs as a secondary alteration component, especially in albitized rocks where it forms as an interstitial replacement mineral and as microveinlets. Calcite is also noted as rounded coarsely crystalline xenoliths in monzogabbro [9707] and in a carbonate-matrix breccia zone in the centre of the zoned pluton of Map A [7200].

Carbon has two stable isotopes: ^{12}C=98.89% and ^{13}C=1.11%. Carbonates of a biological origin have typically heavy isotopes with $d^{13}C$ around 0‰ (permil), while magmatic or *juvenile* carbon from carbonatites and kimberlites have $d^{13}C$ from -4.0 to -8.0‰ (*e.g.* Deines & Gold, 1973; Taylor & Bucher-Nurminen, 1986). Mean $d^{13}C$ value for volcanic gas (CO_2) in geothermal areas is -3 to -5‰, whereas liquid lavas have a wide range of $d^{13}C$ values (-14 to -28‰). Carbon in hydrothermal systems can originate from juvenile magmatic carbon, from limestones (average $d^{13}C$ value near zero), or from organic carbon ($d^{13}C$ lighter than -20‰). However, hydrothermal carbon is strongly influenced by intrinsic functions such as fO_2, pH and temperature (Rye & Ohmoto, 1974). Deines & Gold (1969) have demonstrated the isotopic compositions of both carbon and oxygen in a contact metamorphosed limestone are lowered with progressive increase in alteration.

Oxygen has three major isotopes: ^{16}O=99.763%, ^{17}O=0.0375%, and ^{18}O=0.1995%. $^{18}O/^{16}O$ range from +41‰ (atmospheric CO_2) to -60‰ (Antarctic snow). Geothermal and meteoric waters range from -24 to +7‰, and igneous rocks from +5 to +9‰ (except pegmatites: 7 to 14‰) (Brownlow, 1979). Magmatic carbonates have $d^{18}O$ values generally between +6 and +10‰ (Deines & Gold, 1973), whereas magmatic fluid in hydrothermal systems will readily exchange oxygen isotopes with contiguous mineral species thus modifying $d^{18}O$ values (Hoefs, 1980).

Stable isotope geochemistry for the Peake and Denison Ranges is presented in Table 5.6.2. As previously mentioned (*cf. ch.* 1.5.4), vein carbonates and breccia carbonates have $d^{13}C$ and $d^{18}O$ values, like those of marine limestones, suggesting a low-temperature groundwater genesis. Secondary carbonate from albitites [7516, 7564, 9541] are uniformly and considerably more depleted in $d^{13}C$ and $d^{18}O$ than calcite from the host strata. Thus isotope evidence indicates a carbonate genesis through hydrothermal alteration in association with the interaction of altering groundwater and the intruding pluton. This further supports the contention that albitization occurred during magmatic emplacement, and not due to regional metamorphism.

The coarse carbonate in a breccia zone within the zoned pluton of Map A has distinctly different $d^{13}C$ (-4.68‰) and $d^{18}O$ (+12.01 ‰) values. These values indicate crystallization from a deep-seated carbonate magma source as opposed to originating from low temperature groundwater percolations. Similar figures are obtained from a rounded carbonate xenolith [9707] in a monzogabbro body (-1.77 $d^{13}C$, +7.15 $d^{18}O$) suggesting formation from magmatic carbonate, but later effected by partial hydrothermal isotope exchange.

In contrast to the progressive lowering of isotopic compositions with hydrothermal alteration, the $d^{13}C$ content of a carbonate xenolith [9706] and zone of carbonate brecciation within the zoned pluton of Map A [7200] are demonstrably low, and the corresponding $d^{18}O$ values are relatively high. The oxygen isotopes indicate, like the carbonate within the Adelaide Geosyncline, a groundwater source. The xenolith has probably exchanged isotopes with the intrusive body, thus recording lower $d^{18}O$ values. The low $d^{13}C$ values cannot be readily accounted for by low-temperature groundwater genesis. However, Faure (1977) has documented that extremely low $d^{13}C$ values in sedimentary carbonates, particularly from the Precambrian, are derived from the bacterial or inorganic oxidation of methane. Alternatively, the low $d^{13}C$ values may be due to an igneous or geothermal origin, but then the corresponding $d^{18}O$ values are too high for a magmatic source.

5.7 Synopsis.

The Bungadillina suite of the Peake and Denison Ranges contain igneous rocks with a very wide silica range: from 47 to 75 wt.% SiO_2. They also range from normative silica undersaturation to silica oversaturation. High alumina and alkalis give the suite a metaluminous alkali-calcic character. Altered samples are characterized by albitization, resulting in the preferential loss of K, Ba and Rb in exchange for Na. Albitized samples are ten times more depleted in Rb, K and Ba concentrations, and up to five times more depleted in Sr concentrations (Fig. 5.7.1.A & B) in comparison with unaltered equivalents. Other trace elements (*e.g* HFS, Sc and V) have been little effected by albitization. Albitized samples are readily identified by having Na_2O/Na_2O+K_2O greater than 0.7. Strongly albitized samples are depleted in iron in preference to magnesium.

The Bungadillina suite is strongly depleted in Cr and Ni, even in the gabbroic lithologies, which may have resulted from early extraction of olivine and chrome spinel from the parental magma. Zirconium is also generally depleted for rocks of relatively high silica. Similar depletions are apparent for Nb, Ce and Nd. These low values correspond to the lack of REE-bearing mineral phases in general. In contrast, Sc and V are enriched in response to high concentrations of locally abundant magnetite and hornblende.

The general major and trace element concentrations by the syenogabbro-syenite-quartz syenite-alkali syenite and the monzogabbro-monzonite-quartz monzonite trends reflect a common, consanguineous association (*e.g.* Figs. 5.7.1.A & B; 5.7.2 A & B). Alkai syenite may be the most differentiated member of this suite, reflected in both its late stage of formation and its high concentration of large ion lithophile elements. This feature of high LIL element concentrations, readily recognized by the positive Sr anomaly, is punctuated in the comparison of the quartz syenite average compositions with average "I-type" (igneous source granites) and "A-type" (anorogenic granites) concentrations from the Devonian granites of the Lachlan Fold Belt (Fig. 5.7.2.B). The petrogenetic significance of this mode of granite classification will be elucidated in proceeding chapters. Higher LIL element concentrations in the Bungadillina suite are similar to "A-type" values, whereas lower HFS element concentations more closely resemble "I-type" contents. These unusual chemical relations makes the

Bungadillina suite comparatively unique.

All attempts at geochronology are too erroneous to be used for determining age of the plutons. The zircon data are far too discordant to provide reliable age information. Furthermore, the MSWD of 150 means the line is useless; there could easily be a component of older inherited zircon hidden within the analyses. Data for Rb-Sr isochron plots are too scattered. The MSWD values would undoubtly be enormous. There are no valid isochrons, no valid age data and no worthwhile information on initial $^{87}Sr/^{86}Sr$ ratios of the plutons. Regardless, Morrison & Foden (1989) suggested that the western zoned pluton of Maps A & A′ recorded a relatively low initial $^{87}Sr/^{86}Sr$ ratio that required a mantle-derived component.

Rb-Sr isotope systematics for the intrusives of the Peake and Denison Ranges may have had original magmatic ratios re-equilibrated by Delamerian Orogenic activity, disturbed by sodic metasomatism, contaminated by carbonate veining, or marginally contaminated during emplacement. Poor analyses may also have been a factor.

Carbon and oxygen isotope data from carbonate material in the Bungadillina suite are analogous to carbonates that formed from groundwater, whereas both a carbonate-hosted breccia within the zoned pluton (Map A) and a carbonate xenolith have contradicting $d^{13}C$ and $d^{18}O$ values which could either reflect a high temperature (magmatic) or a low temperature (groundwater) origin.

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Chapter Six: Comparative Geochemistry of the Intrusives of the Peake and Denison Ranges with Igneous Rocks of the Adelaide Geosyncline, Lachlan Fold Belt and Gawler Craton.

"The chemical variability of 39 groups of igneous rocks has been investigated using a data base of 26,373 published analyses... Nine variation diagrams are also given for each group."

Abstract of *The Chemical Variability of some Common Igneous Rocks* by R.W. Le Maitre (1976).

6.1 Introduction.

Outlined in the previous chapters is a compendium of the present knowledge of the igneous intrusive rocks of the Adelaide Geosyncline, and more specifically, in the Peake and Denison Ranges. In this chapter, these and other igneous suites are defined with respect to their ages, tectonic settings and geochemistries, and compared and contrasted to the Bungadillina suite of the Peake and Denison Ranges.

There are four well-defined igneous events distinguishing the geologic history of the Adelaide Geosyncline. The first two are predominantly volcanic in nature, erupting during Early (Callanna Group volcanics) and Middle (Emeroo Subgroup volcanics) Adelaidean time. The third event, also largely expressed as extrusive, occurred during the Early to Middle Cambrian (*e.g. Truro Volcanics, Warburton Volcanics*). The last magmatic event is largely plutonic; forming the granites of the Nackara Arc and Kanmantoo Trough through to western Victoria and Antarctica as part of the Cambro-Ordovician Delamerian Orogeny. These igneous suites provide a tectonic time-scale to compare and contrast magmatic events which have accompanied the development of the Adelaide Geosyncline as well as the Bungadillina suite of the Peake and Denison Ranges.

Comparative geochemistry of the intrusives of the Adelaide Geosyncline is based on the geochemistry of the intrusives of the Peake and Denison Ranges, the Anabama Granite, the plutons of the Arkaroola region, and the intrusives of the Willouran Ranges as presented in previous chapters of this thesis and as found within published and unpublished literature. They are compared to the better-known chemistries of Delamerian (Kanmantoo Trough) plutons intruding the Cambrian Kanmantoo Group sediments to the southeast of the Adelaide Geosyncline, Late Proterozoic (post-Kimban Orogeny) igneous rocks of the Gawler Craton, and Lachlan Fold Belt granites of eastern Australia. Recent data from Foden *et al.* (1989) has permitted the subdivision of the Kanmantoo Group intrusives into "syn-tectonic" and "post-tectonic" granites. Unfortunately, insufficient data available for the Delamerian intrusives within the Mt. Painter Inlier prevents their inclusion. These plutons should be considered as the subject of future research.

One of the most thoroughly studied suites of Silurian-Devonian granites on earth is that of the Lachlan Fold Belt. Work by Chappell & White (1974) on the petrology of the Lachlan Fold Belt granites led to the development of the "S-type" and "I-type" classification scheme. Work by (Collins *et al.*, 1982) has refined the classification of "A-type" granites from the same fold belt. Data from these studies have been used in comparison with the geochemistry of the intrusives of the Peake and Denison Ranges (*e.g.* Fig. 5.7.2).

Recent work by numerous authors including Hilyard (1986), Woodget (1987), Gum (1987) and Gatehouse (1986) have provided geochemical databases for the volcanic sequences of the Adelaide

Geosyncline and adjacent basins. These data have been used as well for comparing the intrusive rocks of the Adelaide Geosyncline as they may represent coeval extrusive equivalents of plutonic occurrences.

Two of major Middle Proterozoic igneous events in South Australia are represented by the intrusion of post-tectonic granites of the Gawler Craton (*e.g. the Hiltaba Granite; ca.* 1514 Ma) (Cooper *et al.*, 1985) and the extrusion of voluminous felsic volcanics (the *Gawler Range Volcanics; ca.* 1592 Ma.) (Fanning *et al.*, 1988). Thus this comparative suite is intended to span both the pre-Adelaidean and post-Adelaidean provinces in Australia.

6.2 Major Element Comparative Geochemistry.

One of the most outstanding differences between the intrusives of the Peake and Denison Ranges and igneous rocks elsewhere is the concentration and mobility of the alkali elements. Figure 6.2.1 demonstrates these differences. The Bungadillina suite is enriched in the alkalis with respect to silica, revealing an alkaline character which is contrary to the subalkaline tendencies for Lachlan Fold Belt types, Kanmantoo Group and Anabama granites. One notably displaced sample of the Bungadillina suite [7575] into the subalkaline field is interpreted to be a mafic cumulate phase and not a true representation of parental melt (Fig. 6.2.1.A). Figure 6.2.1.B shows little distinction between the Adelaide Geosyncline volcanic rocks and the intrusives of the Willouran Ranges. The bimodal character of the Cambrian volcanics is clearly demonstrated along with the very SiO_2-rich nature of the altered intrusives of the Arkaroola region (Fig. 6.2.1.B).

Figures 6.2.1.C-F illustrate the relative behaviour of Na and K for these suites. The tendency for sodic metasomatism is well established for some samples of Bungadillina intrusives where sodium is preferentially concentrated at the expense of LIL (large ion lithophile) elements, notably potassium, rubidium and barium. In contrast, no alkali alteration is viewed for the granites of Anabama, Lachlan Fold Belt or Kanmantoo Group. As *albitites* are included in the sample group of the Willouran and Arkaroola intrusives, it is not unexpected that they exhibit consentient chemistries with albitites of the Bungadillina suite. This style of alteration is also present for some felsic members of Cambrian volcanics and the Burra Group volcanics.

The intrusives of the Peake and Denison Ranges display a wide range of aluminium concentrations. Their relative enrichment in comparison to average Lachlan Fold Belt granite values is the dominant feature in figures 6.2.2.A-F. This difference is most pronounced in comparison the "A-type" granites and most of the post-tectonic granites of the Kanmantoo Group which are characterized by low (12-14 wt.%) Al_2O_3, whereas the monzonites of the Peake and Denison Ranges have greater quantities (16-19 wt.% Al_2O_3). Aluminium concentrations are similar for syn-tectonic Kanmanto Group granites, the Anabama Granite and those of the Bungadillina suite. Aluminium values for the intrusives of the Willouran Ranges and Arkaroola region encompass the gap between these Al-rich and Al-depleted suites. These are similar to the average Lachlan S- and I-type granites, but MgO, CaO and *FeO (total iron expressed as ferrous iron) values are, of course, substantially greater in the more mafic Willouran gabbros, Callanna Group volcanics (basalts) and the more basaltic phases of the Cambrian volcanics (Figs. 6.2.2.B, D & F).

The negative linear relation of CaO, *FeO and MgO with respect to aluminium for the more mafic samples of the Bungadillina suite is in sharp contrast to the generally positive relations expressed in the trends for the Anabama Granite, the pre-tectonic Kanmantoo Group granites or the post-tectonic Kanmantoo Group granites. These contrasting trends correspond to the dominance of hornblende and clinopyroxene fractionation in the Peake and Denison Ranges intrusives, while calcic plagioclase exerts more substantial control of composition for the other granites. Deviations from this positive linear trend by both the Anabama and post-tectonic granites of the Kanmantoo Group may correspond to the importance of biotite as well as plagioclase in influencing the resultant composition (Fig. 6.2.2.A, C & E).

Although not graphically represented, the trend for "I-type" (Kosciusko Batholith and Jindabyne Suite) granites from the Lachlan Fold Belt has slightly higher MgO and CaO for according SiO_2 than the intrusives of the Peake and Denison Ranges (Griffin *et al.*, 1978; Hine *et al.*, 1978). The Peake and Denison suite is characteristically intermediate in composition while the Lachlan Fold Belt Granites are more felsic, as indicated by the position of average values.

Alteration of the intrusives of the Arkaroola region has resulted in uniformly low calcium, iron and magnesium concentration. This situation is similar, but not nearly as extreme, for the most felsic of the suite of Cambrian volcanics. The gabbros of the Willouran Ranges, the Callanna Group volcanics and the Gairdner dyke swarm all have broadly similar FeO, MgO and CaO concentrations as illustrated in figure 6.2.2 (B, D & F). However, the bimodality of the

Willouran intrusives and the Cambrian volcanics, and the high iron and relatively low calcium concentrations for the Burra Group (Port Pirie) volcanics are indicative of more evolved source material and tectonic environment, which is in contrast with the primitive continental (tholeiitic) flood basalts of the Callanna Group.

A strong negative linear trend is demonstrated by TiO_2 against silica for the samples of figure 6.2.3.A. The intrusives of the Peake and Denison Ranges, however, are notably more depleted in TiO_2 in comparison to either the Kanmantoo Group or Anabama Granites. Titanium is also consistently more enriched in the "I-type" granites of the Lachlan Fold Belt (Griffin *et al.*, 1978; Hine *et al.*, 1978). The Bungadillina suite is also strongly TiO_2 depleted in comparison with the Willouran intrusives and the Adelaidean and Cambrian volcanics. However, the severe depletion of titanium in the Arkaroola intrusives reflects the want of any mafic phase which possibly could retain TiO_2 in these altered rocks; a situation also demonstrated in few samples of Cambrian volcanics, but not in the altered Willouran intrusives (Fig. 6.2.3.B).

Along with the characteristic range of values for the alkali elements for the Bungadillina suite as previously discussed, another distinguishing chemical characteristic is their extremely high P_2O_5 concentrations (Fig. 6.2.3.C). The intrusives of the Peake and Denison Ranges commonly have greater than 1 wt.% P_2O_5 reflected in the abundance of apatite. This is in distinct contrast to all other compared samples, bar one or two, which do not exceed 0.5 wt.% P_2O_5. In contrast, the P_2O_5 trend for the Moruya Suite from the Lachlan Fold Belt is similar to, or slightly more phosphorous-enriched (with respect to similar SiO_2 concentrations) than the Bungadillina suite (Griffin *et al.*, 1978).

Thus in consideration of the major element parameters for these suites of rocks, the intrusives of the Peake and Denison Ranges form a readily identifiable group characterized by high alkalis, aluminium and phosphorous, low titanium, and the development of negative trends for MgO, CaO and *FeO against aluminium. In contrast, the syn-tectonic Kanmantoo Group granites have similar major element variations to the Anabama Granite, which in turn has characteristics more akin to Lachlan Fold Belt "I-type" granites than either "S-" or "A-type" granites.

Intrusives of the Peake and Denison Ranges are not the only Adelaide Geosyncline igneous rocks which have experienced sodic metasomatism. Albitites of the Willouran Ranges and Arkaroola region have similar characterstics as well as Cambrian volcanics. Many of the more gabbroic rocks of the Willouran Ranges have chemical characteristics identical to Adelaidean volcanics, as do the Cambrian basalts, indicating a continental tholeiitic source (Woodget, 1987). But the distinctive bimodal character of the Cambrian volcanics, which displays a negative trend with respect to CaO, *FeO and MgO against aluminium, resembles that of the Bungadillina suite.

Although Teale & Lottermoser (1987) have described the intrusives of the Arkaroola as "Palaeozoic" "A-type" granites, it appears that these altered rocks have too high aluminium contents with respect to other major oxides to be considered equivalent to typical "A-type" granites or Kanmantoo Group post-tectonic granites (Turner and others, *in prep.*). Alteration of this specific group has led to extreme depletion in most calcium, iron, magnesium and titanium. Care must be especially exercised in affording a tectonic setting by means of chemical parameters to any intrusives that have been strongly influenced by any commanding alteration processes.

6.3 Comparative Trace Element Geochemistry.

The use of trace elements to compare and contrast the igneous rocks of the Adelaide Geosyncline and elsewhere is limited by the sets of elements available. Not all authors analysed identical trace element sets. Of the suites of rocks under consideration, the most consistently analysed of the trace elements include Ce, Sc, V, large ion lithophile (LIL) and high field strength (HFS) elements. Scanty information has been published for the halogen elements as well as most of the rare earth elements. The proceeding section synthesizes the comparative characteristics of the most applicable and available trace elements.

The post-tectonic and "A-type" granites display a sudden decrease in barium with increasing silica; from over 1500ppm to 50ppm accompanied by a gain of 8 wt.% SiO_2. No other suite behaves in such a manner. The intrusives of the Peake and Denison Ranges commonly have greater than 500ppm Ba for unaltered samples; a broad scatter similar to that for the Anabama and syn-tectonic granites of the Kanmantoo Group (Fig. 6.3.1.A). The Willouran intrusives also display a wide range of Ba values comparable to that of the Cambrian volcanics. In contrast, the Callanna Group basalts and the Gairdner dyke swarm are relatively depleted in barium (<500ppm Ba) and show a more restricted range of variation. The altered intrusives of the Arkaroola region all have less than 70ppm Ba except one recording 1149ppm Ba. This trend of extreme Ba concentration with increasing silica is similar to that of the Cambrian volcanics (Fig. 6.3.1.B).

In the "I-type" granites of the Lachlan Fold Belt, barium increases with increasing silica (Hine *et al.*, 1978), whereas in comparison with the Bungadillina suite, the Lachlan Fold Belt "I-type" granites are depleted in barium. In contrast with the Bungadillina suite, the Anabama Granite has similar "I-type" barium concentrations as the Laclan Fold Belt "I-type". For some samples of both the Anabama Granite and the intrusives of the Peake and Denison Ranges, alteration has caused respective enrichment and depletion of Ba.

The large ion lithophile element, rubidium, concentrates in alkali feldspar. As the amount of alkali feldspar varies widely in the intrusives of the Peake and Denison Ranges (from albitite to alkali syenite), the plot of Rb is invariably scattered (*cf.* Fig. 5.4.1.A). Like barium, altered members of the Bungadillina suite have depleted rubidium. However, the general trend approximates Ba/Rb<5 (Fig. 6.3.1.C). The Anabama Granite has correspondingly scattered values, but Ba/Rb is less than 5, which is similar to the ratio for Lachlan Fold Belt "I-types", while the post-tectonic Kanmantoo Group granite suite, although having two exceptionally Ba-rich deviants, has Ba/Rb<1. In contrast, the post-Kimban Gawler Range Volcanics have relatively high concentrations of Rb (~100ppm Rb = 60 wt.% SiO_2, ~200ppm Rb = 70 wt.% SiO_2) and Ba (up to 3000ppm Ba) (Giles, 1980).

The wide compositional variation of both Ba and Rb for the syn-tectonic Kanmantoo Group granites prevents accurate association. The range and enrichment of Rb in the Arkaroola intrusives is considerable (over 700ppm; Fig. 6.3.1.D), while the intrusives of the Willouran Ranges record Ba/Rb ratio greater than 12. Although the

Callanna Group volcanics and dykes show limited variation in Ba and Rb concenrations, the Port Pirie volcanics are notably Rb enriched while the Cambrian volcanics have an wide spread of concentrations, akin to the intrusives of the Peake and Denison Ranges.

The diagram of Sr against Rb (Fig. 6.3.1.E) illustrates that the intrusives of the Peake and Denison Ranges have twice to three times the amount Sr in comparison with Lachlan Fold Belt "I-type" granites (Hine *et al.*, 1978; Griffin *et al.*, 1978), Gawler Range Volcanics (Giles, 1980) and Kanmantoo Group post-tectonic granites. The syn-tectonic Kanmantoo Group granites and the Anabama Granite generally show a negative linear trend for Rb/Sr. The trend has a similar slope, but with slightly higher concentrations, to the "I-type" granites of the Lachlan Fold Belt. Many samples of the Anabama suite show enrichment in Rb with little change in Sr, probably in part controlled by biotite fractionation. The Arkaroola intrusives contain little Sr which is probably the result of their unique style of alteration. In contrast, the intrusives of the Willouran Ranges show little Rb enrichment while varying considerably in Sr. Again, all the Callanna Group volcanics behave as a cohesive unit, bar one diapiric volcanic, with low concentrations in both Rb and Sr. The Cambrian volcanics have contiguous Rb and Sr concentrations as the Willouran intrusives (Fig. 6.3.1.F).

In consideration of the relatively immobile high field strength elements (Fig. 6.3.2), the intrusives of the Peake and Denison Ranges have low quantities of niobium in comparison to the Anabama Granite, but are still in keeping with average values for Lachlan Fold Belt "I-" and "S-type" granites. The range of Nb and TiO_2

for the syn-tectonic Kanmantoo Group granites is remarkably similar to that for the Anabama Granite, whereas the post-tectonic granites have notably high Nb and low TiO_2 (Fig. 6.3.2.A), as do the post-Kimban Gawler Range Volcanics (Giles, 1980). Niobium concentrations are very high for the limited number of analyses from Teale & Lottermoser (1987) for the Arkaroola intrusives, and both the Cambrian volcanics and the intrusives of the Willouran Ranges display very high and very low Nb and TiO_2 contents (Fig. 6.3.2.B).

With respect to zirconium, the intrusives of the Peake and Denison Ranges are notably depleted and have a very narrow range of composition (<220ppm Zr). This is similar to the low Zr values recorded for "I-type" Kosciusko granites (Hine *et al.*, 1978). The Anabama Granite (100-350ppm Zr) again mimics the range of compositions for the syn-tectonic Kanmantoo Group granites (Fig. 6.3.2.C). Both post-Kimban Gawler Range Volcanics and post-tectonic Kanmantoo Group granites display high Zr and Nb concentrations. As with niobium and titanium, the intrusives of the Willouran Ranges and the Cambrian volcanics have extreme ranges of compositions for zirconium, although the intrusives of the Willouran Ranges appear to become more enriched in Nb with respect to Zr than the Cambrian volcanics (Fig. 6.3.2.D).

The intrusives of the Peake and Denison Ranges record yttrium values up to 60ppm, although most fall between 10 and 40ppm Y. Again, these values are similar to Lachlan Fold Belt granite averages, most of the Kanmantoo Group syn-tectonic granites, and the Anabama Granite (Fig. 6.3.2.E). The Willouran Ranges intrusives and the Cambrian volcanics have similarly restricted yttrium ranges (Fig. 6.3.2.F). The most outstanding characteristic demonstrated by yttrium is its relative enrichment (up to 96ppm Y) in the post-tectonic

Kanmantoo Group granites (Fig. 6.3.2.E), similar to Lachlan Fold Belt "A-type" granite average (76ppm; White & Chappell, 1983) and "M-type" plagiogranites.

In the Peake and Denison Ranges, both Sc and V demonstrate a linear relation with respect to TiO_2. Scandium(ppm)/TiO_2(wt.%) is approximately 27, whereas V/TiO_2 is approximately 200 (Fig. 6.3.3.A & C). In contrast, the Sc content of the Anabama Granite does not correspond as neatly to a linear relation; a situation analogous to the syn-tectonic granites of the Kanmantoo Group (Fig. 6.3.3.A). In the post-Kimban *Gawler Range Volcanics*, Sc ranges from 1 to 25ppm and V from 1 to 200ppm, which is similar to the range (with respect to equivalent range in silica) for the Bungadillina suite and "I-type" Lachlan Fold Belt granites (Griffin *et al.*, 1978), and can be similarly accounted for by amphibole and pyroxene fractionation (Giles, 1980; *cf. ch.* 7). Insufficient Sc data for Willouran intrusives and Cambrian volcanics prevents an accurate comparison. However, the Cambrian volcanics show a good linear relation for vanadium (V/TiO_2 is approximately 150). The intrusives of the Willouran Ranges record scattered V concentrations. In contrast, the Sc and V compositional range for the Callanna Group volcanics is relatively restricted, and only two samples of the Willouran intrusives approximate the Sc and V concentrations in the Callanna Group volcanics (Fig. 6.3.3.B & D).

Cerium concentrations of the intrusives of the Arkaroola region record less than 20ppm. In contrast, the relatively enriched intrusives of the Peake and Denison Ranges have much higher Ce contents (34-146ppm Ce), and post-Kimban Gawler Range Volcanics have higher still (100-200ppm Ce; Giles, 1980). Both the intrusives of the Willouran Ranges and the Callanna Group volcanics have corresponding Ce concentrations (approximately 20-40ppm Ce), whereas the Cambrian volcanics have slightly higher values (45-95ppm Ce).

Nickel is generally lacking in the Anabama Granite and the intrusives of the Bungadillina suite with only two samples recording values in excess of 40ppm (Fig. 6.3.3.E). The trend is similar to that for "I-type" Kosciusko granites (Hine *et al.*, 1978). In contrast, the Callanna Group volcanics display an asymptotic Ni relation with respect to TiO_2 (Fig. 6.3.3.F). Half of the set for the intrusives of the Willouran Ranges follows this asymptotic trend, while the other half is notably depleted in Ni, as is the Cambrian volcanics (Fig. 6.3.3.F). This relation may reflect the bimodal character of the igneous rocks of the Willouran Ranges and the Cambrian volcanics such that the mafic phase has Ni- (and Cr-) bearing phases (olivine and spinel) and the felsic phase does not.

The comparison of halogen elements, although of rare occurrence in the literature, is of great significance, especially with respect to styles of alteration and importance of halogen-based complexing in magma evolution. The intrusives of the Willouran Ranges record over 12,660ppm chlorine, attributed largely to Cl influx during scapolitization. In contrast, the intrusives of the Peake and Denison Ranges have a maximum of 1820ppm Cl, with the majority of samples recording 300-400ppm Cl. No scapolite alteration was noted in these intrusives, but scapolitization is a common feature in the Callanna Group volcanics (Hilyard, 1986).

Fluorine values for the intrusives of the Arkaroola region (100-1900ppm F) are similar to those of the Bungadillina suite (60-

1820ppm F). However, Lottermoser (1987) noted contact metamorphosed "metasomatites" with up to 4.45 wt.% F adjacent intrusives of the Arkaroola region, suggesting the importance of fluorine in alteration originating from halogen-rich magmatic fluids. Although the altered samples from the Peake and Denison Ranges do not record such extreme values, one pyroxenite xenolith [7704] has over 4600ppm F. The presence of fluorite and concentrations of F approaching 2000ppm, in post-Kimban granites of the Eyre Peninsula and the post-tectonic Kanmantoo Group granites (K. Stewart, unpublished data, Univ. Adelaide; Foden *et al.*, 1989), is much higher than the average values obtained for the intrusives of the Peake and Denison Ranges (500-800ppm F, *cf.* Table 5.1).

6.4 Intrusives of the Willouran Ranges and Arkaroola Region.

Unlike the intrusives of the Peake and Denison Ranges, the intrusives of the Arkaroola region are characterized by late-stage volatile-transported B^{3+}, F^- and Cl^- complexing in the alteration of both the immediate strata and the plutons themselves (Lottermoser, 1987). Teale & Lottermoser (1987) claim these intrusives to be characteristic of "A-type" granites. However, application of Pearce *et al.'s* (1984) trace element discrimination diagram is inconclusive (Figs. 6.5.A & B). This is in part due to an incomplete published trace element data assemblage. The style of alteration, and the occasional Rb- and Nb-enriched sample suggests anorogenic alkali metasomatism. In contrast, low LREE, low Y and average Ga argue against an anorogenic setting. The comparison of these altered rocks with other igneous rocks in the Adelaide Geosyncline indicates that the Arkaroola region intrusives are similar, in composition and alteration style, to felsic variants of Willouran intrusives.

The intrusives of the Willouran Ranges are largely gabbroic in character, with minor diorite and albitite, and may represent the intrusive equivalent of Willouran volcanics. This claim is substantiated by the presence of augite, bytownite and kaerstutite, which are typical of gabbros and basalts. These gabbros also have distinctly high chlorine contents, a characteristic feature in scapolite alteration of Wooltana (Willouran) Volcanics (Hilyard, 1986).

The strong bimodal feature of the Willouran intrusives is also a characteristic of anorogenic magmatism. Unlike the albitites in the Bungadillina suite, the albitites in the Willouran Ranges are enriched in trace elements and contain riebeckite, again typical of felsic differentiates in anorogenic regimes. Geochemical variations for this suite are arguably congruous between gabbroic and albititic end-members. These features suggest that the felsic intrusives originated from fractionation of a gabbroic parent, accompanied by a trace element enriched volatile phase.

Trace element tectonic discrimination diagrams of Pearce *et al.* (1984) (Fig. 6.5.A & B) of the Willouran intrusives trend from *volcanic arc* field into the *within-plate* field. This type of trend suggests an initial origin from mafic igneous rocks (*e.g.* Willouran volcanics) which has subsequently been enriched in trace elements through the development of a (?mantle-derived) volatile phase, or through the fractionation of a felsic trace element enriched component. These modes of formation are more likely for the leucocratic intrusives of the Arkaroola region, rather than association with an ambiguous "Palaeozoic" event as stated by Teale & Lottermoser (1987). Thus it may be postulated that early continental rifting, which was responsible for the voluminous extrusion of flood basalts, may have also evolved a minor felsic intrusive phase enriched in trace elements, as noted in the Willouran Ranges and Arkaroola region.

6.5 The Anabama and Bendigo Granites.

The intrusives of the Nackara Arc differ from those of the Peake and Denison Ranges in many ways. The most notable is the style of alteration. The Bendigo and Anabama Granites feature magmatic hydrothermal potassic alteration forming Cu- and Mo-rich greisens enriched in Rb relative to Sr, which is a similar mode of alteration within the intrusives of the Arkaroola region. In contrast, the alteration style of the Bungadillina suite is characterized by albitization, noted in the depletion of Rb. Slight biotite lineation within the Anabama Granite is parallel with the regional east-west signature, forming in response to Delamerian tectonism. Mineral foliation is also a characteristic for syn-tectonic granites of the Kanmantoo Group (Foden and others, 1988). Furthermore, the granites feature a distinctive metamorphic aureole, indicating emplacement as a relatively hot magma in contrast to the surrounding strata which was, at the time of emplacement, metamorphosed to greenschist facies.

Granite foliation designates the granites as either pre- or syn-tectonic. Yet the development of a metamorphic aureole is more likely for a syn- or post- tectonic intrusive. The syn-tectonic environment of regional greenschist facies metamorphic grade would be insufficiently high enough to prevent the development of a contact metamorphic aureole during emplacement of a hot granitic body. In contrast, a pre-tectonic granite would be more susceptible to the metasomatizing effects of circulating meteoric water, perhaps as in the case of the Bungadillina suite where neither a metamorphic aureole nor a regional mineral foliation has developed. Thus field evidence (presence of contact metamorphic aureole and weak biotite foliation) indicates that the granites of the Nackara Arc syn-tectonic, intruding during the Delamerian Orogeny.

The geochemistry of the Anabama Granite reaffirms the importance of biotite in controlling composition. Figure 6.6.1 demonstrates the strong linear trends developed in response to relative biotite concentration in all of Richards' (1980) analyses of unaltered material. These include MgO, total iron (as Fe_2O_3) and TiO_2. However, the alkali element plots (Figs. 6.6.1.E & G) suggests that another alteration, melt or mineral (calcic plagioclase?) is involved.

The linear enrichment of zirconium (Fig. 6.6.1.B) with respect to MgO attests to the early crystallization of zircon and its subsequent inclusion into biotite, thus behaving in harmony to biotite fractionation. Although rubidium forms a vague trend, probably also in response to biotite fractionation, neither Sr, Y or Nb demonstrate any such association (Figs. 6.6.1.D, F, H & J). The very high HFS concentrations, including Y and Nb in the most mafic of samples (<55 wt.% SiO_2) is not immediately apparent.

The Anabama Granite, although metaluminous (Fig. 6.6.2.A), is alkalic (according to Peacock's (1931) scheme), and the AFM diagram (6.6.2.B) reveals a strong linear trend, tending towards being more tholeiitic in character than those of the Peake and Denison Ranges.

Tectonic discrimination utilizing the major-element R1-R2 diagram of de la Roche (1978) shows the Anabama Granite to occupy Batchelor's and Bowden's (1984) *"Caledonian 'permitted plutons' (post-collision uplift)"* field (Fig. 6.6.2), with a linear trend which may be accounted for by progressive fractionation of biotite and calcic plagioclase. The tectonic setting is compatible with the syn-Delamerian tectonism as envisaged from field evidence.

Trace element geochemical data of the Amabama granite plotted utilizing the tectonic discrimination diagrams of Pearce *et al.* (1984) are presented in figure 6.6.2.D-E. The granites plot on a linear trend from well within the *volcanic arc* field (VAG) into the *within-plate* field (WPG) indicating a progressive increase of HFS elements. Samples with the highest conentrations of Y and Nb, however, coincide with anomalous concentrations of Rb, Cu and Zn. These relations suggest that high HFS values are not of a primary magmatic nature, but have been derived as the result of secondary hydrothermal processes. Alternatively, the more mafic HFS element-rich samples may represent a different magmatic event. In anticipation that the high concentrations of Rb, Nb and Y in the Anabama Granite is more likely due to hydrothermal enrichment than intrusion from a tectonically different source, the discrimination diagrams suggest that the granite is more accurately described as *volcanic-arc*, as opposed from that originating from *within-plate* or anorogenic ("A-type") regime (Pearce *et al.*, 1984).

As syn-tectonic granites, the intrusives of the Nackara Arc are more akin to the granites intruding the Kanmantoo Group sediments. These Kanmantoo Group granites often display a regional foliation but lack a contact metamorphic aureole, due to the higher grade (amphibolite) of regional metamorpism (*e.g.* the Palmer Granite). Richards (1980) was inconclusive in defining the Anabama Granite as either "S-" or "I-type", and lamented the problem of applying ascertained Lachlan Fold Belt granite characteristics to granites of the Adelaide Geosyncline and Kanmantoo Trough. Although most evidence indicates "I-type" classification (apatite and biotite inclusions, ACK<1.1, normative diopside), the absence of hornblende as the prime mafic mineral phase in favour of biotite suggests "S-type" origins. The initial Sr^{87}/Sr^{86} ratio determined by Stevson & Webb (1976) is also ambiguous in defining a distinctive "*type*" (0.7074), but may be indicative of an initial "I-type" magma that has undergone some amount of crustal contamination. The prevalence of biotite is more likely a factor of water and potassium activities rather than source material. The style of intrusion indicates emplacement from depth along planes of structural weakness that were present during the Delamerian Orogeny as indicated by Gerdes (1973) and postulated by O'Driscoll (1981). But the question remains of precise tectonic genesis.

The granites of Anabama and Bendigo, having originated from depth, intruded during the largely anhydrous compressional regime of the Delamerian Orogeny, which was much less severe than in the Kanmantoo Trough area. The initial $^{87}Sr/^{86}Sr$ ratio indicates a primitive source with some crustal contamination. These granites are insufficiently enriched in silica, have too great a range of SiO_2, and have no associated migmatites to have possibly evolved from anatectic minimum melt conditions, as would be anticipated in a highly compressional (*i.e.* continental collision) regime. This is also supported by major and trace element data and field relations. These granites intrude (Umberatana Group) Adelaidean strata which have been subjected to greenschist facied metamorphism and open folding during the Delamerian Orogeny. While it is conceivable that the entire granite body(ies) has(have) been tectonically transported in place as (an) allochthonous block(s), as postulated for some intrusives of Kanmantoo Group metasediments (Foden *et al.*, 1988), from general inspection of the surrounding geology this scenario seems unlikely. Thus the number of tectonic regimes for genesis of these granites is limited.

Preiss (1987) suggested that the granites of the Nackara Arc evolved from Andean-type subduction-related magamatism, with the postulated west-dipping trench located approximately 130km to the east. Cu-porphyry style mineralization in the Bendigo and Anabama granites (Morris, 1981) lends support to Andean-type magmatism, if the style of mineralization is indeed thus (Richards, 1980). Yet Preiss (1987) reserves final judgement on a tectonic framework for genesis as many factors argue against a subduction-related process. These include the intrusion into largely synclinal basins and not within uplifted areas, as well as the lack of evidence for obducted ophiolite sequences, blueschist metamorphism and melanges. Other arguments against Andean-type magmatism, or more specifically against "I-(Cordilleran) type" magmatism which is noted for hosting porphyry-Cu mineralization, include the lack of great volumes of associated gabbro, andesite and dacite. Also, hornblende is not a major mineral component, the granites are alkaline as opposed to calc-alkaline, and the initial $^{87}Sr/^{86}Sr$ ratio is not significantly less than 0.706 (0.7074+/-0.009 Anabama Granite; 0.7069+/-0.0021 Bendigo Granite:

Webb, 1976) (Pitcher, 1983).

Subduction-related Andean-type magmatism leads to voluminous granite belts of multiple-batholithic proportions. The combined masses of both the Anabama and postulated extensions of the Bendigo Granite cannot compare with the enormous granite belts of the Cordilleras, for example. Of the granite types outlined by Pitcher (1983), the Anabama and Bendigo Granites have more in common with "I-(Caledonian) type" granites including granodiorite-granite associations, biotite as the dominant ferro-magnesian mineral, the occurrence of rare appanitic (euhedral hornblende the dominant mafic phase) gabbro, and initial $^{87}Sr/^{86}Sr$ ratio between 0.705 and 0.709. But in consideration of any tectonic regime for granite emplacement, the hypothesis that encratonic magmatism can be induced by deep-seated faults (which can cause crustal and sub-crustal melting and provide conduit for transport to higher crustal levels) must also be entertained (Pitcher, 1983; Leake, 1978).

6.6 Synopsis.

The following geochemical characteristics were noted for the igneous rocks of the Adelaide Geosyncline:

(1) The intrusives of the Peake and Denison Ranges are characteristically enriched in alkali elements in comparison with most of the igneous rocks of the Adelaide Geosyncline.

(2) Albitization is a feature common to the Bungadillina suite, the intrusives of the Willouran Ranges, Arkaroola region, and the more felsic variants of Cambrian and Burra Group volcanics.

(3) The Bungadillina suite and the Anabama Granite are enriched in aluminium, and are similar to aluminium concentrations for Kanmantoo

Group syn-tectonic granites and Lachlan Fold Belt "I-type" granites.

(4) Trends developed for Al_2O_3, CaO, MgO and *FeO suggest pyroxene-, amphibole- and late plagioclase-control of fractionation (and accumulation) in the Bungadillina suite in contrast to biotite- and plagioclase-control fractionation in the Anabama Granite and syn-tectonic granites of the Kanmantoo Group.

(5) The Willouran intrusives and the Cambrian volcanics demonstrate distinctive bimodal suites, while the Bungadillina suite is of intermediate composition.

(6) The Bungadillina suite is generally depleted in TiO_2, similar to Lachlan Fold Belt "I-type" granites. The intrusives of the Arkaroola region and some of the Cambrian volcanics are severely TiO_2 depleted, but this may be a feature of their style of alteration.

(7) The Bungadillina suite has characteristically high P_2O_5, similar to Lachlan Fold Belt "I-type" granites.

(8) Congruous barium concentrations exist for the Anabama Granite and the Kanmantoo Group syn-tectonic granites, while the Bungadillina suite is slightly enriched. Low barium contents of the Arkaroola region intrusives and the more felsic Cambrian volcanics, like titanium, are probably alteration induced.

(9) The altered intrusives of the Arkaroola region are demonstrably enriched in Rb, in contrast to altered intrusives of the Peake and Denison Ranges which are typically Rb-depleted.

(10) The Bungadillina intrusives are Sr-enriched. The Anabama Granite has a Sr-range comparable to the syn-tectonic Kanmantoo Group granites, and the Sr-range for the intrusives of the Willouran Ranges are congruous to that of the Cambrian volcanics.

(11) Zironium, Nb and TiO_2 concentrations are depleted in the Bungadillina suite, and are similar to Lachlan Fold Belt "I-type" granites, contiguous in the syn-tectonic Kanmantoo granites and the Anabama Granite, and bimodal in the Willouran intrusives, the Arkaroola region intrusives, and the Cambrian volcanics.

(12) Yttrium is useful in distinguishing post-tectonic Kanmantoo Group granites, and is consistently low in the Bungadillina suite.

(13) Scandium forms a positive linear trend for the Bungadillina suite with respect to TiO_2, whereas the Anabama Granite forms a negative trend and is contiguous with the syn-tectonic Kanmantoo Granites. The post-tectonic Kanmantoo Group granites are depleted in Sc.

(14) Vanadium/TiO_2 forms a steeper positive linear trend for the intrusives of the Peake and Denison Ranges in comparison with the intrusives of the Arkaroola region. Concentrations of vanadium for the Willouran, Bungadillina, Arkaroola and Lachlan Fold Belt "I-type" granites, are contiguous.

(15) Nickel is only enriched in the basaltic/gabbroic end-members of the Willouran intrusives and Adelaidean/Cambrian volcanics, but displays a similar concentration trend in the Bungadillina suite as in the Lachlan Fold Belt "I-type" granites.

(16) High chlorine concentrations are characteristic in scapolitized Wooltana basalts and Willouran intrusives, and low in the intrusives of the Peake and Denison Ranges.

(17) Fluorine concentrations are similar between the Arkaroola and Bungadillina suites, and enriched in the post-tectonic Proterozoic and Palaeozoic granites.

Strong similarities exist between the Anabama Granite and the syn-tectonic Kanmantoo Group granites with respect to major and trace elements, indicating consanguinity. These granites formed early in the Delamerian Orogeny in response to partial melting and intrusion of crustal melt into the tectonically thickened Kanmantoo Trough. It is unclear how much of a role mantle-derived magma played in their petrogenesis. However, the rubidium-strontium systematics suggest the Anabama Granite originated from a less (crustal) contaminated magmatic source, while geochemistry indicates that biotite-controlled fractionation was a key feature in late-stage magma petrogenesis. Intrusion of the Anabama and Bendigo Granites appears to have been fault-controlled, while intrusion of syn-tectonic Kanmantoo granites correspond to the zones of highest regional metamorphism. These petrogenetic features may also apply for the British Empire Granite in the Mt. Painter region.

In contrast, the post-tectonic Kanmantoo Group and post-Kimban igneous rocks form cohesive and unique magmatic group, characteristic of "A-type" granites and originating from a primitive, anhydrous source (Turner and others, *in prep.*). The lack of a magmatic-volatile phase developed in these "A-type" Kanmantoo Group granites is in contrast to the volatile-rich intrusives of the Arkaroola region.

The intrusives of the Willouran Ranges and the Arkaroola region have many similar chemical characteristics to the Cambrian volcanics. The style of alteration of the Arkaroola intrusives is distictly different from any of the other suites, and is indicative of high temperature (?magmatic) hydrothermal activity. The intrusives of the Peake and Denison Ranges have some chemical similarities to those of the Cambrian volcanics and "I-type" granites of the Lachlan Fold Belt, but do not have the basaltic character of the more mafic end-members.

Figure 6.7 provides a comprehensive comparative image for the immediately pre-Adelaidean (post-Kimban) igneous geochemistry, and immediately post-Adelaidean igneous geochemistry (Kanmantoo Group granites), with an average value for quartz syenite from the Bungadillina suite (from Table 5.1). In comparison with average syn- and post-Delamerian values, the Bungadillina suite is collectively enriched in LIL elements (especially Sr where it forms a positive anomaly), depleted in LREE, and similar, if not slightly depleted, in HFS elements.

In comparison with post-Kimban igneous rocks, the quartz syenite is similarly enriched in LIL elements (especially Sr where it again forms a positive anomaly), depleted in LREE, and with similar HFS values. It is interesting to note the close similarities between post-tectonic (Kimban) and post-tectonic (Delamerian) igneous suites.

Exemplifying these geographical and geochronological comparisons with the intrusives of the Peake and Denison Ranges is figure 5.7.2.A (*cf. ch.* 5.7) which illustrates differences with Lachlan Fold Belt "I-" and "A-type" granites. In brief review, the average Lachlan "I-type" has similar LREE and HFS element concentrations, but demonstrates lower LIL element values. These "spider-grams" also illustrate consistently low yttrium and anomalously high strontium in the Bungadillina suite. Contrasting trace element values may correspond to the difference between the typical "A-type" granite, which is modelled after *post-tectonic* high fractionate intrusives (*e.g.* Foden *et al.*, 1989). Such pronounced chemical differences indicate that the Bungadillina suite is not post-tectonic, but perhaps *pre-tectonic* or *syn-tectonic*.

ooOoo

Chapter Seven: Petrogenesis of Intrusives of the Peake and Denison Ranges.

> "It is even more important to realize that there is no one origin of granite - according to Read (1948 in 1957) there are granites and granites - so that there can be no single path of evolution of the magmas."
>
> W.S. Pitcher (1979).

7.1 Introduction.

This study concentrates on the intrusives of the Peake and Denison Ranges, and uses other igneous occurrences within the Adelaide Geosyncline and elsewhere on a comparative basis. The proceeding section focuses on the petrogenesis of the igneous intrusive rocks of the Peake and Denison Ranges utilizing the field, petrographical, mineralogical and geochemical data described from previous chapters. From this grounding, it may then be possible to elucidate the petrogenesis of other igneous bodies in the Adelaide Geosyncline. The success of this chapter, and indeed this entire thesis, will be to forward a better understanding of these igneous rocks; hence further the comprehension of the evolution of the Adelaide Geosyncline.

7.2 Field and Petrographic Evidence.

From field evidence, it is clear that the lithologies comprising the igneous Bungadillina suite are intrusive to the Burra Group. Furthermore, field relations with diapiric breccia indicate the emplacement of the suite postdates initial evaporite diapirism, but predates (Delamerian?) tectonically induced, diapiric breccia remobilization. However, this study has failed to unequivocally determine the precise timing of emplacement with respect to the Delamerian Orogeny. Structural evidence is conflicting, especially as there is no pervasive Delamerian structural fabric that is readily identified on a small scale, due to the low grade of regional metamorphism in the Peake and Denison Ranges. There are data supporting both a pre-tectonic (folded sills, style of emplacement and alteration), and post-tectonic timing for emplacement (lack of deformation fabric, dykes intruding fold hinges). Furthermore, three separate geochronological methods (K-Ar, Rb-Sr, U-Pb) that have been used to date the Bungadillina suite are all erroneous and cannot be used to define the age of emplacement. However, most evidence argues against syn-tectonic timing (lack of either contact metamorphic aureole or intraplutonic minerals foliated parallel to regional fabric; *re.* Anabama Granite). The difficulty in determining the relative timing of emplacement is further enhanced by what appears to more than one period of folding in the Peake and Denison Ranges, and not necessarily due to Delamerian tectonism (*i.e.* pre-Delamerian evaporite diapirism) complicated further by possibly post-tectonic remobilization of diapiric breccia.

Determination of relative timing of pluton emplacement is not a simple and straight forward task. Recent studies on relative timing of emplacement of small plutons (less than 10km in diameter) by Paterson & Tobisch (1988) have shown that field evidence can often be conflicting or misleading.

> "...Pretectonic plutons may or may not (1) appear deformed, (2) have foliations in the wall rocks that bend around the pluton or cut across the pluton - country rock contact, (3) have ductile shear zones along the margin of the pluton and (4) have strain shadows at the ends or along irregular parts of the pluton margin that preserve older structures.
> "...all three pluton types (viz pre-, syn- and post-tectonic) may (1) appear deformed or non deformed (2) have contacts that appear to cut structures in the wall rock, and (3) have porphyroblasts in their aureoles that display varied timing relations."

The plutons comprising the Bungadillina suite are not homogeneous. The largest plutons and some of the smaller bodies have mappable gabbroic zones, and the sills of Map B & B′ vary from monzodiorite to syenogabbro. The second largest westerly pluton has distinctive gabbroic cores and margins, while the eastern side of the largest pluton is punctuated by a syenogabbro zone. Many of the smaller monzonitic bodies have distinctive gabbroic zones whereas other small plutons are exclusively gabbroic in composition. Only the quartz monzonite semi-circular body of Maps A & B′ can be described as massive *and* homogeneous.

Relative emplacement of the various igneous lithologies indicates that the mafic monzonites (and syenites?) preceded the gabbroic plutons (xenoliths of one within the other), followed by quartz monzonites (plugs intruding sills; Map B′). Alkali syenites and lamprophyres postdate all others.

With the exception of one locality which shows a contact displaying a slightly more felsic gabbro re-intruding what is probably the more mafic parent, the contacts between the mafic and felsic phases are commonly gradational over a distance of 0.5-2m. The lack of a sharp contact in many of the contiguous mafic and felsic phases suggests that the original magma was a heterogenous crystal mush which had separated into mafic crystal-rich (cumulate-rich) and mafic crystal-poor (cumulate-depleted) melts. Other field observations indicate mineral cumulates are present in the Bungadillina suite. Some plutons have mafic-felsic banding akin to primary igneous cumulate layers. Indeed, some plutons have amphibolite or pyroxenite xenoliths analogous to exhumed or re-incorporated crystal cumulate products from a more fractionated magma. These cumulate xenoliths, found within felsic sills and both small and large plutons, indicate that crystal cumulates also formed at depth prior to emplacement, and are not necessarily the result of *in situ* fractionation.

Active magma flow is evident from prominent flow-induced mineral lineations of elongate early crystallizing mineral phases such as acicular amphibole and clinopyroxene, and, in the alkali syenite and lamprophyres, alkali feldspar and biotite.

Morrison & Foden (1989) suggested that fractionation of clinopyroxene, amphibole and calcic plagioclase is responsible for compositional variations between mafic and felsic lithologies in the zoned pluton of Maps A and A′. These workers postulated that the more mafic phases represent the parental, primitive melt to the magmatic system. Alternatively, the most mafic phases in any of the lithologically variable plutons may represent the fractionated cumulate of early formed mafic minerals from what originally was a monzonitic or dioritic parental magma. Probable cumulate pyroxenite xenoliths are evidence in support of crystal cumulate influence in magma genesis. Uralitized pyroxenite [7575] occurring as a mappable unit to a small pluton in Map I also indicates that the formation of a cumulate-rich phase could produce a singularly large intrusive unit. Similarly, the gabbroic phase of the largest pluton (Maps F′, G and I) is located adjacent the westerly contact with metamorphosed metasediments. This feature may represent a mafic cumulate-rich basal zone of a fractionated pluton. The orientation is in keeping with the surrounding strata if intrusion occurred prior to tilting during the Delamerian Orogeny (Fig. 7.12). Magmatic layering has been tentatively identified in some outcrops in this pluton, and is also indicative of liquid-crystal differentiation.

The prevalence of Burra Group sedimentary xenoliths with orientations akin to the immediate host strata orientations around the margins of the plutons attests to passive stoping as the main mode of emplacement. Only one sub-circular (late-stage intrusive?) quartz monzonite body (Maps A & B') significantly deforms the surrounding strata, suggesting a forceful mode of emplacement.

Field relations of alkali syenite sills and dykes indicate that their intrusion postdates most all other lithologies with the exception being small biotite lamprophyre dykes. Not only are these lithologies found intruding all other major bodies, but they also preferentially intrude as dykes (rather than sills) within the Burra Group strata. Although the precise date of intrusion of the alkali syenite bodies remains uncertain, it must postdate the bulk of other intrusives and may be post-Delamerian in age. Ambrose *et al.* (1981) have reported the presence of similar alkali syenite spherulitic dykes 2km west of Tarlton Springs, which may be consanguineous with other alkali syenites in the region. Similarly, an 18km-long discontinuous dolerite dyke striking NW-SE intrudes along fault lines and fold hinges 18-20km south of the Bungadillina suite, represents definitive post-Delamerian magmatism.

The general lack of pegmatites, aplites and quartz veining indicates that late-stage volatiles were a minor component of the magma. In the zoned western pluton [7200], there was:

(a) a possible late-stage volatile phase which induced autobrecciation and the injection of sedimentary xenoliths into the pluton and;

(b) a zone of alkali feldspar megacrystic syenite, probably induced by

a water-rich fluid phase under subsolidus conditions.
Margins of some plutons are often characterized by abundant felsic dyking (*cf.* fronticepiece), re-injecting into the pluton itself yet often truncated at contact with surrounding sediments. These dykes are interpreted to be residual late-stage felsic melt which were squeezed out towards the margins of the crystallizing body. Remobilization of diapiric material has usually caused truncation of radiating felsic dykes at pluton margins.

Margins of the intrusive bodies commonly lack any significant contact metamorphism, regardless of the contiguous lithology. This feature has been reported by Morrison (1986) and Morrison & Foden (1989) as the result of intrusion into a wet sedimentary pile where a circulating meteoric water system was able to quickly disperse magmatic heat. Rapid flow of the fluids away from the intruding magmatic body, or the immediate absorption of meteoric water into an anhydrous magma, may prevent the alteration of contiguous sediments. The lack of associated volatile-induced intrusives (*e.g.* pegmatites) indicates the magma bodies were relatively anhydrous, encouraging the influx of surrounding meteoric water. A tectonic setting which would have surrounding meteoric water favours pre-Delamerian intrusion into a wet sedimentary pile. Slightly elevated temperatures and pressures in either a syn-tectonic or post-tectonic setting would expel meteoric waters from the sediments and encourage localized contact metamorphism. However, if intrusion was prior to deformation, stratigraphic measurements by Ambrose *et al.* (1981) indicated that the Adelaide Geosyncline sedimentary pile above the Burra Group was in excess of 14km. It is unlikely that a freely circulating meteoric water system would be present at such a depth.

Alternatively, intrusion may have occurred prior to cessation of sedimention when the sedimentary pile was less than 7km thick.

Only in one location, on the western side of the largest pluton (Map G), was there contact metamorphism resulting in the sericitization and silicification of the immediate sediments. This phenomenon has also been observed by R.B. Flint (*pers. comm.*). The strata around this pluton are trending roughly north-south, upright and dipping steeply to the east, and this side of the pluton is postulated to represent the pre-Delamerian true base (*i.e.* footwall contact of a possible layered intrusion). It is in this specific locality, at the base of the intruding pluton, where sufficient dehydration and heating of the immediate sediments were sufficient to invite contact metamorphism. A similar zone of contact metamorphism was investigated on the western side of the second largest pluton (Maps A and A'). However, none was observered largely due to poor outcrop exposure.

Xenoliths are generally a minor component of the plutons. As previously mentioned, the most common type of xenolith is composed of Burra Group quartzite or metasediments, and is generally restricted to the immediate margins of the pluton. Less frequent are monzonite and monzogabbro xenoliths which are especially prevalent in one of the monzonite sills of Maps B and B'. These xenoliths are commonly rounded or subrounded and extensively altered. They are interpreted to be cognate xenoliths incorporated by the intruding magma from an earlier crystallized magma, or crystal cumulate of earlier formed mineral phases. These xenoliths are evidence for progressive emplacement of a continuously fractionating magma into an expanding magma chamber (*e.g.*

Nabelek *et al.*, 1986). This mechanism is postulated to be the main mode of emplacement for the larger zoned plutons, as more felsic fractionate intrudes the more mafic magma (Morrison & Foden, 1989). High grade metamorphic xenoliths, such as garnet-chlorite schists, are a minor constituent and represent the only evidence for Early or Middle Proterozoic crystalline basement material being injested into the intruding magma. The lack of high grade metamorphic xenoliths indicates that crustal assimilation was not an important factor in magma genesis.

The re-intrusion of a more mafic (cumulate?) monzogabbro by a slightly less mafic monzogabbro is displayed in a small pluton in Map F. This indicates that cumulate crystal-rich magmas were mobile, and could intrude as later, separate bodies. The process of forming an independent cumulate-rich magma is probably represented by the smaller lobate monzogabbro and syenogabbro plutons which occur without a contiguous felsic phase.

The predominance of euhedral and zoned phenocrysts and chadacrysts of calcic plagioclase, hornblende, magnetite and clinopyroxene suggests that crystallization of these phases was in conditions removed from that of final emplacement. This is further substantiated by the presence of biotite pseudomorphing amphibole. Although original magmatic conditions favoured the crystallization of clinopyroxene and amphibole, the crystals were subsequently replaced by biotite, perhaps induced by late-stage hydration reactions involving increasing aH_2O which represented the final stable conditions for emplacement. The presence of biotite as both a primary insterstitial mineral and a secondary replacement mineral supports this claim. Increasing water activity in a magma encouraged the crystallization of biotite from the melt, and made previously crystallized mafic phases metastable in the hydrous conditions, resulting in alteration to biotite.

Cursory examination of the published geological maps of the Peake and Denison Ranges clearly demonstrate that the intrusives are limited to a small area in the northern section of the Margaret Inlier. Ambrose *et al.* (1981) have postulated that the narrow zone displaced by the intrusives coincides with the intersection of a major deep-seated east-west crustal shear-zone, the *Karari Fault Zone*, with the north-south structural trend of the Peake and Denison Ranges. The Karari Fault Zone (Finlayson, 1979) is a linear sub-vertical zone of intense mylonitization defining the northwest margin of shallow crystalline basement of the Gawler Craton, extending 300km in a northeasterly direction towards the Peake and Denison Ranges (Rankin *et al.*, 1987; Flint & Parker, 1982). It is readily identified by a distinct aeromagnetic anomaly, and is thought to have been active in the Early Proterozoic, Early Palaeozoic, Permian and Tertiary. In the Peake and Denison Ranges, however, there is no indication of any such shear zone. If one is indeed present, then it must either traverse the gap between the Margaret and Denison Inliers, terminate prior to the inliers, or occur immediately north of the inliers, and is thus not exposed.

The Bungadillina suite is in distinct contrast to syn-tectonic granites in the Nackara Arc which are characterized by a prominent metamorphic alteration aureole, abundant dyking into the immediate country rock, and slight mineral foliation parallel to the regional deformation trend. Alternatively, the syn-tectonic plutons of the Kanmantoo Trough are situated within a zone of intense regional metamorphism characterized by migmatites and gneisses. The lack of a contact metamorphic aureole around Kanmantoo Group granites, such as the the Encounter Bay Granite, has been attributed to intrusion into an already pre-heated, anhydrous host (Milnes *et al.*, 1977).

Of the three major structural patterns induced from natural intrusive bodies as described by Castro (1987) (concordant plutons, discordant plutons and gneiss domes), examples of both concordant and discordant intrusion can be found in the Peake and Denison suite. A classic concordant pluton was identified by Reyner (1956) from aerial photography.

> "Here the granite has forced its way between two massive quartzite beds, bowing them apart and crumpling the incompetent slates between them."

Further evidence of concordant emplacement is indicated by localised buckling and disruption of shale and siltstone strata in the immediate contact region of smaller plutons. Intrusions into the more competent quartzite beds contain abundant angular quartzite xenoliths along the pluton margins indicating forceful emplacement causing accidental inclusion of country rock which is restricted to the periphery of the pluton (Plate 3.1.D). In contrast, the larger plutons commonly contain large quartzite xenolith rafts which retain orientations similar to the encompassing strata indicating a more passive, discordant mode of intrusion.

The presence of zoned and sub-circular plutons discordant with the regional fabric can be interpreted to be annular complexes, formed through caldron collapse rather than simple stoping. Here, the more mafic, earlier crystallizing and mafic cumulate core of the pluton collapses verically into a rising diapir at high crustal levels, encouraging the intrusion of more felsic residual melt around the newly vacant periphery. Zoned plutons in particular have also been accounted for by *in situ* ballooning (Dixon, 1975; Holder, 1979; Bateman, 1985). This mode of emplacement is characterized by progressively more felsic phases concentrically zoned towards the core of the pluton. The alternate sequence, however, is present for the zoned pluton of Maps A and A′, and is explained by discordant annular complexes; a common mode of emplacement in anorogenic regimes (*e.g.* Carnicero & Castro, 1982; *cf.* Morrison & Foden, 1989). In contrast to larger compositionally zoned plutons, small, relatively homogeneous plutons are concentrated in zones of diapiric disturbances (Maps E, F and F′). These include both very mafic and very felsic plutons intruding apparently independent of each other. The zone into which these smaller plutons intruded is structurally weak or *plastic*, allowing for the independent intrusion of what may have been separate pulses of cumulate-rich and cumulate-depleted magma.

The largest pluton features a well developed metamorphic horizon on its most westerly margin (Ambrose *et al.*, 1981; Plate 3.2.H). It is also laterally zoned with syenogabbro concentrated along the western side, and albitized syenite towards the eastern margin. This may reflect the orientation of the pluton at the time of emplacement. The extensively albitized eastern margin may be the top of the pluton where meteoric water were more likely to cause alteration of the intruding pluton. Similarly, the base of the pluton may be the western margin where greater heat flow could generate substantial metamorphism of the immediate sediments. The denser gabbroic layer with gradational (syenite) contact would also be found at the base of the pluton if gravitational crystal fractionation processes were in effect (Fig. 7.12).

The zoned pluton of Maps A & A′ also demonstrates a mafic-rich western margin and a finer grained felsic eastern margin (*i.e.* [9630]), suggesting the pluton has an easterly top and cumulate-rich westerly bottom, which is in accordance with the easterly younging direction of the enclosing strata. But unlike the larger pluton, no metamorphism was noted (?exposed) in the western contact sediments. Alternatively, monzogabbro bodies along the northern margins of the pluton may represent the altered relict initial mafic phase of intrusion of a progressively expanding pluton (Morrison & Foden, 1989). A similar inter-pluton stratigraphic orientation was also noted for the largest pluton of Map C (Fig. 7.12).

The rising of dense, mafic magma into high crustal levels cannot be readily explained by relative gravitational inversion of a light felsic pluton rising through a denser medium. Alternatively, basic magma can intrude narrow fractures to reach isostatic equilibrium if the overlying crust acts as a singular rigid component. Thus relatively small downward displacement of crustal material may cause the rapid ascent of small bodies of deep-seated basaltic magma via readily available deeply penetrating crustal fractures. If the Karari fault does indeed coincide with the base of the Bungadillina suite, it may provide such a conduit. The presence of small mafic bodies to the immediate west of the exposed Bungadillina suite has been determined by magnetic geophysical surveys, suggesting that the Bungadillina suite extends in line with the proposed Karari Fault Zone (Ashton Mining; *pers. comm.*).

The general style of intrusion is more in keeping with anorogenic or post-orogenic magmatism as there is no relation between the intrusive bodies and the regional deformational structure in the Burra Group strata. If intrusion occurred during or after regional folding, it would be anticipated that intrusions, especially dykes, would correspond to fault lines, fold hinges or other structural weaknesses in the immediated strata. However, few are found. Instead, the preponderance of sills preferentially intruding less competent beds in the Peake and Denison Ranges suggests that stratigraphic controls were the dominant definitive factor in determining location for emplacement. This would most likely have occurred prior to the Delamerian Orogeny.

The lack of interfingering of dykes and sills radiating from more massive intrusive bodies in the Bungadillina suite indicates that stoping and dyke propogation was not a major force in intrusive emplacement. The apparently concordant contacts are consistent with emplacement by highly viscous magma composed of a crystal mush (clinopyroxene+magnetite+calcic+ plagioclase+/-hornblende) which forced aside the immediate strata and inhibited the inclusion of host material to the immediate margins. The large crystal content of the intruding magma is also indicated in cumulate xenoliths, entire cumulate-dominated plutons, and magmatic (crystal) layering.

Some plutons display marginal development of minor late-stage aplite, but the general want of associated pegmatites and aplites intruding contraction fractures in the plutons themselves and the immediate country rock indicates the intrusions were relatively anhydrous, and deprived of late-stage volatile-rich second boiling of residual magma (Burnham, 1979).

Alteration of the Bungadillina suite is a localized phenomenon. Smaller plutons and the margins of larger plutons are more prone to albitization. There is no equivalent alteration in the contiguous sediments. The degree of alteration appears to increase towards the pluton margins, or, as with respect to the sill swarm of Maps B & B′, towards the southern extremity of the sills. Alteration does not extend into the contiguous sediments. Thus field evidence is more consistant with alterant fluids in equilibrium with and derived from the immediate sediments. This is in keeping with a relatively anhydrous magma absorbing surrounding meteoric water upon intrusion, and causing localized low temperature hydrothermal alteration.

7.3 Mineralogical Evidence.

The Bungadillina suite is petrographically characterized by the early crystallization of magnetite, labradorite and magnesian clinopyroxene. Magnetite formation is in response to crystallization from an environment of high oxygen fugacity. Minor ilmenite occurring in the sills (Map B & B′) indicates slightly higher fO_2, suggesting fluctuating fugacity conditions during early crystallization. Magnesian clinopyroxene is indicative of crystallization from a mantle-derived melt. The occurrence of chromite and perovskite also implies a mantle source (Fig. 7.11). The complete absence of Ca-poor pyroxenes accompanied by the appearence of hornblende can be attributed to an increasing water content with increasing differentiation (Cawthorn, 1974). These features are consistent with an initially anhydrous melt. Tentative pressures for the crystallization of hornblende (6-8kbars *cf. ch.* 4.6) support increasing hydration with differentation and suggest middle crustal residency during hornblende crystallization. Similarly, low $aSiO_2$ can account for the absence of orthopyroxene, as indicated in the Bungadillina suite by the prevalence of nepheline-normative whole-rock compositions. This reaction can be expressed as:

$$\begin{array}{c} Mg_2Si_2O_6 = SiO_{2(liq.)} + Mg_2SiO_4 \\ \text{Pyroxene} = \text{silica} + \text{olivine} \end{array}$$

In contrast, silica activity preferentially induces the crystallization of olivine (*cf.* Eggler, 1972; Holloway & Burnham, 1972). The occurrence of perovskite indicates initially low $aSiO_2$. Later increase in $aSiO_2$ may have resulted in preferential crystallization of sphene.

Pyroxene compositions do not correlate systematically with the compositions of the rocks in which they are found. This suggests crystallization in sites substantially divorced from the present locality, possibly even from the mantle where very magnesian clinopyroxenes have been postulated to have originated (*e.g.* Mg value >90, *cf. ch.* 4.5). In contrast, hornblende displays crude chemical correlation between mineral and host rock, while biotite strongly mimics the rock chemistry, indicating relatively *in situ* crystallization. These features support the supposition that initial crystallization evolved in an anhydrous mantle environment, while the last crystallizing phase occurred at high crustal (?sub-surface) levels under hydrous conditions.

The occurrence of titaniferous garnet and aegirine-augite mantling salite in alkali syenite indicates the formation of a felsic peralkaline phase under conditions of low oxygen fugacity. The restricted occurrence of these minerals suggests that changing magmatic conditions, mainly the prevalence of conditions of high oxygen fugacity, resorbed most of this assemblage.

7.4 Major Oxides Evidence.

The presence of a wide range of intrusive compositions, from nepheline-normative to quartz-normative, is not suggestive of a high-silica crustal source. A systematic shift from nepheline-normative mafic end-members towards olivine-, hypersthene-, or even quartz-normative felsic end-members indicates that the mafic parental magmas are not likely to have formed in equilibrium with quartz, and therefore are not derived from crustal melting. Instead, they reflect the combined effects of amphibole fractionation, plagioclase fractionation (Bowen effect, Bowen, 1945), and the formation of cumulates. Starting from an initial mafic to intermediate liquid, the fractionation of stable amphibole will drive the residual liquid towards the quartz-normative field. If amphibole is resorbed, the liquid will conversely become silica undersaturated and peralkaline in character (Bonin & Giret, 1985). For the intrusives of the Peake and Denison Ranges (zoned pluton Maps A and A′ & sills Maps B and B′), the plagioclase effect trend is well recorded whilst the undersaturated values appear to be a mixture between cumulate and amphibole resorption fields (Fig. 7.4.1). The prevalence of amphibole, especially as a cumulate phase, indicates that the Bungadillina suite magma did not resorb this component. Hence the failure of the Bungadillina suite to form a felsic phase with a high normative nepheline (feldspathoidal) component may correspond to the limited occurrence of the aegirine- and andradite-bearing lithologies.

De la Roche *et al.* (1980) developed a comprehensive classification scheme for igneous rocks using major element chemistry compilations on what is known as multicationic parameters, or *R1-R2* diagrams where R1=4Si-11(Na+K)-2(Fe+Ti) and R2=4Ca+2Mg+Al. In general, the more mafic lithologies plot towards the top-right of the field, quartz-rich granites plot to the bottom-right, and alkaline-rich felsic rocks to the bottom-left. The line defining R1=R2 corresponds to silica saturation (Fig. 7.4.2). The intrusives of the Peake and Denison Ranges span a wide range of values across the silica-saturation divide. Most notable are samples comprising the zoned pluton of Maps A and A′ (a) and the sills of Maps B and B′ (b) which trend from syenogabbro and syenodiorite fields across the silica-saturation line into the monzonite and quartz monzonite fields. Alkali syenites (d) plot in the syenite-nepheline syenite fields. The silica-enriched albitites encompass the nepheline-syenite, syenite and quartz syenite fields, and more mafic albitized samples are generally reserved to the silica-undersaturated side of the join (*cf.* Fig. 7.10.B).

De la Roch *et al.'s* (1980) R1-R2 diagram also demonstrates the silica-undersaturated and silica-oversaturated trends for the intrusives of the Peake and Denison Ranges. Initial fractionation of clinopyroxene in the zoned pluton of Maps A and A′ is represented by the trend which is parallel to R1=R2 (a). The fractionation of amphibole and calcic plagioclase represents the change in this trend to being perpendicular to R1=R2. The sills of Map B also reflect the controlling effect of amphibole and plagioclase fractionation (b), but, unlike the zoned pluton of Maps A and A′, has no pyroxene component. The trend developed for the quartz monzonite plutons (c) reflects fractionation from a more evolved source, which again appears to be further evolved for the development of the curvilinear plot for alkali syenites (d). Such trends are thought to be due to multiple mineral fractionates (?garnet, pyroxene and alkali feldspar) (Fig. 7.4.2). The genetic significance of the R1-R2 diagram is further discussed in chapter 7.10.

7.5 Trace Element Evidence.

Large ion lithophile element concentrations (Rb, Sr and Ba) are strongly influenced by albitization and accompanying Na for K exchange. This effect has also been noted by Bonin *et al.* (1978) for an arfvedsonite-bearing hypersolvus anorogenic granites. High field strength elements (Ti, Nb, Y, Zr) are typically in low abundances, as are LREE (Ce and Nd). These features are compatible with "volcanic arc granites" of Pearce *et al.* (1984) which have originated from partial melting of a subducting oceanic plate. There is no evidence to suggesting the presence of such a tectonic regime, but it does indicate a mafic or ultramafic (mantle) source for the intrusives.

The low trace element concentrations appear to be in sharp contrast to a pre-tectonic or anorogenic setting for emplacement. Alkaline anorogenic granites are characteristically enriched in these elements (*e.g.* Bonin, 1986). However, these typical "A-type" magmas require enrichment by means of alkaline volatile fluid phase, possibly derived from CO_2-H_2O induced mantle measomatism (Bailey, 1982; Schneider & Eggler, 1986). There is little evidence to indicate the presence of a mantle derived alkaline volatile phase for the intrusives of the Peake and Denison Ranges. However, it is not unreasonable to propose an anorogenic setting, but without substantial trace element enrichment from a mantle source.

7.6 Least-Squares Fractionation Modelling.

Least-squares fractionation modelling, or the calculation of whole-rock chemical trends based on specific mineral fractionation for major oxide compositions (after Wright & Doherty, 1970), has been applied to two suites of intrusives considered to be closely consanguinous in the Peake and Denison Ranges: the zoned pluton of Maps A and A′, and the sill swarm of Maps B and B′.

The exercise of such modelling tests the validity of mineral fractionation as a means in creating the observed trends in igneous rock suites. Mineral chemistries used in these models were acquired by microprobe analyses of the rocks involved. An exception is the calcic pyroxene quoted for one of the sills calculations, as no pyroxenes were observed (in support of the hypothesis that pyroxene crystallization took place at depth away from the final site of the intrusion). Mineral phases used also included early-crystallizing euhedral hornblende, sphene, apatite, magnetite and calcic plagioclase. Later crystallizing phases included alkali feldspar, biotite and albite. Both albite and alkali feldspar must also be considered as products of alteration.

Major element geochemical variations for the respective suites of samples representing the zoned pluton of Maps A and A′ and the sill swarm of Maps B and B′ are presented in figure 7.6.A & B. Complete results of these calculations are tabulated in Appendix M.

In consideration of the zoned pluton of Maps A and A′, Morrison & Foden (1989) recognized the early predominant fractionation of hornblende and calcic pyroxene in forming the initial trend from the most mafic end- members (*i.e.* 49 wt.% SiO_2) to approximately 58-59 wt.% SiO_2. At this point, equivalent to 5-6 wt.% CaO, the trend becomes enriched in aluminium relative to calcium. Morrison & Foden (1989) also recognized this point of inflection with respect to the high field strength elements (Zr, Nb, Y).

Modelling of this trend (Fig. 7.6.A) was possible by 36% crystallization and extraction from the "initial" melt ([7541]-[9598]) of 61% hornblende and 17% diopside. The domination of horblende, at this early proposed stage in fractionation, contradicts petrographic evidence suggesting pyroxene as the main early fractionating phase. Crystallization conditions which produce an oscillating hornblende-pyroxene assemblage can be accounted for by rapid pressure decrease in the production of andesitic melts (Holloway & Burnham, 1972; Eggler, 1972). Alternatively, the mafic end-member on which the model has been applied may be a crystal cumulate from later fractionation and thus not representative of an "initial" melt. Alteration is suspected in these most mafic lithologies because the improbable fractionation of albite was required to accommodate high sodium contents. Alteration is also implied by the requirement 30% albite and 18% biotite fractionation during 17% crystallization from the residual liquid in order to model the felsic end of the mafic trend ([9598]-[7543]). This section of the trend features the domination of (40%) diopside as the major fractionating phase, in response to sharply increasing aluminium over calcium.

Fractionation towards the felsic end-member (67 wt.% SiO_2) requires the extraction of mainly calcic plagioclase and hornblende without necessitating major fractionation of calcic pyroxene.

Andesine, hornblende and minor magnetite can successfully model most of this felsic trend (3% crystallization and extraction from the residual liquid of 51% andesine & 43% hornblende [7543]-[9588], followed by 2% fractionation of 89% andesine & 5% magnetite [9588]-[7542], then 2% fractionation of 77% hornblende [7542]-[7522], and final 1% crystallization from the residual liquid of an assemblage composed of 52% andesine, 18% K-feldspar, 14% biotite & 9% salite [7522]-[9590]). Minor biotite, alkali feldspar and calcic pyroxene are involved with the most felsic fractionate ([7522]-[9590]). Successful modelling for [7542]-[7522] was demonstrated utilizing 100% of the most mafic end-member [7541], further suggesting that the most mafic members of the suite may represent cumulates from the fractionation of the more felsic spectrum.

The major element fractionation modelling for the sills of Maps B and B′ (Fig. 7.6.B) indicates a similar history as that of the zoned pluton (Fig. 7.6.A). A gabbroic xenolith [7702] from one of the sills, is interpreted to be cognate and the most mafic end-member of the suite. For the most mafic section of the trend [7702]-[7314], 59% crystallization and extraction from the "initial" liquid of an assemblage includes 28% clinopyroxene (although petrographically absent) as well as 27% hornblende and 33% alkali feldspar is required. The inclusion of alkali feldspar, as with any fractionation modelling with these suites, probably indicates the involvement of secondary alteration processes.

Further fractionation towards the felsic end-members involves the progressive removal of calcic plagioclase, hornblende and biotite. After 51% crystallization and extraction from the residual liquid of 82% hornblende and 17% biotite ([7314]-[7304]), the trend reaches the same point of inflection as the zoned pluton of Maps A and A′ (approximately at 5 wt.% CaO). Then 41% fractionation from the residual liquid of labradorite ([7304]-[7315]) followed by 35% crystallization and extraction of an assemblage composed of 51% biotite and 37% hornblende ([7315]-[7312]) removal is all that is required to fractionate to the felsic end-member. As with the zoned pluton of Maps B and B′, the extraction of the most mafic component (70 wt.% [7702]) can be modelled for the most felsic fractionate, indicating again that the most mafic members represent crystal cumulates originating from the fractionation of a more felsic melt.

Fractionation modelling demonstrates the hydrous-anhydrous crystallization history. Both the zoned pluton and sills models indicate alternating hydrous and anhydrous crystallizing mineral phases. In the zoned pluton, fractionation is at first dominated by hornblende (hydrous), then followed by diopside and andesine (anhydrous), then hornblende (hydrous), culminating in the further fractionation of andesine (anhydrous). In the sills, pyroxene fractionation is followed by calcic plagioclase, then both biotite and hornblende. The oscillating crystallization pattern suggests the partial pressure of water played a critical role in determining liquidus mineralogy, the effects of which may also be evident in mineral zoning patterns (*cf. ch.* 4). Thus P_{H_2O} was probably near saturation levels and early crystallization of an anhydrous phase resulted in increasing P_{H_2O} in the liquid. P_{H_2O} build-up continued until the liquidus phase was in equilibrium with the crystallization a hydrous phase instead of anhydrous phase. Then the P_{H_2O} steadily decreased until liquidus equilibrium conditions required the crystallization of an anhydrous phase rather than a hydrous one. This oscillating hydrous-anhydrous equilibrium crystallization mechanism has been used to account for alternating mineral bands in layered igneous complexes (*e.g.* Rockhold *et al.*, 1987). The early fractionation of pyroxene required in the sills of Maps B and B′ (although not petrographically present) reaffirms the importance of fractionation and the formation of cumulate phases in the crystallization processes.

Least-squares modelling has demonstrated that the trends developed from compositions for the Bungadillina suite are largely due to the fractionation of hornblende, clinopyroxene and calcic plagioclase. A two-tier fractionation regime is envisaged, with the initial fractionation dominated by hornblende and clinopyroxene extraction and accumulation. The final, more felsic trend is dominated by calcic plagioclase fractionation. Most mafic members of the suite and gabbroic xenoliths closely resemble fractionate products of felsic differentiation, indicating the mafic end-members are probably crystal cumulates.

7.7 Trace Element Fractionation Modelling.

Trace element modelling was based on a 5% incremental fractional crystallization computer programme devised by Shaw (1970), and implemented by J.D. Foden at the University of Adelaide. This limited exercise was undertaken to determine whether or not trace element concentration variations support the major oxide results from least-squares fractionation modelling. Utilizing the major mineral components and their respective porportions previously developed in least-squares modelling, and applying average partition coefficient values for the modelled trace elements of these minerals (Table 7.7), theoretical crystallization trends were constructed and compared to the known trend for the zoned pluton of Maps A and A'.

Two sets of 50% incremental crystallization were applied to trace element modelling of Rb-Sr and V-Sc to define the mafic and felsic trends. These two sets approximate the two-tier fractionation model estimated in major element least-squares modelling. The mafic trend was composed of 40% hornblende, 40% plagioclase, 17% clinopyroxene and 3% magnetite. The felsic trend was modelled using 60% plagioclase, 30% hornblende, 5% magnetite and 5% clinopyroxene. Accompanying the fractional crystallization trend, the corresponding concentration of the crystallized residue was calculated to investigate the possibility of cumulate equivalents in this suite, as was postulated for a portion of the least squares modelling. Results are presented in Figure 7.7.

The high partition coefficient values of both Sc and V for hornblende (10 & 32), pyroxene (3 & 1) and magnetite (2 & 30) is expressed in the wide modelled fractionation trend from 376ppm V & 33ppm Sc to 82ppm V & 4.4ppm Sc. The calculated trend accurately models that obtained for the suite, although less magnetite fractionation for the felsic section would result in a more accurate Sc-rich end-member. The cumulate, composed of 40% hornblende, is exceedingly enriched in Sc an V. The cumulate for the felsic fractionate, however, more closely approximates the composition for the very mafic sample [7541], plotting immediately above the cumulate curve. The formation of cumulate mafic end-members has also been successfully modelled using least-squares fractionation of the more felsic trend ([7542]-[7522]).

Modelling of the incremental fractional crystallization trend for Rb & Sr using the same mineral proportions as V & Sc is presented in figure 7.7.B. The actual suite is very scattered in comparison with the narrow linear pattern for the modelled trend. The scatter can only be explained by the effects of albitization. As both Sr and Rb are very succeptible to sodic metasomatism, primary crystallization trends would have been invariably altered by secondary alteration. There is a vague corresponding increase in Sr and Rb from the cumulate end-member to the inflection point, followed by a general decrease in Sr and increase in Rb. However, the effects of albitization are too pronounced to competently apply least-squares modelling to large ion lithophile elements in the Bungadillina suite.

7.8 Isotopes.

The lack of post-Kimban deformation of the immediate Middle Proterozoic material in the Denison Inlier, composed of the Wirriecurrie Granite and the Peake Metamorphics, suggests that the crystalline basement (perhaps in the vicinity of the Adelaide Geosyncline in Peake and Denison Ranges) have neither undergone (pre-Delamerian) partial melting nor substantial Delamerian metamorphism. This is substantiated by an Rb-Sr isochron of 1648 Ma (Ambrose *et al.*, 1981) for the Wirriecurrie Granite which accurately delineates the Kimban Orogeny of the Gawler Craton (Webb *et al.*, 1986) without Delamerian overprinting. Acquired K-Ar ages in the Proterozoic crystalline basement become progressively younger towards major faults, suggesting that the Delamerian Orogeny was responsible for basement faulting, but the effects of metamorphism did not extend far beyond immediate fault zones. This absence of Delamerian-induced features in the crystalline basement is in contrast to the widespread regional folding and lower greenschist metamorphism experienced by overlying Adelaidean strata, eventhough the presently exposed basement may have been very removed from that which is immediately conjugate in the Peake and Denison Ranges. Nevertheless, xenoliths composed of a garnet-chlorite schist and minor gneissic/schistose xenoliths found in few Bungadillina plutons do indicate a limited influence from high-grade metamorphic constituents of the Early to Middle Proterozoic crust.

Rubidium-strontium systematics indicate a mantle component in the magma of the Bungadillina suite (initial $^{87}Sr/^{86}Sr$ ratio = 0.704-0.708; Morrison & Foden, 1989), with a possible crustal contamination for the more siliceous quartz monzonite and quartz syenite. These values are similar to those of igneous anorogenic complexes (initial $^{87}Sr/^{86}Sr$ ratio = 0.702-0.709) (Bonin, 1986).

Carbon and oxygen isotope systematics of the albitites and Adelaidean vein and breccia carbonates indicate groundwater derivation. However, a small intra-plutonic breccia with a carbonate matrix recorded isotopes analogous to a magmatic source. Albitite $d^{13}C$ and $d^{18}O$ are indicative of low temperature hydrothermal alteration.

7.9 Alteration.

Alteration of the intrusives of the Peake and Denison Ranges is a ubiquitous feature of the intrusive bodies. It most often involves albitization and is chemically characterized by substitution of Na for K, Rb and Ba. Albitization can be accounted for by three processes: (a) the interaction of the intruding pluton with meteoric water (hydrothermal alteration); (b) regional metamorphism, or; (c) magmatic fluids. Both hydrothermal alteration and regional metamorphism can produce similar (low temperature greenschist facies) mineral assemblages of albite-actinolite-epidote-calcite-chlorite-haematite. Alternatively, albitization by (high temperature) magmatic fluids (*fenitization*) is often associated with carbonatites and anorogenic plutonic complexes (*e.g.* Morogan & Woolley, 1988), and produces a unique mineral assemblage and enrichment in trace elements.

The Bungadillina suite shows field evidence suggestive of both low temperature non-magmatic modes of alteration. Localized albitization of the immediate margin of gabbroic bodies, often autobrecciated and occurring as short dykes re-intruding into the pluton, is more likely due to the immediate interaction of meteoric water. As previously mentioned, the lack of alteration of the sediments argues against a magmatic source for the alterant fluids, where high temperature alterant fluids would be injected into the surrounding sediments (*cf.* Morrison & Foden, 1989).

The prevalence of altered monzogabbro margins to the zoned pluton of Maps A and A′ (Morrison & Foden, 1989) and the eastern margin of the largest pluton (Map I) also attest to localized effects of meteoric water alteration. The eastern side (Map H) would represent the top of the intrusion (*i.e.* hanging wall contact of possible layered pluton), and corresponds to a zone of prominent albitization. Albitization would be more pronounced at the top of an intruding pluton where circulating meteoric fluids have the greatest access. The nature of the altering fluid is not clear, but the lack of scapolite as an alteration product argues against a hypersaline fluid, eventhough the distinct necessity for Na^+ ions (for sodic metasomatism) would suggest some saline component.

Evidence of disequilibrium assemblages (*e.g.* clinopyroxene with actinolite rims) supports a localized fluid access model rather than regional greenschist facies metamorphism. In favour of regional metamorphism, the occurrence of epidote-albite-chlorite-calcite nodules without veining throughout many of the plutons argues against alteration by means of hydrothermal percolations (*e.g.* Marzouki, 1979). However, this specific style of alteration has also been accounted for by very low grade burial metamorphism (Smith, 1968; *ibid.*, 1977).

Rubidium-strontium isotope data failed to precisely determine whether albitization was pre- or syn-Delamerian in age. However, distinctive differences in the carbon and oxygen isotopes between the calcite involved with Delamerian regional metamorphism (as in the diapiric breccia) and the calcite within albitized bodies, indicate origins from unrelated events. Cessation of alteration would be concomitant with pluton cooling and the end of a heat-induced driving force for fluid circulation. Location of albitized sections of plutons would be restricted to peripheral zones in the larger plutons where surrounding groundwater would have the greatest altering effect. Some smaller plutons are completely albitized, indicating emplacement into a vicinity which is readily accessible to alterant fluids. Such features are consistent with alteration due to shallow, syn-intrusive interaction between hot anhydrous Bungadillina magma and surrounding meteoric water.

7.10 Geochemistry - Genetic Classification.

The plethora of geochemical data recovered from various plutonic provinces in different tectonic settings in recent years has prompted many proposals for genetic classification on the basis of chemical parameters. Chappell & White (1974), Hine *et al.*, (1978) and White & Chappell (1983) have designed the "S-" and "I-type" classification scheme for granitic rocks of the Lachlan Fold Belt. "S-types" are resolved from melting of a sedimentary source while "I-types" are derived from igneous material. This scheme was amended by Loiselle & Wones (1979) to include "A-type" granites (for alkaline, anhydrous and anorogenic). "M-type" or mantle-derived intrusives such as plagiogranites are found in ophiolitic complexes, or those derived immediately from subducted oceanic crust (White, 1979; Pitcher, 1982; Bowden *et al.*, 1984).

Collins *et al.* (1982) and Whalen *et al.* (1987) showed that the distinguishing chemical features of "A-type" granites include relatively high concentrations of Cl, F, Nb, Ga, Y and REE, and lower Al, Mg and Ca. They argue against formation by extreme fractionation of an "I-type" magma, but suggest that highly fractionated "S-" and "I-type" granites have some "A-type" characteristics. The source material is defined as dehydrated F- and Cl-rich granulite originating from late orogenic lower crustal remnants. The tectonic environment for Whalen's *et al.'s* (1987) geochemically-based "A-type" granite classifications is considered not to be necessarily reserved to anorogenic or rift-related situations, thus re-specifying the original "A-type" definition of Loiselle & Wones (1979).

Most of the intrusives of the Peake and Denison Ranges are best described as "I-type" with mol Al_2O_3/Na_2O+K_2O+CaO <1.1 (A/CNK;

Fig. 7.10.A), normative corundum <1%, wide SiO_2 range, high (>3.2 wt.%) Na_2O and low initial $^{87}Sr/^{86}Sr$ ratio (0.704-0.706). The trend towards higher A/CNK with increasing SiO_2 never exceeds the 1.1 boundary with the exception of one albitite.

The alkali syenites (*e.g.* [9563]) fit many of the mineralogical pre-requisites for "A-type" granites. The presence of aegirine-augite and garnet attests to a peralkaline and anhydrous character and its intrusion involves a late-stage alkali-rich event. However, most of the chemical characteristics for "A-type" granites are indistinguishable between the fractionated alkali syenites and the general trend for the Bungadillina suite. Although fluorite is present, the overall F content varies little from the Bungadillina average (Fig. 5.3.2.E). The high G/Al ratio, which Collins *et al.* (1982) and Whalen *et al.* (1987) present as a characteristic feature for "A-type" granites, is only evident in probable cumulate phases (*e.g.* [7704, 7575]), and trace-element concentrations are typically low (*e.g.* Zr; Figs. 7.10.C & D). Thus although the Bungadillina suite occurs in an apparently anorogenic setting, it does not have the chemical characteristics for "A-type" granites.

Bowden *et al.*, (1984) and Batchelor & Bowden (1985) proposed a genetic classification scheme utilizing the R1-R2 diagram of de la Roche *et al.* (1980) by defining various fields which describe magmatism associated with a complete orogenic cycle (pre-plate, syn-plate and post-plate tectonism, anorogenic granites, syn-collision anatectic granites and mantle fractionates). The majority of samples plot in the late-orogenic plutons field (C), with the main trend of unaltered rocks in close proximity to the post-plate (Caledonian) collision uplift plutons field (B) as indicated by the trends of the zoned pluton of Maps A and A′ (1) and the sills of Maps B and B′ (2) (Fig. 7.10.B). In contrast, the alkali syenites (5) plot towards the anorogenic field which is also visited by a small collection of mostly altered samples. These two separate lithological groups are separated towards the R2 end by biotite lamprophyres (3) and towards the R1-end by the more fractionated quartz monzonite (4). Most of the undefined and altered samples inhabit the central zone separating these two groups across the silica saturation boundary.

Batchelor & Bowden (1985) pointed out that fractionation of amphibole and plagioclase of a tholeiitic basalt source can develop K-poor calc-alkaline granitoids that plot within the *late orogenic sub-alkaline* field (Figs. 7.4.2 & 7.10.B). The cumulate would then be recorded within the *mantle plagiogranites* field. In this respect, the field as defined by quartz monzonite corresponds to residual melts from amphibole and plagioclase fractionates. Compositions produced from prolonged fractionation or products from crustal melting do not occur (*i.e.* high R1 and low R2).

Pearce *et al.* (1984) and Harris *et al.* (1986) have presented discriminating classification on the basis of trace element concentration, notably Nb, Rb and Y, which defines within-plate granites (WPG), ocean-ridge granites (ORG), volcanic-arc granites (VAG) and syn-collisional granites (syn-COLG). Within-plate granites are analogous to "A-type" granites, ocean ridge granites are equivalent to mantle-derived plagiogranites and syn-collisional granites are minimum-melt anatectic granites. Volcanic-arc granites vary in composition and tectonic setting, but generally imply a mantle component related to the subduction of oceanic crust.

The majority of intrusives of the Peake and Denison Ranges plot in Pearce *et al.'s* (1984) VAG field. Few samples exhibit sufficiently high concentrations of Nb and Y to place them into the WPG field (Fig. 7.10.E & F). The scatter of altered samples towards the bottom of the VAG field is due to Rb depletion from albitization. It is at the base of this field that there is a slight incursion of albitized samples into the WPG and ORG fields. Similarly, the high Rb content of the alkali syenites have placed this group into the syn-COLG field. Pearce *et al.*, (1987) suggested that the Pearce *et al.*, (1984) VAG field may also accommodate incompatible element depleted mantle derived granites.

Other attempts of genetic classification include differentiation of plutonic suites from compressional and extentional tectonic regimes (Petro *et al.*, 1979). The alkali-calcic and metaluminous characteristics of the intrusives of the Peake and Denison Ranges produce an ambiguous tectonic setting. However, the alkaline tendancy with repect to the AFM diagram (Fig. 5.2.1.B) and the broad range of intermediate composition is criteria in keeping with a compressional tectonic setting. Petro *et al.* (1979) suggested that the intermediate compositions may be due to dehydration and partial melting of subducted oceanic crust. The involvement of oceanic crust is also indicated in the trace element discrimination diagrams of Pearce *et al.* (1984).

7.11 Conclusions.

From the discussion in this chapter, it is evident that the intrusives of the Peake and Denison Ranges originated from an upper mantle magma source. The absence of olivine from the Bungadillina suite, in contrast to Adelaidean and Early Cambrian basalts (*e.g.* *Truro Volcanics*) where olivine is commonly preserved as pseudomorphs, indicates early removal from the parental melt or not a stable phase. The fractionation and extraction of olivine is further substantiated by the lack of Ni which would have partitioned into olivine, and reflected in the early fractionation and extraction of chromian spinel which has removed most of the original Cr content (Fig. 7.12).

Early crystallization of pyroxene, followed by hornblende, played an important role in magma development and formation of a cumulate crystal-rich phase. The two magma types; a crystal-rich phase and a crystal-poor phase, often intruded as separate small plutons, while larger plutons commonly have co-existing phases. Biotite was the only mafic mineral phase crystallizing *in situ*, while most of the felsic melt-supported mush originally crystallized at depth.

The concentrations of the trace elements, as demonstrated with Rb-Sr and Sc-V, can be accounted for by crystal-liquid fractionation and modified by sodic metasomatism. Although the intrusives have moderate to high fluorine contents indicating a volatile phase, it appears that fluorine was partitioned into early crystallizing phases (amphibole) as xenoliths are commonly enriched in F. The lack of pegmatites and aplites indicates that the Bungadillina suite was largely anhydrous and never development a late-stage volatile-rich phase.

Most evidence, such as the style of alteration, style of emplacement, geochronology and regional setting, indicates an anorogenic or pre-Delamerian setting for the intrsion of the Bungadillina suite. Anorogenic alkaline intrusive suites have been thought to have originated from a primary mantle magma (*e.g.* van Breemen *et al.*, 1975; Jacquemin *et al.*, 1982), from which felsic melts are derived through crystal fractionation (Bowden, 1985). However, the most characteristic feature of "A-type" granites, is anomalous enrichment in trace elements (>500ppm Zr, >25ppm Nb, >60ppm Y, >230ppm LREE and >35ppm HREE). Taylor *et al.* (1981) demonstrated that such high trace element concentrations cannot be obtained by crystal-liquid fractionation alone, also requiring the evolution of an alkaline volatile fluid phase which often involves Cl^-, F^- and CO_2 complexing (Bowden, 1985). This trace element enriched fluid phase is thought to have been derived through mantle devolatilization along narrow continental rift zones (Bailey, 1982; Schneider & Eggler, 1986). Partitioning of trace elements into residual magmatic liquids in conjunction with this volatile component can lead to characteristic post-magmatic alkali metasomatism (Burnham, 1979), including the formation of characteristic "A-type" minerals such as aegirine and alkali amphiboles (Bowden, 1985). In contrast, the intrusives of the Peake and Denison Ranges lack a trace element enriched volatile phase or high Ga/Al ratios typical of "A-type" granites, but have an anomalously higher proportion of total alkalis than typical "I-type" granites. However, most described "A-type" granites are either from post-orogenic regimes where they have intruded in response to crustal rebound (extension) after a compressional orogenic period, or from active continental rift environments intruding crystalline basement. Neither tectonic environment can be confidently applied to the intrusives of the Peake and Denison Ranges as the suite probably predates the Delamerian Orogeny, intrudes a sedimentary pile, and the

Adelaide Geosyncline represented a fairly stable basin during the Early to Middle Cambrian.

The only evidence for late stage peralkaline magmatism is the formation of alkali syenite (aegirine-augite, andradite, 10 wt.% K_2O and fluorite) and biotite lamprophyre dykes. These unusual occurrences, however, are not enriched in trace elements, although both their major element and mineralogy are characteristic of anorogenic alkaline provinces. Thus for the Bungadillina suite, a mantle-derived trace element enriched volatile phase never modified the original trace element concentrations. One possible explanation is the environment of emplacement. In contrast to many of the characteristic anorogenic provinces in Africa and Scandinavia, the Bungadillina suite appears to have intruded a *wet* sedimentary pile, and not crystalline basement. Any volatile content of the magma would then have the opportunity to quickly disperse into the meteoric groundwater system without any further trace element modifications, in either the crystallizing magma or the immediate host sediments.

The final depth of emplacement remains uncertain. Geothermometry was unable to indicate an accurate depth of final emplacement. If intrusion into the Burra Group occurred immediately prior the Delamerian Orogeny, Ambrose *et al.* (1981) have calculated the stratigraphic thickness above the plutons to be approximately 7km.

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Chapter Eight: Implications of Igneous Activity in the Peake and Denison Ranges within the Adelaide Geosyncline.

"A final philosophy of earth history must be largely founded upon the unshakable facts known about igneous rocks."

R.A. Daly (1933).

8.1 Continental Rifting and Initiation of the Adelaide Geosyncline.

Many processes have been invoked to account for the initiation of continental rifting as the predecessor to the formation of Atlantic-type continental margins or intracontinental basins such as that preserved as the Adelaide Geosyncline. Proposed mechanisms involve lithospheric doming and erosion, extension and thinning, magmatism and partial melting (Royden & Keen, 1980). As rifting proceeds, crustal subsidence leads to sedimentary basin formation by sudden homogeneous lithospheric stretching followed by cooling and sediment loading (McKenzie, 1978).

Recent continental rifts, such as the Rhine graben, are related to crustal thinning in response to mantle upwelling. The rise in geothermal gradient results in crustal doming, and gravitational pull at the flanks of the uplift can initiate rifting (Neugebauer, 1978). Volcanism is closely related to the processes of mantle upwelling, crustal doming and early rift formation (*e.g.* Logatchev, 1976; Wedepohl, 1985), and volcanic activity proceeds doming and faulting, but precedes graben formation (Neugebauer, 1976).

Continental rift-associated volcanics can be voluminous. The Baikal Rift in the Soviet Union contains about 5000km^3 of Cainozoic alkaline, subalkaline and thoeiitic flood basalts. The lava pile in places exceeds 0.5km in thickness, and is related to the early stage of rift formation involving mantle upwelling and domal uplifting (Logatchev & Florensov, 1978; Kiselev, Golovko & Medvedev, 1978). Similarly, the East African Rift is characterized by the extrusion of immense outflows of dominantly flood basalts over the uplifted continental areas encompassing Ethiopia and Kenya (Ethiopian Plateau) (Illies, 1970). The proposed source for East African Rift basalts is similar to mantle-derived metasomatized peridotite xenolites (Auchapt, 1987).

In the Adelaide Geosyncline, initial continental rifting is indicated by the Gairdner Dyke Swarm. These northwest-southeast trending dykes indicate the orientation of continental uplift (*cf.* Preiss, 1987). As flood basalts of mantle derivation would have been extruded onto an uplifted continental crust, subsequent erosion may have destroyed evidence of this primitive volcanic sequence. Woodget (1987) also suggested, based on geochemical evidence, that the Gairdner Dyke Swarm is a separate, less fractionated suite than the volcanics of the Early Adelaidean. Von der Borch (1980) first applied the concept of localized mantle upwellings or "hot spots" to the initiation of continental rifting to form the Adelaide Geosyncline. Gunn (1984) delineated possible initial rift zones from linear geophysical anomalies, one of which runs parallel to and along the length of the Peake and Denison Ranges.

Widespread rifting of the Adelaide *Protosyncline* resulted in the extrusion of voluminous continental tholeiitic flood basalts forming the Beda, Cadlareena and Wooltana Volacanics during middle Callanna Group deposition. Hilyard (1986) suggested that these areally extensive fissure-eruption flood basalts immediately predate rapid basin subsidence and graben formation which initiated rift-valley sedimentation. Insufficient basaltic magma underplating coupled with insufficient crustal thinning prevented complete continental rifting and the formation of oceanic crust within the Adelaide Geosyncline.

Preiss (1987) proposed that the deposition of much of the Callanna Group evaporites postdates this volcanic activity. However, the prevalence of volcanic clasts within diapiric bodies indicates close timing between volcanism and evaporite deposition.

The volcanic fissure system for the Wooltana Volcanics was centred along the Paralana Fault zone (Hilyard, 1986). Fault-controlled volcanism is most common in continental rift environments, as deep-seated crustal faults provide a ready conduit for magma transport to surface levels. The occurrence of Callanna Group volcanics, Cadlareena Volcanics, indicates the presence of these deep-seated faults in the Peake and Denison Ranges. Reactivation of these faults, accompanied by renewed periods of rifting and mantle upwelling, is the likely cause for volcanism during periodic tectonic activity associated with the evolution of the Adelaide Geosyncline. These periods of volcanic activity are not limited to the basal sequences, but also include the Burra Group *Port Pirie Volcanics*, the Umberatana Group *Wantapella Volcanics*, and volcanism during the Early to Middle Cambrian (*e.g. Truro Volcanics*). It is interesting to note that major hiatuses exist immediately prior to Umberatana Group volcanism and Cambrian volcanism. Erosional periods probably represent mantle upwelling and crustal doming which immediately precedes volcanic activity in a rift environment (Neugebauer, 1978).

The basal Callanna Group volcanics are primitive unevolved basalts derived directly from a mantle source. In contrast, Cambrian volcanism in the Adelaide Geosyncline is more commonly characterized by a more evolved bimodal assemblage of acid tuffs and basalts; a feature common to rift environments. This specific event in the evolution of the Adelaide Geosyncline may represent the final resurgence of fault-controlled crustal activity prior to the onset of the 500 Ma, largely compressional, Delamerian Orogeny. The Delamerian Orogeny heralded the end of the development of the Adelaide Geosyncline.

The later formation of intracrustal zoned magma chambers associated to periodically extruded continental rift volcanism can lead to the development of felsic differentiate magmas (*e.g.* Hildreth, 1981). In the Adelaide Geosyncline, there has been no clear identification of rift-associated plutonic suites. Most plutonic occurrences have been associated with Delamerian Orogenic activity (*e.g.* Foden *et al.*, 1989).

8.2 Rift-Associated Plutonism.

As well as being the tectonic setting for voluminous extrusion of largely basaltic lavas, the early development of continental rifts are also host to the intrusion of chemically and mineralogically unique alkaline plutons. Some of the best known examples of relatively recent continental rift-associated plutons are found within the West African rift system. These commonly form annular ring-complexes such as the *Younger Granites* of Nigeria (*e.g.* Imeokparia, 1985; Badejoko, 1986; Turner, 1986), and the *Mboutou Layered Complex* of North Cameroon (Parsons *et al.*, 1986). Bonin (1986) concluded that such complexes are primarily anorogenic, anhydrous and alkaline in character, originating from a mantle source which has subsequently been modified by crustal assimilation. The plutons commonly form layered magma bodies, yielding a gabbro-monzogabbro-syenite-granite evolutionary trend which is controlled by the fractionation of olivine, calcic plagioclase, calcic amphibole and calcic pyroxene. Plagioclase and hornblende fractionation are responsible for the common differentiation trends from nepheline-normative to quartz-normative compositions, with the development of cumulate heterogenous leucogabbroic rocks indicative of derivation from an intermediate magma (Bonin & Giret, 1985). Associated volcanics are felsic at first, but then becoming bimodal as different sections of a layered source are sequentially tapped. Melt viscosity is controlled by fluorine content, while chlorine is generally lacking. Biotite crystallizes with the influx of water as the largely anhydrous plutons interact with meteoric water (Bonin, 1986).

Diameters of individual plutons are usually controlled by the depth of emplacement, and the localization of alkaline magmatism is determined by deep-seated faults reactivated by upper crustal stresses (Black *et al.*, 1985). These plutonic occurrences are typically small in comparison with mobile-belt batholiths, forming at shallow crustal levels. They may represent the eroded roots of a major central volcanoes (*e.g.* O'Halloran, 1985). Plutons are typically subcircular and form a ring dykes swarm surrounding the pluton. The dykes follow the subcircular fracture pattern within the crystalline basement caused by the inflating magma chamber. Felsic ring-dyke propogation is in direct consequence of caldron subsidence, as the upper felsic melt of the zoned pluton is sequentially tapped off (*e.g.* Vellutini, 1977; Castro, 1987). Bonin (1986) proposed four structural zones for anorogenic plutons. Within these zones form specific mafic magma suites:

(1) The surface expression is that of a caldera volcanic complex;

(2) Under this (at 1 to 4km) lies an extensive ring-dyke system;

(3) Magma chambers that feed the dyke system are located at a depth between 7 and 32km (usually at around 15km), where the rheology of the crust changes from brittle to plastic. Bott (1981) suggested that this depth (approximately 20km) corresponds to crustal rheology change from ductile to elastic.

(4) Magma chambers are commonly felsic in composition towards the top, mafic at the bottom.

(5) The source for magma generation is from the upward doming of the aesthenosphere, at a depth of at least 50km.

The felsic members of this style of intrusive were described as *"A-type"* by Loiselle & Wones (1979) and are classified according to the following distinctive chemical characteristics, including high concentrations of HFS (high field strength) elements, high Ga/Al and low Ni and Cr (Clemens *et al.*, 1986). Pearce *et al.*, (1984) have refined the definition of these chemical parameters in their description of the trace element characteristics for *within plate granites* (*cf. ch.* 7.10 for the Bungadillina suite). Bowden (1985) has also summarized the characteristics of alkaline ring complexes. These include (a) limited late-stage sodic and potassic metasomatism, (b) small variations in alkali element contents can have drastic effects on the crystallizing mineral suite in regards to the formation of sodic pyroxenes and sodic amphiboles, (c) high REE concentrations and (d) high HFS element contents.

Apart from the chemical characteristics for "A-type" granites, the intrusives of the Peake and Denison Ranges have many of the features of rift-associated plutons. These include (a) a bimodal assemblage controlled by (b) calcic plagioclase, calcic pyroxene and hornblende fractionation with (c) the later crystallization of biotite from hydration of the intruding magma. Compositions range from (d) quartz normative to nepheline normative with (e) the formation of crystal cumulate lithologies. Magma apprears to have (f) originated from the mantle, and had (g) residency in middle crustal levels. Plutons are (h) small and (i) zoned from bottom to top. There are no circular ring-dyke systems, but the Bungadillina suite has abundant sills, which like ring-dykes, intrude along planes of greatest weakness in the surrounding host rock (j).

Rift-associated plutons may also be represented as noted rafts in diapiric breccia (also interpreted to be coarse centres of thick volcanic flows: Gum, 1987). The diorites, albitites and gabbroic rocks of the Willouran Ranges and Arkaroola region may as well be rift-associated intrusions as they (a) have high REE concentrations and (b) have similar alteration features as Callanna group volcanics.

8.3 Intrusives of the Peake and Denison Ranges.

Attempts to date the Bungadillina suite either by geochronology or by structural evidence (with respect to Delamerian deformation) have proven to be at the best vague, and at the worst misleading. Rubidium-strontium systematics have been overprinted by low temperature sodic metasomatism. Zircon U-Pb dating produced an error range is too great for confident dating, and may involve some degree of extrinsic contamination. Furthermore, much of the structural evidence to establish emplacement relations to Delamerian deformation has been complicated by (a) pre-Delamerian evaporite diapir-induced deformation and (b) diapiric breccia re-mobilization.

Structural information is very scarce as most plutons occur within relatively undeformed sedimentary sequences, without any definitive pervasive tectonic fabric. Although there are undeniable examples of post-Delamerian dykes intruding along faults and fold hinges, the bulk of the Bungadillina suite has conflicting structural evidence for relative age of emplacement. The lack of significantly deformed plutons argues against pre-deformation emplacement. However, is it possible for relatively small and competent plutons be deformed by low-grade regional deformation, especially with the immediate presence of highly mobile diapiric breccia which must have absorbed much of the tectonic stresses (*c.f.* Paterson & Tobisch, 1988)?

The prevalence of remobilized diapiric breccia around plutons may indicate that Delamerian-induced deformational stress was preferentially released via breccia mobilization rather than through pluton deformation. Furthermore, it can be argued that specific structures may have formed in response to diapiric activity and not from regional Delamerian deformation. Much of the evidence indicates that emplacement predates Delamerian folding. The low temperature hydrothermal style of alteration is in keeping syn-intrusion interaction with a groundwater system. This may also account for the lack of contact metamorphism. Could such a system be in effect during or after Delamerian Orogenic activity? In comparison with other plutons in the Adelaide Geosyncline (*e.g.* Anabama Granite), this seems unlikely. Such factors indicate intrusion into a (pre-orogenic) wet sedimentary pile (Burra Group). The prevalence of sills occurring within less competent beds also suggests pre-orogenic sedimentary structures controlled mode of emplacement. The lack of either a contact metamorphic halo or mineral foliation supports a non-orogenic emplacement. Thus it may be concluded that the intrusives of the Peake and Denison Ranges probably represent a pre-Delamerian, anorogenic igneous suite which was re-activated during post-Delamerian (orogenic collapse) rifting.

The Bungadillina suite has many features analogous to typical anorogenic plutons. These include:

(1) subcircular forms;

(2) intra-plutonic compositional zonation;

(3) mafic zones near the base of plutons;

(4) emplacement in usually an extensional regime (stoping);

(5) areally limited and restricted occurrences;

(6) possible association to deep-seated faults (?Karari Fault);

(7) derivation from a mantle source;

(8) coeval with and chemically similar to bimodal (pre-Delamerian) Cambrian volcanism;

(9) high level of emplacement;

(10) associated contiguous dyke (sills) swarm;

(11) alkaline in character;

(12) fractionation towards peralkalinity (alkali syenite).

The close chemical similarities between Cambrian volcanics (*e.g.* Warburton Volcanics) sequences in the Adelaide Geosyncline and peripheral conjugate basins, and the intrusives of the Peake and Denison Ranges suggest that the intrusives of the Peake and Denison Ranges represent a Middle to Late Cambrian (pre-Delamerian) sub-volcanic centre. Present exposures of the Bungadillina suite may represent exhumed high-level magma chambers to large, central, rift-associated volcano(es).

The thickness of Adelaidean sediments stratigraphically above the (Burra Group) *Mount Margaret Quartzite* indicates the plutons were emplaced at a depth of about 7km (Ambrose *et al.*, 1981; Preiss, 1987). Shallow subsurface magma chambers collect upward migrating magma from dykes originating from deep-seated magma chambers in the lower crust or upper mantle. In Iceland, the shallow chamber of "double chamber" systems are normally 1-3km beneath the surface of a lave pile (Gudmundsson, 1986; *ibid*, 1988). However, the Bungadillina suite magma would have been more viscous than Icelandic basalt, inhibiting upward migration. Furthermore, as overlying Adelaidean sediments are much less dense than basalt, a greater thickness is required to obtain similar lithostatic pressures. Thus it is not unreasonable to conjecture that the Bungadillina suite formed at depths greater than 5km.

Mineralogical and isotopic evidence indicate a mantle source for the Bungadillina suite. The base of the Moho under the Adelaide Geosyncline was estimated to be in the order of 38-40km (Preiss, 1987). Under these conditions, accompanied by high oxygen fugacity, are where initial magnetite, calcic pyroxene and clinopyroxene crystallized (Fig. 7.11). The trace mineral chromite indicates even deeper conditions of crystallization. The lack of olivine in the assemblage suggests early resorption or complete fractionation from the initial melt. Hornblende geobarometry indicates that this primitive magma then intruded to middle crustal levels (approximately 20km), ponding at the junction between brittle-plastic (or ductile-elastic) crustal rheologies. Hornblende crystallization at this level was encouraged by conditions of higher water activity (Fig. 7.11).

Some degree of cumulate formation occurred at this or higher levels as the cumulate product is dominated by hornblende, magnetite and clinopyroxene. Upon intrusion into the Adelaide Geosynline itself, biotite crystallized under conditions of higher water activity, and magma interaction with surrounding meteoric water developed localized alteration. Magma ponding at this level was probably encouraged by devolatolization, perhaps accompanied by a volcanic phase (Fig. 8.3).

A modern anologue to the Bungadillina suite can be made with the Tahiti-Nui caldera in French Polynesia. The Tahiti-Nui caldera includes a small (2km) pluton that has many striking similarities including: basal pyroxenite (salite); amphibolite cumulates; differentiation processes dominated by pyroxene and amphibole fractionation; varying feldspar compositions; and syn-emplacement albite-epidote alteration (Bardintzeff *et al.*, 1988). However, whereas the Tahiti-Nui complex has a weakly silica saturated and a strongly silica undersaturated suite, the Bungadillina suite is marked by a weakly silica undersaturated to a more strongly silica saturated suite. The difference between these two suites is that the magmatic evolution of the Tahiti-Nui suite involved the resorption of amphibole to produce its strongly silica undersaturated trend, whereas the Bungadillina suite retained amphibole as a prominent phenocryst (cumulate) phase (*cf.* Fig. 7.4.1).

The chemistry of the intrusives of the Peake and Denison Ranges is characterized by high LIL element concentrations, low LREE and HFS element concentrations, and a positive Sr anomaly. Chemical variations within the suite are shown to be due to crystal fractionation and mafic phase accumulation. The lack of trace-element enrichment, in comparison with typical "A-type" intrusives, indicates that the Bungadillina suite was not accompanied by a magmatic volatile phase, either as postulated from partial melting of a granulite source (Collins *et al.*, 1982) or a mantle metasomatic source (Bailey, 1982; Schneider & Eggler, 1986). Alternatively, Fitton & James (1986) suggested that mantle metasomatism is not necessarily the precursor to the derivation of LIL element enriched magmas. Instead, they invoke a heterogenous source caused by variable degrees in partial melting in the upper mantle (*e.g.* oceanic crust subduction). From a heterogenous source, McKenzie (1985) postulated that very low quantites of melt moving through the mantle will tend to re-equilibrate to bulk mantle values (*i.e.* lose any anomalous LIL element enrichment), whereas large melt volumes will reflect bulk mantle values. It is only middle range melt volumes that will retain any original mantle heterogeneity. Thus the low trace element contents in the Bungadillina suite may simply imply that the melt volume was insufficient to retain any anomalously high concentrations. If the intrusives of the Peake and Denison Ranges are indeed pre-tectonic, then these chemical characteristics may lend support to a new plutonic classification than strictly "A-type" (post-tectonic) or "I-type" (igneous derived).

8.4 Igneous Activity Within the Adelaide Geosyncline.

Table 8.4 has been constructed to present a summarised history of magmatic activity in the Adelaide Geosyncline. The early development of the Adelaide Geosyncline is dominated by volcanics; mantle-derived flood basalts from a deep-seated fault system, indicative of crustal rifting or down-warping of a brittle upper crust. This magma spent little, if any, residency in the crust. Fault reactivation and possible renewed mantle upwelling was responsible for periodic volcanism during the Middle Adelaidean. It is likely that some degree of plutonic activity accompanied volcanic activity. This may be represented by various small occurrences in the Willouran Ranges and Arkaroola region.

Rapid fault-controlled subsidence in the Cambrian associated with the development of the Kanmantoo Trough was synchronous with bimodal fault-related volcanism, originating from the mantle, but ponding in the crust, fractionating and forming felsic differentiates. One locality for high-level (?sub-volcanic), intrusion is represented by the intrusive suite in the Peake and Denison Ranges.

Crustal thickening in a compressional regime occurred with the onset of the Delamerian Orogeny. Renewed mantle activity accompanied by an increasing geothermal gradient at lower crustal levels may have induced melting and the formation of largely hydrous magmas. Subsequent intrusion of these melts into high crustal levels formed the Anabama and Bendigo Granites. These granites are characterized by a high silica component, and often forming a weak foliation parallel to the regional tectonic trend. These granites intruded along zones of upper crust mobilization (*Nackara Arc*) where longer crustal residency promoted greater crustal assimilation. The hydrous character of these granitic magmas led to biotite-controlled fractionation at depressed temperatures.

The Anabama and Bendigo Granites appear to be coeval and consanguineous with the syn-tectonic granites of the Kanmantoo Group which formed granites and granodiorites (*sensu stricto*) in a zone of relatively high regional metamorphism during the Delamerian Orogeny. It was not until after the termination of crustal tension when continued (?residual) mantle activity was responsible for the intrusion of characteristic "A-type" post-tectonic granites in southeastern South Australia along the margins of greatest deformation (Turner and others, *in prep.*; Foden *et al.*, 1989).

Ancient deep-seated faults originally responsible for the initiation of the Adelaide Geosyncline continued to play a role in igneous activity in the Adelaide Geosyncline. They have also been in part responsible for the intrusion of Jurassic dolerites and kimberlites as a precursor to Gondwanaland rifting. The occurrence of mantle-derived kimberlitic bodies within the Adelaide Geosyncline attests to depth of these faults. Periodic seismic activity along these faults have been well recorded in recent times (*pers. comm.* South Australia Department of Mines and Energy).

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