Lithostratigraphy and Lithochemistry of Ordovician volcano-plutonic rocks in the Blayney area, central Molong Belt, NSW

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Abstract

The Late Ordovician Cabonne Group lies in the southern portion of the Molong Volcanic Belt in central western NSW. It broadly comprises an extensive lava-dominated package of high-K calc alkaline mafic volcanics (Blayney Volcanics) overlain by a package of shoshonitic lavas and intrusives (Forest Reefs Volcanics).

Regional aeromagnetic and structural data suggest that thrust style faulting may have caused the extensive lithological repetition observed within the Cabonne Group.

Volcanic facies mapping, combined with geochemical sampling, has provided a basis for re-interpretation of areas within the Cabonne Group. Facies mapping has demonstrated a number of possible stratigraphic correlations, including a possible link between limestones present at and surrounding Browns Creek with limestones within the Weemalla Formation at the base of the Forest Reefs Volcanics.

Geochemical and petrological data define a temporal change in magmatic affinities within the Ordovician volcanics of the Molong Volcanic Belt. This change in magmatism from high K in the Blayney Volcanics to shoshonitic in the Forest Reefs Volcanics is broadly coincident with the late Middle Ordovician limestone interval at the base of the Forest Reefs Volcanics.

This broad lithochemical stratigraphy provides a framework for comparisons with the Ordovician Junee-Narromine volcanic belt located 100 km to the west, where a similar temporal transition exists from high-K in the Nelungaloo Volcanics to shoshonitic in the overlying Goonumbla Volcanics.

The Ordovician volcanics from the Molong belt are also similar to the early to mid-Miocene calc-alkaline to shoshonitic suites from Fiji. On the basis of these similarities, the transition from high-K to shoshonitic volcanism is likely to be the result of fragmentation of a mature oceanic island arc as a result of a major tectonic disturbance as marked by the late Middle Ordovician limestones.
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Chapter 1: Introduction

1.1 Background and Location

This research primarily seeks to investigate the petrology and geochemistry of a region of Ordovician volcanics in the Molong Volcanic Belt (MVB), central western NSW. In doing so, it also emphasises the importance of a multidisciplinary approach into analysing an area's prospectivity by integrating its volcanic facies architecture, structure and geophysical features.

It is now recognised that the Ordovician volcano-intrusive belts of central western NSW constitute a significant metallogenic province in the eastern Lachlan Fold Belt of Australia, with several world-class copper-gold systems known and the strong potential for further discoveries.

In recognition of this, a major exploration effort was initiated by the Centre for Ore Deposit and Exploration Studies (CODES) in early 1998. This forms a major collaboration between industry and research organisations, known as the Strategic Partnership with Industry Research and Training (SPIRT).

The SPIRT program is supported by the Australian Research Council (ARC) and will incorporate and build on current knowledge through a synthesis of the Origin and metallogenesis of Ordovician volcanic belts in central western NSW. It is being conducted over a three year period with the involvement of six exploration companies currently active in central NSW, (Hargraves Resources, North, Newcrest, Goldfields, Alkane and Homestake) as well as a major contribution by the Geological Survey of New South Wales (GSNSW).

The petrology, geochemistry and tectonic framework component of this program aims to document the regional and temporal inter-belt and intra-belt variations in igneous suites to determine whether mineralisation is associated with any particular magmatic suites. In addition it will also compare the Ordovician suites with modern analogues to establish a tectonic model for this area of the LFB. This honours project is being conducted within
the framework of this research and will contribute to the regional synthesis of the prospective Ordovician rocks of central NSW.

The study area is located in the southern Molong Volcanic Belt (MVB) near the township of Blayney, ~35 km south of Orange in central western NSW. It encompasses a region of prospective Ordovician volcanics exposed in a field area of approximately 45 km² directly north from the Browns Creek Au-Cu Mine. The research effort is focussed within this area, however due to the extensive nature of Ordovician volcanics throughout the district, reconnaissance sampling and field observations were also made in areas of interest outside of and marginal to the field area.

The fieldwork component of the study was conducted between February and April 1999 and involved the careful sampling of the extrusive and intrusive Ordovician units. In addition, detailed geological mapping (1:5000) determined the distributions of each of these units and also mapped the continuation of some important structural zones north from the Browns Creek Au-Cu Mine.

1.2 Aims and Methodology

The main objectives of the research are:

• To identify distinct lithostratigraphic units by using geological and geochemical methods, enabling correlations to be made over the field area and also potentially at a regional scale.

This task essentially reduces to the subdivision of the regionally extensive Ordovician packages and determining their internal boundary relationships. To achieve this a volcanic facies architecture for the area has been developed and integrated with the petrological and geochemical variation documented for the various units.

• To document the spatial and temporal variation in magmatic affinities of the Ordovician units in the Blayney area.

• To review whether Au-Cu mineralisation is associated with any particular magma type in this region of the Molong Volcanic Belt.
This aim considers the spatial and temporal variations in magmatic affinities of the Ordovician volcanics, which is considered to have significant implications for the physiochemical control of solubilities and deposition of metals derived from magmas.

- Finally, by considering modern analogues, produce a plausible tectonic model, constraining the settings of eruption for the southern portion of the Molong Volcanic Belt and placing it within the tectonic framework of the eastern province of the Lachlan Fold Belt, central NSW.

The geochemistry and magmatic affinities of the various units provide important information for constraining the tectonic setting. An effort is also made to incorporate these interpretations with previously published data from the other two main Ordovician volcanic belts in this region of the Lachlan Fold Belt.
Chapter 2: Regional Setting

2.1 Lachlan Fold Belt

The Lachlan Fold Belt (LFB) lies within the Tasman Fold Belt System of eastern Australia (Fig 2.1). It comprises several lithotectonic assemblages, ranging from Cambrian to Late Devonian-Early Carboniferous in age (Fergusson and Coney, 1992). This chapter aims to outline some of these assemblages and introduce some of the key problems in interpreting the LFB geology.

Prior to the breakup of the Gondwana supercontinent, an apparently continuous Early Palaeozoic foldbelt system, including the LFB, extended some 20000 km through Australia, Antarctica and South America (Coney et al., 1990). Within eastern Australia, the LFB is about 600 km at its maximum width and extends north from northeastern Tasmania into southern Queensland.

Four broad lithotectonic associations have been recognised within the LFB. These are the Cambrian greenstones, widespread Ordovician-Early Silurian turbidites, Ordovician volcanics and an assemblage of Silurian-Early Devonian predominantly felsic volcanics and sedimentary lithologies (Suppel et al., 1998).

The Ordovician stratigraphy of the LFB is dominated by an extensive quartz-rich turbidite succession. In addition to these and strongly contrasting with them in terms of lithological association are the Ordovician volcanics. These occur in three main volcano-intrusive belts within the eastern portion of the LFB (Fig 2.1 & 2.2). They include igneous suites of distinctly shoshonitic basalts and andesites and are discussed further at the end of this section.

Several deformation episodes have been identified for the LFB, however their effects does not appear to be regularly distributed over the whole belt (Glen, 1992). The deformation episodes which have been identified include the Late Ordovician-Early Silurian Benambran Orogeny, Mid-Silurian Quidongan Orogeny, Late Silurian-Early Devonian
Bowning-Bindi Orogeny, Middle-Devonian Tabberabberan Orogeny, and the latest event, the Early Carboniferous Kanimblan Orogeny (Suppel et al., 1998).

The partitioning of deformation events across the evolving Lachlan orogen has resulted in the complex, variable nature of structural histories documented across the belt (Glen, 1992). However, one emerging fact for the entire LFB is the importance of thrust related deformation (Fergusson and VandenBerg, 1990). This is perhaps best seen in the eastern belt (Fig 2.1), where repeated deformation has resulted in detachment at depth in the Cambro-Ordovician during west-dipping thrusting (Fergusson and VandenBerg, 1990). This period resulted in widespread repetition of strata along steeply dipping contractional faults in the Ordovician turbidites (Fergusson and Coney, 1992).

Following this initial period of deformation, the Late Ordovician-Early Silurian Benambran Orogeny, the Lachlan orogen was dominated by an extensional stress regime accompanying retreat of the Australian-Pacific Plate margin to the northeast (Glen, 1999). This resulted in the development of a series of volcano-sedimentary rifts forming throughout the LFB, including the Hill End and Cowra-Yass Troughs within the eastern belt (Fig 2.1). This period of deformation was also accompanied by extensive intrusion of granitoids into the upper crust, many of which include zones of intense ductile, high temperature deformation, suggesting that magmatism was at least partly synchronous with deformation (Patterson et al., 1990).

Within the eastern belt of the LFB, the dominant fabric is the result of mid-Devonian deformation along a conjugate strike-slip fault system. This deformation event is known as the Tabberabberan Orogeny and resulted in significant E-W shortening (Powell 1984), with the reactivation of existing regional structures (e.g. Copperhannia Fault) (Fig 2.3). These structures were again reactivated during closure of the Hill End trough during the Early Carboniferous Kanimblan Orogeny, resulting in a further episode of thrusting along the Copperhannia and Godolphin fault systems (Graham, 1998) (Fig 2.3).
Figure 2.1 Regional map showing the distribution of Ordovician and younger lithotectonic units within the Lachlan Orogen. The relationships between the Ordovician volcanic belts of central western NSW are shown in Fig. 2.2 over the area highlighted in pink. Modified from Glen and Wyborn, (1997) & Glen et al (1998).
2.2 Ordovician Volcanic Belts of Central Western NSW

Four outcropping volcano-intrusive belts of Ordovician volcanics form an extensive lithotectonic association within the eastern belt of the LFB (Fig 2.1).

The three main belts of this association occur in central western NSW where they are dominated by Ordovician to Early Silurian volcanics, subvolcanic intrusives and minor volcaniclastic rocks separated by Early to Late Silurian rift basins comprising granites and felsic volcanics (Glen et al., 1998) (Fig 2.2). The fourth belt (Kiandra Belt) occurs as a long narrow belt extending south into Victoria and consists of a similar assemblage of rocks to the northern belts (Meffre and Scott, 1999).

The main belts of central western NSW are from west to east, the Junee-Narromine Volcanic Belt (JNVB), the Molong Volcanic Belt (MVB) and the Rockley-Gulgong Volcanic Belt (RGVB) (Fig 2.2). The origin of these three belts remains controversial, however, one hypothesis proposed by Glen et al., 1998 is that the prolonged period of extension following the Benambran Orogeny resulted in the dismembering of a single Ordovician arc and arc apron system (Macquarie arc). This period of extension formed the mid-Silurian to Early Devonian Cowra and Hill End troughs, which separate the Ordovician belts in this region of the LFB (Fig 2.2). This theory infers the presence of Ordovician volcanics at depth beneath these troughs and will be discussed further with the tectonic implications of this study in Chapter 7.

The volcanics of the Ordovician belts dominantly have a shoshonitic to high-K calc-alkaline chemistry, although medium-K calc-alkaline to low-K calc-alkaline compositions have also been described (Glen et al., 1998). The shoshonitic volcanic centres are mostly Late Ordovician in age with low to high K calc-alkaline volcanic rocks ranging from Early to Late Ordovician (Glen et al., 1998). Major Late Ordovician centres have been interpreted to be concentrated along two main WNW trending structural zones in the belts known as the Lachlan transverse zone (LTZ) and the Hunter River transverse zone (HRTZ) (Fig 2.2). Glen and Walshe (1999) suggest that these zones may have had a major long lived control on the distribution of the Ordovician shoshonitic volcanism. The significance of these structures will also be considered further in Chapter 7.
The central MVB is the focus for this study and lies between the other two main belts in central western NSW, separated from the JNVB to the west by the Cowra trough and the RGVB to the east by the Hill End trough. It comprises a ~200 km long, narrow belt of Ordovician lavas, intrusives, volcaniclastics and occasional limestone bodies extending from Dubbo to ~50 km south of Orange (Fig 2.1 & 2.2).

Figure 2.2 Showing the location of the Molong belt with respect to the other two main Ordovician volcanic belts of central NSW. The red highlighted area corresponds to Fig. 2.3, a district map of the study area. Modified from Glen et al (1998).
2.3 District Geology

The project field area lies in the southern portion of the MVB located ~35 km south of Orange in central western NSW (Fig 2.2). It encompasses a 45km² region directly north from the Browns Creek Au-Cu skarn deposit (Hargraves Resources NL), approximately 8km west of the township of Blayney (Fig 2.3).

The Blayney district is dominated by rocks of the Late Ordovician to Early Silurian Cabonne Group, which are the oldest rocks in the area and comprise a package of mafic volcanics and volcaniclastics intercalated with occasional limestone horizons.

The Blayney Volcanics is the most extensive formation within the Cabonne Group. It comprises a Late Ordovician sequence of basaltic lavas and volcaniclastics covering an estimated area of 200km² (Fig 2.3). Henderson (1991) documented a limestone facies within the sequence, known as the Cowriga Limestone Member, which he places in the upper portion of the Blayney Volcanics. Other interpretations have placed it towards the base of the Blayney Volcanics package (Taylor, 1983). The Blayney Volcanics is considered by many to represent the oldest Ordovician volcanic package in the district. Henderson (1991) recognised the presence of pyroxene basaltic sills documented from the Late Ordovician Coombing Formation south of Blayney (Fig 2.3). He suggests that these have similarities to the pyroxene basalts ubiquitous throughout the Blayney Volcanics and interprets the Blayney Volcanics as underlying or interfingering with the Coombing Formation. This interpretation along with that of Wyborn (1992) supports an older age for the Blayney Volcanics with respect to the other Ordovician lithologies in the area.

Another Late Ordovician formation within the Cabonne Group dominated by mafic volcanics and volcaniclastics is the Byng Volcanics (Pogson and Watkins, 1998). These occur in NNW trending lenses southeast of Orange and show a close spatial relationship with unusual ultramafic lavas also considered to be Ordovician in age. These lithologies appear to be controlled by a set of regional north-northwest trending, easterly dipping structures related to the dominant regional fault array (Fig 2.3). These structures are likely related to the Godolphin Fault system, which itself forms a composite portion of a
duplex/imbricate thrust system, marking the eastern extent of Ordovician strata and the western boundary of the Hill End Trough (Glen and Watkins, 1994).

Perhaps the most prospective package of rocks in the Blayney district is the Forest Reefs Volcanics. This formation extends northwest from Carcoar covering an estimated area of 100km² and hosts a number of significant mineral occurrences, including the Cadia Hill, Cadia Ridgeway and Ferndale Cu-Au deposits (Fig 2.3). It is inferred to be the latest Ordovician package, from superposition relationships with the underlying Weemalla Formation, and also from isotopically dated comagmatic intrusives (Pogson and Watkins, 1998). The internal structure and facies relationships of the Forest Reefs Volcanics is not well understood, however it comprises a sequence of andesitic lavas, volcanic conglomerates and occasional limestone horizons, which are intruded by extensive comagmatic intrusives. These include diorites, monzonites and syenites and are often closely associated with porphyry style Cu-Au mineralisation, such as the Cadia and Ridgeway deposits.

Underlying the main Forest Reefs Volcanics is a volcaniclastic siltstone dominated association known as the Weemalla Formation. Enclosed within the Weemalla Formation is an interval of pillow basalt lava flows represented by the Mt Pleasant Basalt Member. The eastern extent of the Forest Reefs Volcanics and underlying Weemalla Formation is currently thought to be marked by a major regional structure known as the Carcoar Fault. This structure can be clearly seen on aeromagnetic data where it frequently changes orientation along its length, possibly as a result of deformation from late oblique structures. This structure also marks the western extent of the Late Silurian Carcoar Granodiorite in the Blayney district (Fig 2.3).

Other Silurian lithologies in the area include the felsic volcanics, sediments and occasional limestones of the Wombiana Trough (Fig 2.3), a rifted north-northwest trending basin parallelling the Godolphin Fault system and underlying the Blayney township.

Finally, the youngest rocks in the Blayney district are the Tertiary (Mid to Late Miocene) basaltic lavas and trachytic intrusives associated with the Canobolas Volcanic Complex.
located ~10 km southwest of Orange. These unconformably overly much of the Ordovician stratigraphy to the north of Blayney (Fig. 2.3).

Figure 2.3 Simplified geological map of the Blayney district, highlighting main lithologies and structures. Geological boundaries from AGSO (Pogson, 1998).
Chapter 3: Geophysics and Structure

3.1 Introduction

Analysis of aeromagnetic data proved a very useful technique when combined with surface mapping and geochemical sampling to both determine the distribution of the key Ordovician units and constrain structural interpretations within the study area.

3.2 Structural Overview

3.2.1 Regional Geophysical Interpretation

A preliminary interpretation of geophysical data was conducted based on previous regional mapping and a variety of geophysical images.

Radiometric data proved useful in the preliminary mapping stage for constraining outcrop distribution, especially considering the potassium band, which reflects the potassic nature of the Ordovician volcanics. The most useful geophysical responses allowing delineation of the key units, is seen in variations of magnetic susceptibility as a result of the relative abundance of primary titanomagnetite and magnetite in the units (Chapter 5).

The aeromagnetic data has been analysed using a variety of filtering techniques to highlight specific elements of the dataset. However, for the purposes of this discussion a colour scale total magnetic intensity (TMI) image adequately highlights the relevant features (Fig. 3.1). Perhaps the most obvious magnetic features in the study area coincide with regions mapped as Byng Volcanics. These are characterised by high amplitude anomalies, which occur in elongate NNW trending zones (Fig. 3.1). From the aeromagnetics these units appear to be more extensive than previously mapped and can be subdivided into three outcropping regions; the Byng Volcanics eastern, central and western areas (Fig. 3.1).

A zone with similar magnetic character to the Byng Volcanics occurs in the west of the study area overlain by extensive Tertiary basalt and probably represents an extension of the Forest Reefs Volcanics located immediately to the west (GR: 700000mE 6290000mN). The Forest Reefs Volcanics in the study area occur in a broad region characterised by a...
strong magnetic response and appear to be truncated to the east by a NNW trending lineament (Fig. 3.1).

Between the NNW trending zones of Byng Volcanics and Forest Reefs Volcanics are widespread regions, characterised by a low magnetic response. These mark the extent of Blayney Volcanics which have subsequently been subdivided into two main regions; the Blayney Volcanics eastern and western areas (Fig. 3.1).

A north trending zone of low magnetisation passing through the study area disrupts the obvious NNW trending fabric and is interpreted to represent the northern continuation of a major regional fault, known as the Carcoar Fault. The Carcoar Fault can be clearly seen on the aeromagnetics passing through the Browns Creek Mine area (Fig. 3.1).

The presence of ENE trending faults is also suggested from the aeromagnetics, these structures appear as a series of lineaments which truncate the NNW fault system at several locations (e.g. Site 444: 702740mE 628961mN).

3.2.2 Structural Field Mapping

The aeromagnetic interpretation outlined in the previous section has been used in conjunction with surface mapping in order to identify the geometry of the main structural elements within the study area. The majority of the structural observations were made in the northern extents of the area (Fig. 3.1) due to the concentration of outcrop in this region (Appendix 4). However, this discussion also incorporates pre-existing data into a structural overview, including unpublished work undertaken by Scott (1999) for the SPIRT program, in the area directly surrounding Browns Creek Mine.

3.2.2.1 Faulting

The identification of the NNW trending boundaries separating the key Ordovician units was hampered due to poor outcrop in critical areas; however, a similarly oriented spaced fabric was commonly mapped close to the inferred contacts (e.g. Site 93: 6291527mE 698964mN). Cooper and Gernett (1996) also reported the presence of a set of NNW trending faults complicating the structure at the Browns Creek Mine and therefore faulted contacts between the key Ordovician units in the study area is suggested.
The dominant structural feature observed from the magnetics and surface mapping is a northerly trending ‘structural corridor’ (Fig. 3.1) characterised by the development of an intense subvertical, to steeply east dipping, spaced cleavage (Fig. 3.2a). The corridor can be correlated with a high strain zone directly north of Browns Creek, known as the “Eastern Shear Zone” (Cooper and Gernett, 1996). A major north-trending fault, mapped in the Forest Reefs Volcanics, has a similar orientation to this intense fabric. The fault is well exposed in the Bunyar Quarry (Site 102: 699169mE 6291033mN) where it is defined by a narrow region (5 m) of fault gouge separating volcaniclastic siltstone from chlorite-altered mafic volcanics (Fig. 3.2b). A stretching lineation is also observed within the ‘structural corridor’, especially south of Matthews Lane (701284mE 6290110mN), suggesting dominantly dip-slip movement on these fabric surfaces.

In many areas the ENE structures inferred from the aeromagnetics are marked by zones of massive quartz veining, up to 5 m across (Fig. 3.2c). These structures appear to represent late brittle faults with an apparent dextral sense of movement as indicated by offset of the “Eastern Shear Zone” immediately north of Browns Creek Mine (Scott, 1999). From the aeromagnetic and structural interpretations this area immediately surrounding Browns Creek Mine is interpreted to be a major convergence zone. Where the intersection of the Carcoar Fault and the NNW and ENE fault systems is marked by a zone of very low magnetism, perhaps the result of demagnetisation of the host rock due to high fluid flow.

3.2.2.2 Folding

Folding is rarely observed in the study area, and was only noted at a few locations. The best examples occur in the Bunyar quarries where upright open to tight asymmetric parasitic folds (wavelength ~1 m), have axial planes dipping moderately to the east and generally plunge gently to the south-south east. These folds appear to have been affected by later events, causing beds to pinch out laterally and fold plunges to vary (Fig. 3.3a). In the aeromagnetics this region corresponds to an area of structural complexity, marking the intersection of the north-trending structural corridor and an inferred NNW trending fault (Fig. 3.1). Similar folds to those at the Bunyar Quarries are present along Bunyar Creek (Site 99: 699365mE 6291253mN) (Fig. 3.4) and also in the Kingham Quarry (Site 256: 699762mE 6293285mN) (Fig. 3.5). The cleavage observed at these locations has a similar spacing, morphology, and orientation to the dominant fault-related fabric observed throughout much of the study area. As a result, overprinting relationships constraining...
their relative ages could not be determined and the S\textsubscript{1} cleavage mapped in areas of folding most likely reflects a composite fabric related to multiple deformations.

3.3 Discussion

The main NNW fabric defining the boundaries of the Blayney and Byng Volcanics and marking the eastern extent of the FRV is interpreted to represent a regional fault array. Repetition of the volcanic packages, combined with a dominance of dip-slip movement recorded within the study area, suggest that the packages were assembled along thrust surfaces, likely to be easterly dipping from the westward verging character of the asymmetric folding.

The thrust interpretation is consistent with a northwest trending easterly dipping duplex/imbricate thrust system reported by Glen and Watkins (1994) 8 km to the east of the study area (Chapter 2). Thrust style faulting is also documented elsewhere within the eastern region of the LFB. For example Glen and Wyborn (1997) have demonstrated that the interleaving of lithological units in the region south of the Molong volcanic belt, within the Early Ordovician turbidites could be explained by this mechanism.

The exact age of deformations within the study area cannot be determined conclusively, however, some inferences can be made from the geophysical and structural features described. Within the study area the thrusting event appears to be mostly Early Devonian or older as these structures are truncated by the Early Devonian Carcoar Granodiorite.

The consistent north trending fabric and faulting correlated with the Carcoar Fault appears to disrupt the slices of highly magnetic Byng Volcanics bound by the interpreted NNW fault array, implying that this deformation event postdated the thrust related ‘stacking’ of the blocks into their current positions. A further feature of the Carcoar Fault is that it marks the western extent of the Carcoar Granodiorite, suggesting that it may have controlled its emplacement during the Late Silurian-Early Devonian.

The aeromagnetic and structural interpretation has identified a series of main outcropping regions of the key Ordovician units; the Blayney Volcanics, Byng Volcanics and the Forest Reefs Volcanics. Volcanic facies and geochemical data presented in subsequent chapters further constrain the distribution of these units.
Figure 3.1 Structural/aeromagnetic interpretation showing the locations of inferred structures based on aeromagnetics and surface mapping.

Regional aeromagnetic and radiometric data was obtained from Hargraves Resources NL to assist in geological and structural mapping. The geophysical survey was flown by Geoterrex for the NSW mines Department and AGSO, in 1992. It was acquired with east-west flight lines at a line spacing of 250m. The terrain clearance was 80m with a tie line spacing of 5 kilometres. A combination of GPS and Cyledis systems was used for positioning. The magnetometer used was a Scintrex Caesium Vapour stinger mounted system with a 0.2 sec sample interval.
Fig. 3.2 a) Blayney Volcanics, showing typical intense subvertical to steeply-E dipping anastomosing fabric associated with the Carcoar Fault (Site 190: 700594mE 6291769mN).

b) Northerly trending fault, marked by a ~5 m zone of fault gouge separating volcaniclastic siltstone from chloritised mafic volcanics of the Forest Reefs Volcanics, (Site 102: 699169mE 6291033mN).

c) Massive quartz veining, marking the location of late stage ENE trending faults. (Site 3: 702316mE 6290590mN).
Fig. 3.3 a) Volcaniclastic siltstone, with individual beds pinching out laterally. Note the variation in fold plunge (Site 102: 699169mE 6291033mN).
b) Volcaniclastic siltstone, showing asymmetric folding of siltstone and mudstone layers (Site 256: 699762mE 6293285mN).
c) Volcaniclastic siltstone, showing intensely deformed zone truncating volcaniclastic siltstone and siliceous mudstone layers. (Site 256: 699762mE 6293285mN).
Figure 3.5 Kingham Quarry Form Surface Map showing the distribution of fabrics with an inferred antiformal closure (Site 256: 699762mE 6293285mN)
Chapter 4: Lithostratigraphy/Volcanic Facies Architecture of the Key Ordovician Units

4.1 Introduction

Three key Ordovician units are present in the Blayney district. These are the Blayney Volcanics (BLV), which is the most widespread unit within the Cabonne Group and is considered to represent the oldest rocks in the district, underlying or interfingering with the Late Ordovician Coombing Formation. The BLV are separated from the second most extensive key unit, the Forest Reefs Volcanics (FRV), by a volcaniclastic-dominated transition known as the Weemalla Formation (Pogson and Watkins, 1998). The third key unit is the Byng Volcanics (BYV), which in the Blayney district is restricted to areas controlled by the major NNW regional fault system. The age relationships of the BYV are poorly constrained due to lack of exposed contacts with the other key units, however in the area surrounding Orange it is considered to be younger than the BLV (Pogson and Watkins, 1998).

This section describes and interprets the volcanic facies present within the key units in the study area to develop a volcanic facies architecture for the key Ordovician units. This architecture will later be used in conjunction with the geochemistry (Chapter 6) to constrain the distribution and also to investigate possible correlations between these key units. The petrographic character of the lithofacies is mentioned in the following descriptions; however, it is described in more detail, in conjunction with the mineral chemistry, in the following chapter.

4.2 Volcanic Facies and Facies Associations

4.2.1 Blayney Volcanics (BLV)

The Blayney Volcanics (BLV) is the main lithostratigraphic unit in the study area. The aeromagnetic interpretation outlined in the previous chapter indicates that it occurs within two main regions; the BLV western and central areas, each of which is separated by fault bounded areas of BYV or FRV (Fig. 4.1).
The sequence consists of a series of compositionally similar units of interstratified dark green porphyritic basaltic lavas with subordinate dolerite intrusions. Volcaniclastic units within the package are rare, elsewhere being restricted to areas near the contact with the underlying Coombing Formation (Pogson and Watkins, 1998).

**4.2.1.1 Principal Lithofacies**

Despite the compositional homogeneity of units within the BLV it is possible to identify three principal lithofacies based on the texture and structures present. These are considered collectively within a basalt lava-dominated association and include the following principal lithofacies:

**Facies A: Clinopyroxene-phyric massive basalt**

**Description**

This lithofacies occurs intercalated with the other facies types throughout the study area; however the best exposures occur in the eastern BLV, along the western ridge, parallel to the Orange Road (Site 329: 702693mE 6293378mN) (Fig. 4.1). The facies typically consists of 2-10 m-thick layers of coherent basalt showing little internal structure. The boundary relationships between these units and the surrounding ones are difficult to constrain due to paucity of outcrop. However the units are commonly overlain by a 1-2 m interval of clast-supported monomictic breccia with a diagnostic silty matrix (Facies B1). Individual units within this lithofacies commonly have a massive tabular geometry. However, elsewhere within the BLV a pillow basalt facies with a similar composition to these massive units has also been observed (Pogson and Watkins, 1998) (Fig. 4.2a) (GR 712700mE 6286000mN). The basalt is strongly porphyritic dominated by augite with lesser olivine and plagioclase phenocrysts.

**Emplacement Processes**

The massive, non-stratified nature of this lithofacies combined with the strongly porphyritic composition suggests an effusive lava or shallow sill origin, with the absence of peperitic style contacts with the surrounding units favouring an effusive lava origin. The massive, tabular morphology of these units is likely to be largely the result of high discharge rates controlled by the low viscosity of the basaltic magma composition. The
presence of pillowed lava elsewhere within the BLV sequence provides good evidence for subaqueous emplacement for the lavas.

**Facies B: Clast-supported monomictic basaltic breccia**

*Description*

This lithofacies is the most widespread within the BLV in the study area. Good exposures occur along the southern portion of the western ridge in the eastern BLV area, parallel to the Orange Road (Site 436: 705170mE 6290413mN) (Fig. 4.1). This lithofacies is spatially associated with the coherent lavas (Facies A), occurring on their upper and marginal contacts. The breccia consists of a monomictic population of subangular clasts, which have a maximum clast size of ~30cm (Fig. 4.2b). The clasts consist of clinopyroxene-phyric basalt, similar in composition and texture to that described from the coherent lava facies, separated by a fine cpx-rich granular matrix (Fig. 4.2b).

*Subfacies B 1: Clast-supported silty monomictic basaltic breccia*

*Description*

A distinct subfacies occurs within the clast-supported monomictic breccia lithofacies described above. This subfacies occurs in layers up to 5 m thick directly overlying units of the massive lava facies (Facies A). The most diagnostic feature of this subfacies is a matrix composed of silt-sized crystals and crystal fragments. The matrix between the closely-packed subangular basalt clasts typically shows well preserved sedimentary structures, including planar delicate laminations and normal grading (Fig. 4.2c, & 4.2d).

*Emplacement Processes*

The close spatial association of this lithofacies with the massive lava units suggest that the two are genetically related. This facies may therefore represent flow-top and flow-front breccia generated by autobrecciation of moving lava. The cpx-rich granular matrix typical for this lithofacies is most likely the product of mechanical attrition of adjacent clasts during flowage. A conspicuous lack of quench textures, such as glassy clast rims and jigsaw fit textures suggests that interaction of hot lava with seawater was not a major fragmentation process in the formation of these extensive breccia units. However, in a submarine environment, as is interpreted for the massive lava units (Facies A), both quenching and autobrecciation fragmentation processes are likely to be closely linked.
The well developed grading and delicate lamination of the matrix suggests that sediment settled from suspension into the polygonal gaps between the clasts following brecciation.

**Facies C: Clinopyroxene-phyric dolerite**

**Description**

This facies is restricted to an area within the western BLV region of the study area. It occurs at the intersection of Bunyar and Cowriga Creeks (Fig. 4.1), which lies within a northerly trending zone of intense deformation passing through the study area, known as the Carcoar Fault (Chapter 3). The facies is well exposed in an area 20 m across within and on the banks of Cowriga Creek (Site 134: 700337mE 6291357mN) where it appears to have an evenly spaced parallel planar joint set (Fig. 4.3a). In one location a possible chilled selvage defined by a planar fabric suggests a conformable contact with the overlying lava units, alternatively, this may just reflect the intense fabric development prominent in the area. The dolerite is a medium grained, holocrystalline rock dominated by augite, with lesser plagioclase crystals.

**Emplacement Processes**

The distinctly equigranular, holocrystalline texture of this facies suggests the dolerite represents a shallow intrusion, possibly a sill, although this interpretation is tentative as no obvious field relationships were observed.

**4.2.2 Byng Volcanics (BYV)**

The Byng Volcanics (BYV) occur in three outcropping regions within the study area. As defined by the aeromagnetic interpretation these are the BYV eastern area located immediately east of the Blayney-Orange Road, the BYV central area, passing north from the old ‘Limestone’ homestead, and the BYV western area trending NNW on the ridge just east of the Matthews Lane/Cowriga Creek crossing (Fig. 4.1). Each of these regions have faulted boundaries with the more expansive areas of BLV.

**4.2.2.1 Principal Lithofacies**

The principal lithofacies in the BYV are grouped into a limestone facies association, which comprises the following principal facies:
Facies D: Clast-supported polymictic conglomerate

Description

This lithofacies is widespread throughout the BYV in the study area. The best exposures are located on the eastern ridge parallel to the Orange Road within the BYV eastern area (Site 341: 704273mE 6293554mN) (see Fig. 4.1). This facies comprises a massive, poorly sorted, polymictic, clast-rich conglomerate (Fig. 4.3b). The clast population includes siltstone, several mafic to intermediate volcanic clast types, minor diorite and rare fossiliferous limestone clasts (Fig. 4.3c). The siltstone clasts are generally small, up to 10 cm across and commonly subrounded. The volcanic clasts in contrast, vary from 5 cm up to 40 cm and are generally subrounded; however they also show localised areas of subangular clasts with jig-saw fit textures. The volcanic clasts are strongly porphyritic, dominated by augite and plagioclase phenocrysts. The matrix separating the clasts is crystal rich, dominated by detrital ~ 1 mm clinopyroxene and plagioclase crystals and has no internal sedimentary structures.

Emplacement Processes

Deposition of this lithofacies most likely involved mass flow processes. The limestone clasts have important implications for the volcanic setting. Their occasional fossiliferous nature indicates that these deposits have originated in relatively shallow submarine conditions on the flanks of a volcanic edifice, at least within the photic zone. The subrounded nature of most of the clasts within the conglomerate suggests that there may have been temporary storage and some reworking prior to the final transport event. The localised areas of jig-saw fit textures within the volcanic clasts most likely represent clasts that were entrained cold with prepared fractures that progressively opened during transport. This is supported by the lack of chilled margins and of an indurated intervening matrix. The concentration of the clasts and the crystal rich matrix suggests the involvement of a high-concentration particulate suspension with clasts being supported by grain/clast interactions causing dispersive pressure within a flow. Combined with the lack of any stratification and traction sedimentary structures, this possibly indicates that bed-load rolling was a dominant emplacement process involved in the deposition of this facies.

The features described are consistent with a model proposed by Walker (1975). His 'disorganised bed model' involves coarse-grained conglomerates and suggests rapid deposition on relatively steep slopes. Therefore, this facies is interpreted to represent...
proximal apron deposits on the flank of a shoaling, subaqueous, basaltic andesite volcanic centre.

**Facies E: Clinopyroxene+plagioclase phryic massive andesite**

*Description*

This lithofacies occurs in isolated outcrops in the northern extents of the BYV western area, within the intense zone of deformation related to the Carcoar Fault (Chapter 3) and also near the ‘Old Limestone Homestead’. It consists of a massive unit or units with a total thickness of 5-10 m. The composition of the andesite is similar to the volcanic clasts documented from the polymict conglomerate facies (Facies D). It consists of a strongly porphyritic texture, dominated by augite and plagioclase phenocrysts.

*Emplacement Processes*

The lack of contact relationships with other facies makes any genetic interpretations for this facies tenuous. However, the mapped association with the BYV may suggest that this massive basalt lithofacies represents larger blocks associated with the polymict conglomerate facies. Alternatively this facies may be an isolated discrete lava unit/units representing a possible source of clasts for the polymict conglomerate facies (Facies D).

**Facies F: Interbedded crystal-rich volcanioclastic siltstone**

*Description*

This facies is restricted to the BYV western area where it outcrops on the eastern bank of Limestone Creek (Site 163: 701947mE 6291796mN) (Fig. 4.1). Here it consists of interbedded tabular thinly bedded (5-10cm) layers of siltstone with no internal structure (Fig. 4.3d). It is composed of moderately sorted silt-sized particles of dominantly fresh clinopyroxene+plagioclase and hornblende phenocrysts together with lithic debris. Detrital clinopyroxene and plagioclase accounts for up to 60 modal% with hornblende, detrital opaques and lithic fragments comprising the remainder. Alignment of particles forming a foliation fabric is often observed highlighting cleavage planes, especially near high strain zones.
Subfacies F1: Interbedded volcanioclastic siltstone and siliceous mudstone

Description

This facies is mostly located in the northern extent of the BYV western area. The best outcrops occur within and surrounding the Kingham Quarry (Site 256: 699762mE 6293285mN) (Fig. 4.1). It consists of interbedded fine feldspathic siltstone of similar composition as the interbedded siltstone described above (Facies E) with occasional diagnostic siliceous mudstone layers (Chapter 3, Fig. 3.3b). Siltstone beds are the most common and occur as tabular thin (5-10 cm) layers with sharply defined planar bases, and are generally laterally continuous with an even thickness except proximal to high strain zones, such as in the Kingham Quarry where the beds typically pinch out. The mudstone interbeds are subordinate compared to the siltstone layers; they occur as single massive tabular beds (0.5-1 m) with planar conformable contacts. Normal grading is occasionally observed within the siltstone layers and the mudstone layers are internally massive.

Emplacement Processes

The tabular massive, sometimes normal graded, nature of this subfacies combined with an absence of traction current bedforms suggest deposition from low-density turbidity currents (Lowe, 1982). This interpretation implies that the depositional environment was sub wave base with the lack of development of the classical Bouma turbidite divisions possibly indicating rapid deposition; however, this could also reflect a high particle supply.

Facies G: Massive recrystallised limestone

Description

This lithofacies is known as the Cowriga Limestone Member and hosts Au-Cu mineralisation at Browns Creek. Near the mine Cooper and Gernett (1996) have interpreted it to be a conformable horizon towards the top of the BLV package. Further north, in the study area, this facies is mapped within the central and western BYV where it occurs as laterally discontinuous lenses along the Cowriga and Limestone Creeks (Fig. 4.1 & 4.4a). An outcrop is also present at the Matthews Lane/Cowriga Creek crossing which shows a spatial association with the mapped extent of FRV (Site 461: 701068mE 6290054mN). The lenses are typically around 20 m across and appear to be overlain by
units of the clast-supported polymictic conglomerate facies (Facies D). Contact relationships are not exposed, however field observations suggest the limestone lenses are conformably dipping to the east. The lenses typically appear to be intensely recrystallised, with some relicts of fine layering, (possibly bedding), and isolated zones of calc-silicate mineral development.

**Emplacement Processes**

These massive limestone lenses are most likely the source for the fossiliferous limestone clasts present in the overlying conglomerate facies (Facies D) and hence are interpreted to be the result of carbonate accumulation in a shallow (photic zone), low energy subaqueous environment. The laterally discontinuous nature of the lenses combined with the mass flow emplacement processes interpreted for the overlying coarse conglomerates, suggests that the limestones may represent large allochthonous blocks, which have been resedimented through genetically similar mass flow processes or possibly by slumping.

### 4.2.3 Forest Reefs Volcanics (FRV)

The Forest Reefs Volcanics (FRV) include lavas, volcaniclastic sediments and shallow intrusions occurring in a broad NNW trending zone in the far western extent of the study area. The eastern boundary of this region is interpreted to be marked by a NNW trending fault (Chapter 3, Fig. 3.2b). Several additions have been made to the current mapped distribution of FRV in the area, based on the facies mapping and diagnostic mineral and wholerock geochemical evidence presented in the following chapters (Chapter 5 & 6).

#### 4.2.3.1 Principal Lithofacies

The FRV within the study area contain two key facies associations. These are a lava-dominated association restricted to the area immediately north of the Browns Creek Mine and a volcaniclastic siltstone-dominated association. The former consists of the following principal lithofacies:
Facies H: Clinopyroxene, plagioclase-phyric massive andesite

**Description**

This facies type is common throughout the FRV in the study area. It consists of massive, coherent units with little internal structure. This facies is compositionally similar to the clinopyroxene+plagioclase-phyric massive andesite facies identified for the BYV.

**Emplacement Processes**

The massive, non-stratified nature of this lithofacies suggests an effusive lava or shallow sill origin. The absence of peperitic style contacts with the surrounding units and the evenly porphyritic texture of this facies (Chapter 5) would favour the effusive lava origin. This interpretation is also supported by the massive, tabular nature of the units, which may reflect high discharge rates in a vent proximal volcanic setting.

Facies I: Hornblende+clinopyroxene+plagioclase-phyric massive andesite

**Description**

This lithofacies is the least common within the FRV within the study area. Examples occur in the area directly north from Browns Creek Mine surrounded by massive andesite lava units (Facies H). In addition, a minor outcrop was also mapped close to an inferred NNW trending fault separating the eastern BLV and eastern BYV (Site 335: 703727mE 6294261mN) (Fig. 4.1) (Fig. 4.4b). No contact relationships with the surrounding units are exposed. Elsewhere in the Blayney district similar examples have been observed crosscutting the stratigraphy (Pogson and Watkins, 1998).

**Emplacement Processes**

The origin of this distinctive lithofacies is far from certain, because of its limited extent and lack of exposed contact relationships with the surrounding units, however, an evenly porphyritic texture and moderate grain size (Chapter 5) are consistent with either a lava or shallow intrusion origin. The presence of the facies within both the FRV and the BLV eastern zone combined with the crosscutting relationships observed elsewhere (Pogson and Watkins, 1998) support a late stage intrusive origin for this lithofacies.
Facies J: Clinopyroxene+plagioclase-phyric massive monzonite (Tallwood Monzonite)

Description

The Tallwood Monzonite is located in the far western region of the study area. It occurs as a poorly outcropping facies within the FRV package, overlain by the extensive Tertiary basalt coverage in this region of the study area. It consists of a holocrystalline, equigranular rock dominated by augite, plagioclase and lesser hornblende and quartz. Representative surface sampling suggests a heterogenous body varying from diorite, quartz diorite, monzonite to monzodiorite compositions (Chapter 5) (Fig. 4.4c).

Emplacement Processes

Due to the lack of exposure, no contact relationships were observed and therefore much of the interpretation is based on petrographic observations (Chapter 5). The distinctly equigranular, holocrystalline texture of this facies suggests a shallow intrusion origin. The variation in composition probably reflects a polyphase intrusive history with the presence of several intrusions making up the Tallwood Monzonite.

In contrast to the lava-dominated facies association described above, a volcaniclastic-dominated association appears to be common in the northern extents of the FRV and contains the following principal lithofacies:

Facies K: Interbedded crystal-rich volcaniclastic siltstone

Description

This facies is widespread throughout the FRV in the study area. The best outcrops occur within and along the Bunyar Creek (Fig. 4.1). It consists of thin tabular layers of interbedded fine feldspathic siltstone. Individual siltstone beds are thin (5-10 cm) layers with sharply defined planar bases and are laterally continuous with an even thickness except proximal to high strain zones, such as at the Bunyar Quarry where the beds typically pinch out (Site 102: 699169mE 6291033mN). Sedimentary structures other than bedding are rare, however, along Bunyar Creek occasional normal grading, load cast and scour features are observed (Site 101: 699494mE 6291301mN). The siltstone is composed of moderately sorted silt-sized particles of dominantly fresh clinopyroxene, plagioclase and hornblende phenocrysts together with lithic debris. Detrital clinopyroxene and plagioclase
accounts for up to 60 modal% with hornblende, detrital opaques and lithic fragments comprising the remainder.

**Emplacement Processes**

The tabular massive, sometimes normal graded, nature of this facies, combined with the absence of traction current bedforms suggest deposition from low-density turbidity currents (Lowe, 1982). This interpretation implies that the depositional environment was sub wave base with the lack of development of the classical Bouma turbidite divisions possibly indicating rapid deposition; however, this could also reflect a high particle supply.

**4.3 Discussion**

The recognition of facies associations provides a framework in which to compare the volcanic facies between the key Ordovician units. Consideration of the compositional, textural, and structural similarities between units as well as a comparison of their interpreted emplacement processes is required.

The basalt lava-dominated association of the BLV is a distinct widespread association unlike anything observed within the other key units. The additional presence of the dolerite facies (Facies C) in the BLV western area is illustrated in Fig. 4.5.

The limestone association of the BYV comprises similar facies to the volcaniclastic association of the FRV. This is perhaps best highlighted by the presence of limestone lenses in both packages. The similar compositional and textural character of the surrounding thinly interbedded crystal-rich siltstone lithofacies in both the BYV and FRV (Facies E & Facies K) suggest that they at least shared essentially the same provenance, sedimentation processes, and environment of deposition. This data, combined with the presence of discontinuous limestone lenses, indicates that they may represent stratigraphic equivalents.

Thus areas previously interpreted as BYV (Pogson and Watkins, 1998) may instead represent additional areas of FRV and that the limestone lenses previously mapped as the Cowriga Limestone Member within the BLV (Henderson, 1991), may represent limestones within the FRV.
Consistent with this proposed correlation is the presence of the distinct polymict conglomerate facies (Facies D) overlying the limestone lenses in the BYV central and western areas (Fig. 4.5 & 4.6). This facies comprises distinctly more fractionated lava and intrusive clasts than the lavas and intrusions observed in the BLV and lavas sampled outside the study area within the BYV. This suggests a more evolved source possibly represented by the more fractionated lavas and intrusions of the FRV.

4.4 Implications for Stratigraphic Correlation

A correlation between the mapped areas of BYV with FRV has been proposed. This correlation would suggest that the limestone facies association, in the BYV, may represent a stratigraphic equivalent to the limestones seen elsewhere within the FRV, for example, those found at Junction Reefs and Cadia (see Chapter 2, Fig. 2.3).

Within the Weemalla Formation, towards the base of the FRV, limestone is present along with volcaniclastic siltstones (Packham et al., In press). These siltstones are thinly bedded often with a distinctly hornblende rich composition similar to those observed within the limestone association recognised in the study area. In addition, several conglomerate horizons have also been reported from the Weemalla Formation. These contain andesite, basalt, shale, siltstone and limestone clasts in a lithic rich matrix (Pogson and Watkins, 1998); consistent with the composition of the polymict conglomerate facies (Facies D) mapped in the BYV within the study area.

A similar polymict conglomerate is also present overlying the limestones hosting the Browns Creek mineralisation. Here the Cowriga Limestone Member is hosted within a sequence of volcaniclastics with overlying polymict conglomerate containing rare limestone clasts with clinopyroxene-phyric basaltic clasts and plagioclase-phyric clast populations (Cooper and Gernett, 1996) (Fig. 4.6). Therefore, a possible correlate between the BYV limestone association within the study area and those within the Weemalla Formation may also apply for the limestones at Browns Creek.

Recently, palaeontological age-dating (Packham et al., In press) has constrained the timing of formation of limestones within the Weemalla Formation to the middle Late Ordovician (late Eastonian). The possible correlation with the limestone lenses of the Cowriga
Limestone Member implies that they are also middle Late Ordovician (late Eastonian) in age.

The facies relationships and associations defined from the key Ordovician units are almost certainly more complex than has been described due to factors such as lateral variations in emplacement processes. However, the facies associations and relationships discussed have highlighted the possibility of a number of stratigraphic correlations within the Ordovician volcanic sequence which will be constrained further by the incorporation of geochemical evidence (Chapter 6).
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| **Forest Reefs Volcanics (FRV)** |
| - Cpx+plag-phyric massive andesite (Facies H) |
| - Hbl+diop+plag-phyric massive andesite (Facies I) |
| - Cpx+plag-phyric massive monzonite (Facies J) |
| - Interbedded crystal-rich volcaniclastic siltstone (Facies K) |

| **Byng Volcanics (BYV)** |
| - Clast-supported polymictic conglomerate (Facies D) |
| - Cpx+plag. phyric massive andesite (Facies E) |
| - Interbedded crystal-rich volcaniclastic siltstone (Facies F) |
| - Interbedded volcaniclastic siltstone & siliceous mudstone (Facies F1) |
| - Massive recrystallised limestone (Facies G) |

Figure 4.1 Blayney study area - showing extent of key Ordovician units and facies distribution (Cited locations are marked)
Fig. 4.2 a) Blayney Volcanics Pillow rim with amygdaloidal edge (PBD 15: 712700mE 6286000mN)
b) Blayney Volcanics, monomictic breccia, showing the contact between two clasts, separated by a granular matrix (PBD 66: 700728mE 6290825mN)
c) Blayney Volcanics, monomictic breccia, showing the fine laminations within the silty matrix (PBD136/SITE 314: 702973mE 6292969mN)
d) Blayney Volcanics, monomictic breccia outcrop, showing the fine laminations within the silty matrix (SITE 403: 704002mE 6291186mN)
Fig. 4.3 a) Blayney Volcanics dolerite intrusive outcrop with planar joint set (Site 134: 700380mE 6291297mN)
b) Byng Volcanics, polymictic breccia, showing the clast rich nature of this facies, (PBD 158/SITE 411: 704944mE 6292606mN)
c) Byng Volcanics, polymictic breccia outcrop, showing rare limestone clasts (Site 47: 701663mE 6290770mN)
d) Byng Volcanics, volcaniclastic siltstone outcrop, (Site 13: 701807mE 6291601mN)
Fig. 4.4  

a) Byng Volcanics, massive limestone outcrop at the head of Limestone Creek (Site 169: 702117mE 6291971mN)

b) Hornblende-phyric late stage dyke sample, with occasional chalcopyrite veinlets (PBD143/SITE 335: 703727mE 6294261mN)

c) Tallwood Monzonite sample showing two distinct compositional zones, reflecting its polyphase intrusive character (PBD 181: 696694mE 6291991mN)
Figure 4.5 Simplified stratigraphic logs for the key Ordovician units, showing the lava-dominated facies association of the BLV and the limestone facies association within the BYV central area. Facies A - Cpx-phyric massive basalt, Facies B - Clast-supported monomictic basaltic bx, Subfacies B1 - Clast-supported silty monomictic bx, Facies C - Cpx-phyric dolerite, Facies D - Clast-supported polymictic conglomerate, Facies E - Cpx+plag-phyric massive andesite, Facies F - Interbedded crystal-rich volcaniclastic siltstone, Facies G - Massive recrystallised limestone.
Figure 4.6 Simplified stratigraphic log of the BYV western area. Facies A - Clinopyroxene massive basalt.

Facies B - Clinopyroxene phryic basalt, trachytic texture and autobrecciated, probably subaerial.

Facies C - Clinopyroxene phenocryst-bearing gneisses.

Facies D - Clinopyroxene trough conglomerate, subaerial.

Facies E - Clinopyroxene phenocryst-bearing gneisses, subaerial.

Facies F - Clinopyroxene andesite, subaerial.

Facies G - Clinopyroxene andesite, subaerial.

Coarse pyroclastic clinopyroxene phryic basalt:

Facies H - Clinopyroxene phryic basalt, subaerial.

Facies I - Clinopyroxene phryic basalt, subaerial.

Facies J - Clinopyroxene phryic basalt, subaerial.

Facies K - Clinopyroxene phryic basalt, subaerial.

Facies L - Clinopyroxene phryic basalt, subaerial.

Facies M - Clinopyroxene phryic basalt, subaerial.

Facies N - Clinopyroxene phryic basalt, subaerial.

Facies O - Clinopyroxene phryic basalt, subaerial.

Facies P - Clinopyroxene phryic basalt, subaerial.

Facies Q - Clinopyroxene phryic basalt, subaerial.

Facies R - Clinopyroxene phryic basalt, subaerial.

Facies S - Clinopyroxene phryic basalt, subaerial.

Facies T - Clinopyroxene phryic basalt, subaerial.

Facies U - Clinopyroxene phryic basalt, subaerial.

Facies V - Clinopyroxene phryic basalt, subaerial.

Facies W - Clinopyroxene phryic basalt, subaerial.

Facies X - Clinopyroxene phryic basalt, subaerial.

Facies Y - Clinopyroxene phryic basalt, subaerial.

Facies Z - Clinopyroxene phryic basalt, subaerial.

Massive and well laminated clinopyroxene andesite, recrystallized to coarse-grained marble.

Lower contact not encountered but unit considered to be 150-200 m thick.
Chapter 5: Petrography and Mineral Chemistry of the Key Ordovician Units

5.1 Introduction

This chapter discusses the petrographical and mineral chemistry characteristics of the key Ordovician units in the study area; the Blayney Volcanics, Byng Volcanics and the Forest Reefs Volcanics. Phenocrystal clinopyroxene and Cr-spinel compositions were analysed using the Cameca electron microprobe (SX50) facilities at the Central Science Laboratory (CSL), University of Tasmania (Appendix 2).

5.2 Petrography of the Key Units

5.2.1 Blayney Volcanics (BLV)

The Blayney Volcanics consist of a lava-dominated sequence of strongly porphyritic augite+plagioclase+chromite-phyric basaltic lavas with subordinate more mafic lavas with occasional altered former olivine phenocrysts. The lavas have previously been described in chapter 4 as massive tabular flows (Facies A) closely associated with extensive clast-supported breccias (Facies B). They are occasionally vesicular and have experienced prehnite-pumpellyite grade regional metamorphism.

Euhedral augite phenocrysts (>20modal%) dominate the phenocryst assemblage (Fig. 5.1a). These are zoned, clear to pale green crystals, typically occurring as individual 2-5 mm phenocrysts, occasionally up to 10 mm long or as large glomeroporphyritic aggregates. Lesser plagioclase phenocrysts (<5modal%) are subhedral and are typically replaced by very fine-grained albite, sericite and/or granular epidote. The groundmass of the BLV lavas is typically dark, composed of a sugary textured mosaic of alteration phases, including sericite, epidote and chlorite intergrowth after glass. The remainder is composed of plagioclase microlites, granular augite and interstitial FeTi oxides. Additional alteration phases present include occasional prehnite veinlets and lesser patchy pumpellyite rods.
A rare lithotype within the BLV, which is also observed within the Forest Reefs Volcanics is a hornblende+clinopyroxene+plagioclase-phyric late stage andesitic intrusive (Facies I). The hornblende occurs as euhedral, fresh laths up to 15 mm long and also as glomeroporphyritic aggregates (Fig. 5.1b). They show distinct brown-green pleochroism with occasional simple twinning and comprise ~20 modal% of these rocks. Euhedral to subhedral, fresh augite phenocrysts up to 3 mm long show moderate compositional zoning and comprise ~5 modal% with subhedral plagioclase phenocrysts typically replaced by albite comprising a further 5 modal% of the crystal assemblage. The groundmass of these lavas comprises a mosaic of alteration phases including microcrystalline epidote and chlorite together with microlites of plagioclase and euhedral to subhedral microphenocrysts of augite.

The clinopyroxene-phyric dolerite lithotype (Facies C) has a similar composition to the BLV lavas. The dolerite is a medium-grained, holocrystalline rock dominated by augite (~20modal%) with lesser plagioclase and interstitial FeTi oxides (Fig. 5.1c). Augite typically occurs as moderately zoned euhedral crystals up to 5 mm across with euhedral plagioclase up to 1 mm set in a groundmass composed of common albitized plagioclase laths, granular augite and interstitial FeTi oxides.

5.2.2 Byng Volcanics (BYV)

The Byng Volcanics (BYV) within the field area is dominated by the polymict conglomerate lithofacies described previously (Facies D), as well as isolated massive lava units (Facies E). The rocks are moderately porphyritic augite+plagioclase+FeTi oxide-phyric andesites with common apatite microphenocrysts; all have experienced prehnite-pumpellyite grade metamorphism.

Plagioclase phenocrysts are more abundant than in the BLV (>5modal%). These typically occur as ~5 mm long subhedral phenocrysts which have been replaced by albite. Augite phenocrysts are less abundant than in the BLV lavas (<20modal%) but also appear euhedral and zoned. They are commonly clear to pale green crystals about ~2 mm across containing rare opaque inclusions and small apatite rods. The microphenocrysts of apatite form a minor component of the phase assemblage (~2modal%), but are a reliable petrographic indicator for this suite. The apatites are typically stout, commonly clear microphenocrysts around 250μm in diameter. They occasionally occur as distinct...
brownish crystals, possibly the result of tiny sulphide inclusions (Fig. 5.1d). The groundmass of the BYV is typically a sugary textured mosaic of sericite, epidote, chlorite after glass, with plagioclase microlites, granular augite and interstitial FeTi oxides.

5.2.3 Forest Reefs Volcanics (FRV)

The Forest Reefs Volcanics (FRV) lavas form a compositionally and geochemically distinct volcanic suite in the Blayney district. They appear to be more fractionated than the other suites, typically occurring as moderately porphyritic augite+plagioclase+FeTi oxide-phyric andesite lavas (Facies H).

Subhedral phenocrysts of plagioclase are generally 1-2mm across and account for > 10 modal% of the phase assemblage. Lesser augite (<10modal%) occurs as up to 5 mm phenocrysts set in a dark groundmass composed of a fine mosaic of sericite, epidote and chlorite probably after glass, with plagioclase laths, occasional small equant microphenocrysts of augite and interstitial FeTi oxides. Elsewhere within the FRV, outside the study area, these lavas can be distinguished easily by the additional presence of apatite microphenocrysts (Squire, 1999 pers. comm.).

Also present within the FRV are extensive poorly outcropping shallow intrusives. These are represented in the Blayney study area by the Tallwood Monzonite (Facies I), which intrudes the FRV lavas in the western extent of the field area. The Tallwood Monzonite is a multiple-phase intrusive body dominated by medium to coarse-grained holocrystalline monzonites and diorites, characterised by abundant augite with lesser hornblende, plagioclase and K-feldspar. Augite is typically the most abundant mafic phase (>20modal%); however hornblende-rich examples also occur, the mafic phases are set in a groundmass dominated by plagioclase laths, well formed stout apatite crystals, K-feldspar, equant FeTi oxides with lesser interstitial biotite and quartz. Alteration phases present include fine-grained albite, sericite after plagioclase with occasional epidote-chlorite alteration of the mafic phenocrysts.
5.3 Mineral Chemistry of the Key Units

Mineral chemistry of the key units has been used to identify diagnostic features to aid in constraining the distribution of the facies within the study area and also to assist in constraining the composition and affinities of the source magmas (Chapter 6). In turn, this helps to elucidate the tectonic setting of the erupting magmas, which will be discussed in a subsequent chapter (Chapter 7).

Variations in mineral chemistry are perhaps best seen in clinopyroxene compositions (Fig. 5.2) as this phase comprises a dominant proportion of the unaltered phenocrysts present in each of the key Ordovician units. Phenocrystal augite TiO₂ content is a useful discriminant between the units. This is especially useful in delineating the BLV, which show significantly higher TiO₂ contents than for the other suites at the same Mg#. The Tallwood Monzonite shows the lowest TiO₂ values, with the BYV and FRV showing overlap between the two endmember fields (Fig. 5.2).

The various suites can also be defined using clinopyroxene Na₂O/TiO₂ ratio as a discriminant versus Mg# (Fig. 5.2). This reflects the higher TiO₂ contents and generally lower Na₂O content of the augite from the BYV, FRV and Tallwood Monzonite suites compared with the BLV.

Chromites from the Blayney Volcanics show a restricted compositional range, with Cr-rich compositions (Cr# 77.6-88.4) and Mg# between 0.21-0.65. They also have low TiO₂ (0.09 to 0.15 wt%) and low Al₂O₃ (5.6 to 10.9 wt%) contents (Fig. 5.3).
Fig. 5.1 a) XPL view of Blayney Volcanics basalt lava, dominated by augite phenocrysts. (PBD 66: 700728mE 6290825mN)

b) PPL view of hornblende-plagioclase-phyric andesite dyke (PBD143/SITE 335: 703727mE 6294261mN)

c) XPL view of Blayney Volcanics dolerite intrusive, showing holocrystalline fabric dominated by augite with sparse plagioclase and Fe/Ti oxides (PBD 69/SITE 134: 700380mE 6291297mN)

d) PPL view of Byng Volcanics andesite clast, showing distinct brownish stout apatite microphenocryst (PRD80/SITE 160: 709117mE 6291971mN)
Figure 5.2 Composition of clinopyroxene phenocrysts (oxide wt%). Mg# = Mg/(Mg+Fe).
Figure 5.3 Composition of Cr-spinel from the Blayney Volcanics lavas (oxide wt%). Fe$^{3+}$ # = Fe$^{3+}$/($\text{Cr} + \text{Al} + \text{Fe}^{3+}$). Magma group fields taken from Kamenetsky et al. (1999).
Chapter 6: Petrology & Lithochemistry of the Key Ordovician Units

6.1 Introduction

The geochemistry component forms the focus of this research and aims to identify distinct lithostratigraphic units within the Ordovician volcanics and also to evaluate regional correlations. This involves investigating the spatial and temporal variations in the magmatic affinities of the units and discussing them within the framework established from the structural and volcanic facies architecture of the study area (Chapters 3 & 4).

6.2 Sample Preparation and Procedures

Over 200 samples were taken from the field, out of which 43 of the freshest were selected for geochemical analysis. These were selected from handspecimen and petrographic examination to gain a representative sample suite over the Ordovician volcanics, with great care taken to avoid samples containing amygdales, veinlets, monomineralic domains, sulphides and oxidation patches.

The samples were crushed using a jaw crusher set to yield pea sized pieces (~10 mm), which were examined carefully to select the freshest fragments for grinding into a powder using a tungsten-carbide ring mill.

Major and trace element (Y, Rb, U, Th, Pb, Zn, Cu, Ni, Nb, Zr, Sr, Cr, Ba, Sc, V, La, Ce, Nd) analyses were performed by a standard X-ray fluorescence (XRF) technique at the School of Earth Sciences, University of Tasmania, using a Philips PW1410 spectrometer (Appendix 3). The major element data is expressed in oxide weight percent and has been recalculated to 100% volatile free for comparing analyses. The trace element data is expressed in parts per million. Loss on ignition values were measured following fusion of an aliquot of the sample powder heated to 1000°C with returned losses < 5%.

REE data was obtained for a representative subset of the Ordovician volcanics sampled, using inductively coupled plasma mass spectrometry (ICP-MS) at the School of Earth Sciences, University of Tasmania (Appendix 3). This technique allows direct
determination of the REE elements (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) with a high sensitivity and low background levels which facilitate low detection limits.

The dataset for this research was compiled with an effort made to integrate preexisting data from the Ordovician volcanics. In addition to this research, additional analyses have been acquired from the Australian Geological Survey Organisation (AGSO) database and also from a PhD thesis focusing on the Browns Creek skarn deposit (Kjolle, 1996).

6.3 Lithochemistry and Petrology of the Key Units

6.3.1 Blayney Volcanics (BLV)

6.3.1.1. Geochemistry

A data set of 22 representative samples was selected from the Blayney Volcanics lavas (BLV). These analyses range between 6.4-15% MgO (47.8-57.2 % SiO₂) with an average of 8% MgO, suggesting basaltic compositions, which corresponds to basalts and basaltic andesites from the total alkalis versus silica (TAS) classification of Le Maitre et al (1989) (Fig. 6.1). 19 of these samples represent lavas or clasts from the coeval clast-supported monomictic breccia facies (Chapter 4), with the remaining 2 samples representing a dolerite sill, mapped up Cowriga Creek in the BLV western area.

Major and trace element bivariate plots show that the BLV cluster, with some scatter about broad linear expected fractionation trends for many elements (Figs. 6.1 & 6.2).

The main wholerock geochemical features of the BLV include:

\textbf{Fe₂O₃, MgO and CaO} – 7.6 to 12.1, 6.1 to 15.0 and 7.0 to 13.7 wt\% respectively; these values are high, reflecting the more primitive nature of this suite compared to the others. In particular, a few analyses with 11.1-15.0 wt\% MgO represent a distinct more mafic group characterised by abundant mafic phenocryst assemblages.

\textbf{Al₂O₃} – between 9.4 and 15.7 wt\%; with one anomalously high value of 17.6 wt\%, compared to the remainder. These values are distinctly lower with respect to most lavas from the other suites. The increasing Al₂O₃ with advancing fractionation suggests little removal of plagioclase from the magma.
K₂O - These values show significant scatter due to the prehnite-pumpellyite grade metamorphism, however K₂O concentrations (0.53-2.6%) in BLV basalts are comparatively lower than for the other suites.

P₂O₅ - between 0.18 to 0.41 wt%; these values are lower than for the other suites which is petrographically supported by the absence of apatite microphenocrysts throughout the BLV lavas. Over the range 6-10% MgO, little regular distribution is apparent in the BLV P₂O₅ data, suggesting slightly different parental magmas may contribute to the suite.

Trace element data indicates that the BLV in comparison to the other suites show lower values for large ion lithophile elements (LILE P, Rb, Sr, Pb) as well as for the light rare earth elements (LREE La, Ce) (Fig. 6.3).

The trace and major element data suggest an clinopyroxene±olivine control on the fractionation of the BLV in accord with the main phenocryst phases present within the lavas and intrusives.

Representative REE data for the BLV lavas (Fig. 6.4) reflects broad fractionation trends showing more elevated REE patterns at the more evolved composition. They are characterised by smooth REE patterns ([La/Yb]N~3.3) with moderate LREE enrichment ([La/Sm]N~2.1) relative to chondrite and flat HREE patterns ([Sm/Yb]N~1.6).

At equivalent MgO the BLV appear to be less enriched in the LREE than the other suites, and the overall REE pattern is flatter than the other units ([La/Yb]N~3.3) (Fig. 6.5).

6.3.1.2 Magmatic Affinities

At 8% MgO (~53% SiO₂), the BLV K₂O contents cluster around 2%, suggesting high-K calc-alkaline affinities for the BLV lavas and dolerite intrusives. This is shown on a K₂O-SiO₂ discrimination plot (Le Maitre et al., 1989) (Fig. 6.1) with most samples plotting in the high-K field. Occasional samples plot in the low-K field of this classification reflecting more intense alteration of the more glassy lavas. The glass-free, holocrystalline dolerite samples from the BLV are considered to be more resistant to alkalis element mobility and with ~2% K₂O, also suggest an original high-K calc-alkaline affinity for the BLV. In addition, proxy immobile elements that display similar magmatic behaviour to K, such as P and La show contents consistent with fresh high-K calc-alkaline suites from...
modern settings, where in the basaltic andesite – andesite range lavas have ~0.3% P₂O₅ (Gill, 1981).

6.3.2 Byng Volcanics (BYV)

6.3.2.1 Geochemistry

A data set of 18 samples has been compiled from the three outcropping areas of Byng Volcanics (BYV) within the study area (Appendix 3). These represent lavas and lava clasts from the polymictic conglomerate facies and consist of more evolved compositions than the BLV lavas, with 8.9-2.7 % MgO and 49-61% SiO₂. These correspond to basaltic trachyandesite and trachyandesite compositions using the total alkalis versus silica scheme from Le Maitre et al (1989) (Fig. 6.1).

From many of the bivariate plots shown in Fig. 6.2 and 6.3 there are clearly 2 groups that make up the BYV suite. These correspond to a dominant group (BYV Group 1), including clasts and the lavas, with a minor cluster (BYV Group 2) representing a subordinate population of clasts, characterised by more mafic phenocryst assemblages.

The main whole rock geochemical features of the BYV include:

**MgO** – between 2.7 and 8.9 wt%. These values show two broad clusters highlighting the two compositional groups of BYV. Group 1 shows a broad range between 6.1 and 2.7 wt% MgO (49-60.7% SiO₂) and a less evolved suite (Group 2) between 8.9 and 7.6 wt% MgO (51.6-53% SiO₂).

**Al₂O₃** – Group 1 clasts show values between 15.8 and 19.4 wt%; their values are consistently higher compared to the BLV, reflecting the early crystallisation of FeTi oxides and late appearance of plagioclase as a crystallising phase. Limited fractionation of plagioclase is suggested for this group by one low value (13.1 wt%) compared to the remainder. The less fractionated BYV group 2 clasts have lower Al₂O₃ content than the BLV at equivalent MgO.

**Fe₂O₃** – Group 1 clasts have between 7.9 and 12.1 wt%; these values are relatively low compared to the BLV suite and are mostly less than the Group 2 clasts, which range from 10.7-12.4% Fe₂O₃. The BYV range shows a tight inflection with a decrease in abundance.
with increasing fractionation reflecting the crystallisation of FeTi oxide, at around 5.5 wt% MgO.

**K₂O** – between 0.37 and 6.68 wt%; these values show significant scatter due to low grade metamorphism of these often glassy lava clasts; however, the concentrations from both groups are comparatively higher than for the BLV suite.

**P₂O₅** – 0.37 to 0.52 wt%; these values are high compared with the BLV suite. This is supported by the presence of common stout microphenocrysts of apatite, with the exception of one sample with a low value (0.29 wt%), where apatite microphenocysts are conspicuously absent. The Group 2 clasts show slightly lower P₂O₅ contents than the main cluster of Group 1 samples. Over the range 4-10% MgO, little regular distribution is apparent in the BLV P₂O₅ data, suggesting slightly different parental magmas may contribute to the suite.

Trace element data shows that the BYV are enriched in large ion lithophile elements (LILE P, Rb, Sr, Pb) as well as the light rare earth elements (LREE La, Ce) with respect to the BLV. Group 2 HFSE (e.g. Zr, Ti and Y) show lower values than do the BLV at the same MgO.

The trace and major element data suggest a clinopyroxene+plagioclase+FeTi oxide fractionation assemblage which is supported from the phenocryst assemblage present (Chapter 5).

Representative REE data for the BYV has been plotted as chondrite normalised patterns (Fig. 6.4) and shows a higher enrichment in the LREE at equivalent MgO compared to the BLV (Fig. 6.5). They are characterised by moderate to high LREE enrichment ([La/Sm]ₙ ~2.8) and a flat HREE pattern ([Sm/Yb]ₙ ~2.2).

**6.3.2.2 Magmatic Affinities**

The least altered BYV samples around 4% MgO (53% SiO₂) have ~ 4% K₂O, and are best classified as shoshonites. This is reflected on the K₂O-SiO₂ plot (Fig. 6.1), with the BYV ranging from high-K to shoshonitic affinities. Trace element data also matches best with modern shoshonitic suites as defined by (Morrison, 1980). These include characteristically
enriched values for LILE (P, Rb, Sr, Pb) and LREE (La, Ce) with depleted HFSE (Zr, Ti & Y) at equivalent MgO to the BLV.

6.3.3 Forest Reefs Volcanics

6.3.3.1 Geochemistry

A data set of 18 analyses has been compiled from the FRV (Appendix 3). These have the most evolved compositions of any of the units discussed. They dominantly consist of andesites with 7.2-1.8% MgO (50.2-60.3% SiO₂) with basaltic trachyandesite, trachyandesite and occasional trachyte compositions using the total alkalis versus silica (TAS) classification from Le Maitre et al (1989).

The main wholerock geochemical features of the FRV lavas include:

Al₂O₃ – between 15.9 and 19.3 wt%; these values are high compared to the BLV, BYV (Group 2) and the majority of BYV (Group 1), reflecting the late appearance of plagioclase as a crystallising phase.

Fe₂O₃ – between 5.6 and 11.5 wt%; these values are low compared to the BLV, showing a distinct decrease in abundance with increasing fractionation reflecting the early fractionation of titanomagnetite as a crystallising phase at around 5.5% MgO.

K₂O – between 2.0 and 6.6 wt%; this range shows significant scatter due to low-grade metamorphism; however, the concentrations are comparatively higher than for the BLV at equivalent SiO₂.

P₂O₅ – between 0.3 and 0.5 wt%; these values are high compared with the BLV and lower compared to the BYV at the same MgO. The lack of enrichment in P₂O₅ with advancing fractionation evident for this suite is probably due to apatite crystallisation across the fractionation range represented. This is consistent with the typical presence of apatite microphenocrysts in many of the Forest Reefs Volcanics lavas (Chapter 5).

Trace element data shows that the FRV become progressively enriched in large ion lithophile elements, (LILE P, Rb, Sr, Pb) with fractionation compared with the BLV and BYV.
The trace and major element data supports an early control by clinopyroxene and olivine fractionation, up to ~5.5% MgO where FeTi oxide begins crystallising until the magma reached ~4% MgO, where apatite and plagioclase became important fractionating phases. This interpretation is in accord with the phenocryst assemblage present in the FRV lavas (Chapter 5).

Representative REE data from the FRV lavas show similarly elevated values for LREE to the BLV at equivalent MgO (Fig. 6.5). The FRV is characterised by a smooth pattern ([La/Yb]N ~4.2 with moderate to high LREE enrichment ([La/Sm]N ~2.3) and a flat HREE pattern ([Sm/Yb]N~1.8).

6.3.3.2 Magmatic Affinities

At around 3% MgO the FRV lavas mostly have >4% K2O and are best classified as shoshonites. The K2O content shows a range of values for the lavas and holocrystalline intrusives (Tallwood Monzonite) that plot well within the shoshonite field of Le Maitre et al (1989) (Fig. 6.1). This is further supported by high contents of K-proxy immobile elements such as La and P in addition to high values for Al2O3, total alkalis, K2O, LILE and LREE. The FRV lavas also show relatively low HFSE (e.g. Zr, Ti and Y) contents compared with typical calc-alkaline suites, typical of modern shoshonitic suites (Morrison, 1980).

6.3.4 Tallwood Monzonite (TM)

The main intrusive rocks in the Blayney area occur intruding the lavas of the FRV. These comprise the Tallwood Monzonite, which occurs as a poorly outcropping body in the west of the study area.

6.3.4.1 Geochemistry

The Tallwood Monzonite data set consists of 8 analyses, these range in composition between 4.7 and 2.3 % MgO (54.1 to 61.6.% SiO2) and correspond to mostly trachyandesites using the TAS classification from Le Maitre et al (1989) (Fig. 6.1).

The major and trace element characteristics essentially mimic those observed for the lavas of the FRV. They show distinctly higher Al2O3, K2O, P2O5, LILE and LREE contents with generally lower Fe2O3 and TiO2 values in comparison to the BLV and of the BYV suites at...
equivalent MgO. In addition the geochemical trends also mimic those observed for the FRV, including a tight negative trend, from about 5.5% Fe₂O₃ reflecting the onset of FeTi oxide crystallisation.

The trace and major element data supports a strong control by FeTi oxide fractionation, below around 5.5% MgO with lesser influence from apatite and plagioclase fractionation. This interpretation is in accord with the dominant phenocryst assemblage present in the TM (Chapter 5).

The representative REE data has been plotted as chondrite normalised patterns (Fig. 6.4) and indicates that the TM samples have the most enriched LREE values of the suites at equivalent MgO. They are characterised by a steep REE pattern ([La/Yb]N~5.6) with a high LREE enrichment ([La/Sm]N~2.5) relative to chondrite and a moderate enrichment in HREE ([Sm/Yb]N~2.1). These patterns appear considerably more enriched in all REE than the FRV lava analysis at equivalent MgO (Fig. 6.5).

6.3.4.2 Magmatic Affinities

At around 3% MgO the Tallwood Monzonite has ~4% K₂O and is best classified as a shoshonite suite. Similar to the FRV lavas, the Tallwood Monzonite shows consistently higher values of Al₂O₃, total alkalis, K₂O, with enrichment in LILE and LREE with relatively low TiO₂ contents, compared with typical calc-alkaline suites, as defined by (Morrison, 1980). This is also evident from the mineral chemistry discussed in the previous chapter, where the low TiO₂ contents of phenocrystal augites (~0.1) from the Tallwood Monzonite suite are low relative to the compositions from modern high-K orogenic andesites (~0.5%) (Gill, 1981). Similar to the FRV lavas these features are largely reflecting the early fractionation of the FeTi oxide phase and suppression of plagioclase in shoshonitic magmas.
6.4 Discussion

Major and trace element variation plots for the key Ordovician units show broad trends, often explainable by expected fractionation processes. The units are easily distinguishable on the basis of their geochemical characteristics and magmatic affinities.

A useful geochemical method of distinguishing the units is by using $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ ratio as a discriminant against MgO (Fig. 6.6). This highlights the increase in $\text{Al}_2\text{O}_3$ and corresponding decrease in $\text{Fe}_2\text{O}_3$ for the higher K suites. Both the BYV and FRV lavas show distinctly increasing $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ ratios with increasing fractionation, whereas the Blayney Volcanics show no apparent increase. The Tallwood Monzonite shows the same strong increase in $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$, as do the FRV lavas, reflecting the early crystallisation of FeTi oxide and suppression of plagioclase typical of shoshonitic suites, and on this basis, the Tallwood Monzonite is regarded as comagmatic with the FRV lavas.

Likewise, the holocrystalline dolerites within the BLV are similar compositionally to the BLV lavas, highlighted by the low $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ values and other key immobile element contents/ratios, and are therefore considered comagmatic with the BLV lavas. Within the BLV lavas two broad groups have been recognised, corresponding to varying degrees of fractionation. The dominant lava units show a slightly higher range of $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ values and have more evolved compositions than a subordinate group of more mafic lavas found in the southern extents of the study area with $>11\%$ MgO (Fig. 6.6).

The BYV show many compositional and geochemical similarities with the FRV. They both comprise lavas and volcanic conglomerates sourced from a shoshonitic basaltic trachyandesite to trachyandesite volcano-intrusive package. Two broad groups have been identified from the BYV. The major group (Group 1) comprises lavas and a dominant proportion of clasts from the polymict conglomerate facies. A lower $\text{Al}_2\text{O}_3$-group (Group 2) have less evolved compositions ($>7\%$ MgO), with typically higher $\text{Fe}_2\text{O}_3$ contents than Group 1 and also shows a tight positive trend for most incompatible elements with increasing fractionation. These low-$\text{Al}_2\text{O}_3$ BYV are distinct from the mafic BLV lavas in that they have much higher $\text{P}_2\text{O}_5$ and $\text{K}_2\text{O}$ contents at equivalent MgO. This reflects their shoshonitic affinities in contrast to the high-K calc-alkaline association of the BLV.
Some of the differences between the BYV and the FRV include the slightly lower $\text{Al}_2\text{O}_3/\text{Fe}_2\text{O}_3$ ratios, and lower $\text{K}_2\text{O}$, $\text{P}_2\text{O}_5$ contents of the BYV compared to the FRV (Fig. 6.6). This transition possibly indicates a gradual change in lava compositions from BYV Group 2 to BYV Group 1 into the FRV suite (Fig. 6.6), suggesting that the source of the lavas and conglomerate of the BYV may represent an earlier manifestation of the main Forest Reefs magmatism episode. Subsequently, the BYV Group 2 clasts are interpreted to represent an even earlier manifestation of this magmatism. One possibility is that these lower-$\text{Al}_2\text{O}_3$, Group 2, clasts were sourced from lavas within the Mt Pleasant Basalt Member which is located beneath the main Forest Reefs Volcanics, enclosed within the Weemalla Formation (Chapter 2). This hypothesis is supported by compositional and geochemical similarities with the Mt Pleasant Basalt Member (Fig. 6.1), which, if the inferred correlation with the pillow lava seen at Browns Creek is correct (Chapter 4), show a close association with the polymictic conglomerate unit. This emphasises that the BLV is not comagmatic with the FRV as has been previously interpreted (Pogson and Watkins, 1998).

A further observation from the geochemical data is the distinct geochemistry of the late-stage hornblende-phyric dykes, which show consistently similar immobile element abundances and ratios as the Late Ordovician FRV.

The units within the study area can be considered within a lithochemical stratigraphy, with each of the main packages forming a compositionally and geochemically distinct suite. Analysis of these spatial and temporal variations has proved to be a useful technique in constraining the distribution of the units. The identification of geochemical and petrological similarities between the BYV and the FRV suites adds further weight for a correlation between these two areas, as was proposed in Chapter 4.

6.5 Comparison with the Junee-Narromine Belt, western NSW

As outlined in chapter 2, the main Ordovician volcanic belts in central western NSW are dominated by high-K to shoshonitic magma associations. Any temporal and spatial magmatic similarities between the belts are of importance when assessing the regional stratigraphy and might also enable correlations to be made between these belts.
In the Blayney district the Blayney Volcanics (BLV) is considered to be the oldest Ordovician package and is interpreted to form the basement to the Forest Reefs Volcanics (FRV) (Chapter 2). A useful regional marker horizon in the stratigraphy is discontinuous limestone lenses, represented by the Cowriga Limestone Member, interpreted to be near the base of the FRV (Chapter 4). Overlying the limestone in the Blayney study area and at Browns Creek are extensive polymictic conglomerate units, possibly sourced from the Mt Pleasant Basalt Member. This district stratigraphy provides the basis for a lithochemical stratigraphy of the Blayney district, allowing comparisons to be made at a regional scale, in particular with the better known western (Junee-Narromine) volcanic belt.

The BLV of the Molong Volcanic Belt show compositional and petrological similarities with the basement Early Ordovician Nelungaloo Volcanics of the Junee-Narromine Belt (Crawford, 1999). Although the BLV has distinctly more mafic compositions than the Nelungaloo Volcanics, the two packages represent extensive suites with high-K calc-alkaline magmatic affinities (Fig. 6.6). Likewise, the lavas and intrusives within the overlying Late Ordovician FRV display similar compositions and geochemical affinities to those present in the Late Ordovician Goonumbla-Wombin package in the Junee-Narromine Belt (Crawford, 1999) (Fig. 6.6). One difference between these is the presence of consistently less fractionated lavas of the FRV with MgO 7.2-2.7% and 50.2-60.3% SiO₂, than the Goonumbla Volcanics which are mostly ~1-3% MgO, although more mafic compositions do exist (Heithersay and Walshe, 1995).

These similarities are also evident in the distinct increase in Al₂O₃/Fe₂O₃ content with increasing fractionation, and consistently higher K and P concentrations of the Late Ordovician FRV and Goonumbla Volcanics with respect to their basement sequences; the BLV and Nelungaloo Volcanics respectively. These basement sequences, in contrast, show no increase in Al₂O₃/Fe₂O₃ with increasing fractionation.

In addition to these similarities, the REE data comparing the volcanics from both belts indicate that BYV and FRV show patterns consistent with the Goonumbla suite (Fig. 6.7), with similar enrichment in LREE. The Blayney Volcanics show lower LREE enrichment with similar flat HREE patterns to the least evolved Nelungaloo Volcanics; partly explained by the more mafic composition of the Blayney Volcanics lavas and reflecting the
variation in REE patterns characterising the Nelugaloo Volcanic package (Crawford, 1999 pers. comm.).

Interestingly, the presence of Late Ordovician limestones at the base of the Goonumbla Volcanics marks the broad location of the temporal change in magmatic affinities in the Junee-Narromine Belt. Similarly, it appears that the late Middle Ordovician limestone located towards the base of the FRV, within the Weemalla Formation marks the change in magmatic affinities within the stratigraphy around Blayney. Therefore the temporal progression from high-K calc-alkaline to shoshonitic affinities evident from the Junee-Narromine belt (Crawford, 1999), is consistent with the chemical stratigraphy evident for the Molong Volcanic Belt. This correlation has significant tectonic and exploration implications for the Molong Volcanic Belt and the Blayney district, and will be discussed in more detail in the following chapters.
Figure 6.1 Classification of the Ordovician key units, including a field for Mt Pleasant Basalt Member (AGSO). Total alkalis versus SiO$_2$ (TAS) classification fields taken from Le Maitre et al, (1989). K$_2$O versus SiO$_2$ diagram fields taken from Rollinson, (1993).
Figure 6.2 Major element variation diagrams, showing major element oxides versus MgO for the Ordovician key units
Figure 6.3 Minor element variation diagrams, showing minor element (ppm) versus MgO for the Ordovician key units (NB. Kjolle Blayney Volcanics data does not include V & Nb).
Figure 6.4 REE plots for representative samples from the Ordovician key units, normalised with respect to chondritic values. Chondrite data taken from Taylor and Gorton, (1977).
Figure 6.5 REE plots for four selected samples from the Ordovician key units normalised with respect to chondrite values. Normalising data obtained from Taylor and Gorton, (1977). MgO values shown in red.
Figure 6.6 Major element variation diagrams (wt% oxides), comparing Molong Volcanic Belt with Junee-Narromine volcanic fields. K₂O versus SiO₂ fields taken from Rollinson, (1993). Symbols are identical to those used in Figure 6.3.
Figure 6.7 REE plots for representative samples from Blayney/Byng/Forest Reefs Volcanics compared with the Nelungaloo/Goonumbla Volcanics, normalised with respect to chondritic values. Chondrite data taken from Taylor and Gorton, (1977) MgO values shown in red.
Chapter 7: Tectonic Implications

7.1 Introduction

The high-K nature of the volcanics within the Ordovician belts has been ascribed to a range of tectonic settings, including hotspot mantle plume (Campbell and Hill, 1988), oceanic intraplate (Wyborn, 1992) and both intraoceanic (Oversby, 1971) (Scheibner, 1973) (Pemberton and Offler, 1985), and continental island arc settings.

This chapter aims to assess the tectonic significance of the possible correlation of the Molong Volcanic Belt (MVB) with the western (Junee-Narromine) belt. It also aims to constrain the tectonic setting of the Ordovician volcanics in the study area on the basis of the data presented in the previous chapters and also by consideration of modern analogues.

The overall compositional range of the key Ordovician units in the Blayney district vary from the relatively primitive basalts of the Blayney Volcanics into, more evolved, andesites of the Forest Reefs Volcanics. This range in composition is typical of arc-derived volcanic sequences worldwide (Wilson, 1989). Wholerock geochemical and REE data from this study provide compelling evidence for an arc-related setting for the Ordovician volcanics.

Magmatic Cr-spinel compositions have been used to discriminate between different magma types occurring in well-constrained tectonic environments (Kamenetsky et al., 1999). Electron microprobe analyses were conducted on chromites from the Blayney Volcanics which have compositions consistent with those in island arc mafic lavas (Kamenetsky et al., 1999) (Chapter 5, Fig. 5.2).

Another line of evidence supporting this proposed arc setting is the composition of volcanioclastic sediments within the study area. These show a conspicuous absence of craton derived quartz fragments, implying little or no mixing of continental detritus, typical of sandstones from intraoceanic island arcs (Dickinson et al., 1983).
7.2 Significance of Regional Correlations

The possible temporal correlation between the western Junee-Narromine and central MVB, discussed in the previous chapter, is consistent with the hypothesis of Glen et al. (1998), which suggest that the three volcanic belts in central western NSW are not primary Ordovician palaeogeographic features. Instead, they represent structural belts, essentially slices of a much more extensive arc and arc apron (Macquarie Arc), which has been subject to repetitive separation and accretion during the formation of the intervening Silurian to Early Devonian Cowra and Hill End troughs. This arc-rifting hypothesis is supported by the convergence of the central and eastern volcanic belts towards their ends, where there appears to have been less extension. In addition it is also supported from geochemical, geophysical and structural evidence suggesting the existence of Ordovician volcanics beneath the Cowra and Hill End troughs (Glen et al., 1997).

An alternative explanation for the similarities is that the belts may represent discrete terranes which originated from different locations but were formed under similar magmatic conditions. These terranes were later assembled during post-arc processes, such as strike-slip tectonics and/or the closure of major oceanic basins. Both hypotheses are compatible with the petrological and geological similarities discussed in the previous chapter and some correlations appear to exist between the belts.

Many authors (Muller and Groves, 1993) (Heithersay and Walshe, 1995) have interpreted the shoshonitic Goonumbla Volcanics in the Junee-Narromine belt as representing a late-oceanic arc setting. Therefore on the basis of the demonstrated similarities between the Goonumbla and Forest Reefs Volcanics, a late oceanic-arc setting is preferred for the MVB.
7.3 Discussion

The temporal change in magmatic affinities, identified from the high-K calc-alkaline Blayney Volcanics to the shoshonitic Forest Reefs Volcanics, has important implications for the tectonic evolution of the MVB.

The significant change in magma composition towards the end of the high-K calc-alkaline Blayney Volcanics magmatism is marked, near the base of the Forest Reefs Volcanics, by a late-Middle Ordovician limestone horizon, represented in the study area by the Cowriga Limestone Member.

As previously mentioned, the temporal change in magmatic affinities is also documented from the western (Junee-Narromine) belt where it is similarly broadly marked by an interval of limestone. In this locality, the period of limestone deposition/accumulation has been attributed to a major break (‘hiatus’) in volcanism in the mid to late Ordovician due to attempted subduction and collision with a seamount (Glen et al., 1998). On the basis of the demonstrated similarities between the two Ordovician belts this event may also be manifested within the MVB. The limestone horizon near the base of the Forest Reefs Volcanics, within the Weemalla Formation would therefore have also been deposited during this late Middle Ordovician break in volcanism.

7.3.1 Modern Analogues

The tectonic setting of shoshonites from modern arc environments has been examined in a literature review (Appendix 1). This review demonstrates that shoshonites are erupted in a wide variety of tectonic settings.

Within modern oceanic-arc systems the shoshonite association is mainly restricted to mature systems, often characterised by complex tectonic and petrogenetic histories. For example, in Fiji a slowing of subduction along the Vanuatu-Fiji-Lau-Tonga arc during the early to mid-Miocene was followed by a period of extensional and strongly rotational tectonics associated with shoshonitic magmatism (Rogers and Setterfield, 1994). The late stage rifting of the Vanuatu-Fiji-Lau-Tonga arc was coeval with fragmentation of the adjacent north Fiji basin (Solomon, 1990) and the opening of the Lau Basin (Fig. 7.1)
resulting in a transition from tholeiitic to shoshonitic volcanism. These shoshonites have many geochemical similarities to the Ordovician shoshonitic suites in central NSW, including the Forest Reefs Volcanics within the MVB.

Figure 7.1 Regional tectonic setting of the Fiji region showing the position of the now extinct Vitiaz trench following rifting and fragmentation of the Vanuatu-Fiji-Lau-Tonga arc (Rogers and Setterfield, 1994).

The Fijian shoshonites from Tavua, Viti Levu, are characterised by SiO₂ (50-55%), TiO₂ (0.6-0.7%), and high K₂O (3-5%) along with low HFSE abundances and slight LREE enrichment (Rogers and Setterfield, 1994). These compositional characteristics are similar to the shoshonitic Forest Reefs Volcanics from the Molong Volcanic Belt at equivalent MgO (Fig. 7.2). Further similarities between the suites include the dominance of clinopyroxene over olivine in the fractionating assemblages, and the suppression of plagioclase fractionation for the Tavua lavas (Rogers and Setterfield, 1994).

Another similarity between the Ordovician and Fijian scenarios is the distinct hiatus within the Tavua suites, occurring between the eruption of absarokites (high MgO, high-K) and shoshonites (Rogers and Setterfield, 1994). The shoshonites show a rapid increase in K₂O content with increasing fractionation, not observed for the more mafic absarokites. Other authors, including Gill and Whelan (1989) also emphasise the importance of this temporal
The early absarokite suite from Rogers and Setterfield (1994) show some similarities in major and trace element compositions at equivalent MgO, to the Blayney Volcanics (Fig. 7.1) and the Fijian shoshonitic suite is similar to the Forest Reefs Volcanics. Therefore, Fijian Miocene rocks display a similar transition, from high-K calc alkaline to shoshonitic associations, as has been demonstrated within the study area; suggesting that similar tectonic and petrogenetic processes were involved in their formation.

Rogers and Setterfield, (1994) propose two alternative explanations for the geochemistry of shoshonites at Tavua, Fiji. The first implies that the high-K signature originated from a large fluid input from the slab caused by changes in the convective regime of the mantle wedge, in turn causing fluctuations in the concentrations of elements being transported by magmatic fluids. The second model incorporates changes in arc tectonics to explain the shoshonitic association.

Changes in arc tectonics are common throughout the southwestern Pacific due to the dynamic interplay of tectonic processes throughout the region. Collisional events, involving collision of an arc, continent or oceanic plateau/fragment with an active arc system have significant local and regional effects, often resulting in the cessation of subduction (Appendix 1). These processes combined with post-collisional extensional tectonics as observed in Fiji, provide the opportunity for high degrees of mantle metasomatism/hybridisation by slab-derived fluids and subsequent decompression partial melting of the enriched mantle wedge required to produce the LILE and LREE enriched, shoshonitic magmas.

The geological and geochemical evidence presented in this study is consistent with the intraoceanic island arc setting for the Ordovician Volcanics suggested by Oversby (1971), Scheibaer (1973), Pemberton and Offler (1985) and more recently by Glen et al (1998). This setting is also supported by the presence of several similarities between the key Ordovician units and modern oceanic arc environments, such as those demonstrated for Fiji.
Figure 7.2 Variation diagrams, comparing Molong Volcanic Belt Ordovician volcanics with Fiji suites, taken from Rogers, et al (1994). K₂O versus SiO₂ fields taken from Rollinson, (1993).
Chapter 8: Summary and Conclusions

8.1 Introduction

As outlined in Chapter 1, the key aims of this project are:

- to identify distinct lithostratigraphic units by employing geological and geochemical methods, enabling correlations to be made over the field area and also potentially at a regional scale

- to document the spatial and temporal variation in magmatic affinities of the Ordovician units in the Blayney area

- to review whether Au-Cu mineralisation is associated with any particular magma type in this region of the Molong Volcanic Belt

- finally, to produce a plausible tectonic model, by considering modern analogues, constraining the settings of eruption for the southern portion of the Molong Volcanic Belt and placing it within the tectonic framework of the Lachlan Fold Belt, central NSW

8.2 Key Results

The main results from this study may be summarised as follows:

- geological and structural mapping, in conjunction with geochemical sampling, of the key Ordovician units has clarified local structural interpretations and highlighted the probable importance of fault related repetition of Cabonne Group rocks in the study area

- volcanic facies mapping, combined with detailed geochemical sampling, has elucidated a possible correlation between the Byng Volcanics, within the study area, and areas of Forest Reefs Volcanics. Discontinuous limestone lenses, previously interpreted within the Blayney Volcanics, show a close association with shoshonitic volcanioclastics and...
lavas within these areas of Byng Volcanics. Both facies and geochemical data indicate that these areas are similar to the base of the Forest Reefs Volcanics and the underlying Weemalla Formation, where limestones also occur in close proximity to volcaniclastics. This possible correlation implies that the limestone lenses of the Cowriga Limestone Member in the Blayney district may represent a stratigraphic equivalent to late Middle Ordovician limestones within the Forest Reefs Volcanics, like those present at Junction Reefs and Cadia.

- the petrological component of this study, suggest a temporal transition in magmatic affinities exists within the Molong belt volcanics from the dominantly high-K calc-alkaline affinities of the Blayney Volcanics to the shoshonitic affinities displayed by the Forest Reefs Volcanics. The compositional change in magmatism is broadly coincident with the late Middle Ordovician limestone interval at the base of the Forest Reefs Volcanics which is possibly represented by the Cowriga Limestone Member within the study area.

- the lithochemical stratigraphy determined for the Ordovician volcanics in the Molong belt demonstrates several similarities to the stratigraphy in the western (Junee-Narromine) belt. This is evident by the temporal transition from high-K to shoshonitic affinities, which occurs during a period of limestone deposition in both belts.

- the geochemical and geological results of this study attribute the Ordovician volcanics to oceanic arc related magmatism, consistent with current interpretations of the Junee-Narromine belt volcanics. The demonstrated temporal transition in magma affinities show several similarities to the temporal change in compositions observed within late oceanic arc settings such as Fiji. Therefore, by consideration of modern analogues the transition into shoshonitic affinities is attributed to the stalling of subduction due to some sort of tectonic disturbance, possibly a collision event, with subsequent fragmentation/rifting of an arc resulting in the eruption of intensely metasomatised mantle, wedge-derived shoshonitic melts.
8.3 Exploration Implications

- The similarities between the stratigraphy within the study area and that reported from the Weemalla Formation and Forest Reefs Volcanics to the west implies that the Browns Creek mineralisation is hosted within Forest Reefs Volcanics and not associated with the Blayney Volcanics as was previously interpreted.

- Most mineralisation in the district is associated with the shoshonitic Forest Reefs Volcanics, generally related to shallow intrusive monzonite to dioritic porphyries, which intrude the sequence. The FRV is considered highly prospective for porphyry Au-Cu targets including Browns Creek-style skarn mineralisation. The temporal change in magma composition demonstrated for the Ordovician Volcanics has significant exploration implications as the common association of economic deposits implies that the mineralised magmas are associated with the distinctive Late Ordovician Forest Reefs Volcanics.

- The re-interpretation of the distribution of Ordovician units within the district has resulted in the recognition of additional areas of Forest Reefs Volcanics, previously mapped as Blayney or Byng Volcanics. This re-interpretation suggests a strong potential for further mineral discoveries in the Blayney region, especially Browns Creek style skarn mineralisation associated with the Cowriga Limestone Member.