The Geology and Geochemistry of the Naringla Monzodiorite, and the mineralization and alteration of the associated Porphyry Copper Deposits, Yeoval, Central-Western N.S.W.

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ABSTRACT

A study of the petrology, geochemistry and field relationships of sedimentary, volcanic and plutonic rocks from the Yeoval district has revealed a complex and varied geological history. Volcanics derived from the nearby Molong Volcanic Rise were deposited with marine sediments in the Middle to Late Silurian. They were then deformed during the Bowning Orogeny.

Intrusion of the Naringla Monzodiorite occurred in the Early Devonian. This is a heterogeneous body ranging in composition from pyroxenite cumulates to microgranodiorite and dacite porphyry. The latter two rock types are the host to disseminated porphyry copper style mineralisation. Co-genetic basaltic andesites were erupted above the monzodiorite body prior to final crystallization of the monzodiorite. The pyroxenites, pyroxene bearing basaltic andesites and pyroxene bearing monzodiorites formed by crystal fractionation of augite from a primitive magma of basaltic andesite composition. The chemical variations in the Naringla Monzodiorite (apart from the low-Si rocks) is thought to have been derived by chemical fractionation of hornblende, plagioclase and possibly biotite, although magma mixing and restite unmixing cannot be ruled out as formation processes.

Hydrothermal alteration associated with the porpyritic intrusions has produced propylitic mineral assemblages in most of the rocks of the Naringla Monzodiorite. Alteration is most intense around the copper deposits, and occasional albitic alteration is developed. Alteration is of a weak and patch nature, and lateration zones are generally not developed.

A small body of gabbro that outcrops adjacent to the Naringla Monzodiorite is probably unrelated due to chemical inconsistencies between the two units.

The Obley Adamellite intruded during the Middle Devonian, and contact metamorphosed the gabbro and a body of quartz-hornblende-diorite. The intrusion of rhyolite dykes into the Naringla Monzodiorite may have been related to the emplacement of the adamellite.
The final geological event in the area was the emplacement of small basic dykes along east-west joints in the Naringla Monzodiorite. These dykes are of probable Tertiary age.
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CHAPTER 1 - INTRODUCTION

1.0 Introduction

Most porphyry copper deposits are Mesozoic or Cainozoic in age and appear to be intimately related to subduction processes. These deposits occur both in island arc settings and in mountain belts at active continental margins. Porphyry style deposits are also found in Palaeozoic and Precambrian rocks, although these are rarer than the more contemporary deposits. In the Palaeozoic Lachlan Fold Belt in New South Wales, small uneconomic copper-gold deposits that exhibit porphyry copper style characteristics occur. These deposits are Siluro-Devonian in age.

At Yeoval in central N.S.W., a monzodiorite pluton contains a number of small copper-gold deposits which exhibit some of the characteristics of porphyry copper deposits. The monzodiorite is of an Early Devonian age, and has intruded moderately deep water Silurian sediments. In the Late Devonian, a large adamellite pluton has intruded the monzodiorite and sediments.

The aims of this thesis are:

(1) To study in detail the mineralization and alteration associated with the copper-gold deposits in the monzodiorite and the surrounding country rocks, with particular emphasis on the Goodrich deposit. (See figure 1).

(2) To compare and contrast the Goodrich deposit with the well documented Yeoval prospect north of Yeoval. (See figure 2).

(3) Analyses of relationships between the dykes and plutonic rocks.

(4) A study of the variations within the monzodiorite in the hope that a petrogenetic model can be obtained.

(5) Comparison of the Naringla Monzodiorite with the Young Grano­diorite, and typical suites from the Lachlan Fold Belt.
1.1 **Location and Methods Employed**

The Naringla Monzodiorite is an elongate NNE-SSW trending body with a strike length of some 22 kilometres and a maximum width of 7 km. The pluton is centred on the small town of Yeoval in central west N.S.W. (see figure 1). Yeoval is located about 50 km south of Dubbo, 80 km north-west of Orange and 370 km north-west of Sydney (see figure 1.1).

Sealed roads connect Yeoval with Wellington to the east and Molong to the south-east, and unsealed roads connect Yeoval with Parkes, Peak Hill and Dubbo (see figure 1.1). Farm tracks are present over most of the mapping area providing good access. The exception is the heavily timbered adamellite ridges on the western side of the area, where access proves to be more difficult. Outcrop is generally poor, and is restricted to low lying hills. The exception is the adamellite, which outcrops beautifully in a prominent ridge around the north, west and southern margins of the monzodiorite. The boundary between the adamellite and monzodiorite is well defined and was mapped by ground traverses and air-photo interpretation. Weathering is a problem in the rest of the mapping area, and contacts are almost always unexposed. Because of this, outcrop mapping was conducted and the contacts have been inferred. Mapping was done directly onto aerial photographs, and this was then transferred to a 1:50,000 base map from which the final map was constructed.

Detailed outcrop mapping has been conducted around the Goodrich Mine and the Yeoval Prospect (see figures 2 and 3 respectively). Mapping was done directly onto enlarged aerial photographs. These were then enlarged again to produce the final map. Sketch maps were prepared of the Yeoval and Cyclops mine areas (see figures 4 and 5 respectively).

Geochemical sampling was conducted mainly around the Goodrich mine (figure 2). Due to the pervasiveness of the alteration, the samples collected were the least altered representative samples found. Samples were also collected of the most altered rocks for the purpose of determining the chemistry of alteration.

Surface prospecting for scheelite was conducted at night using an ultraviolet lamp.
Figure 1.1 - Locality Diagram
1.2 Physiography

Yeoval is part of the Western Slopes region of New South Wales. The Western Slopes region is composed of low, rolling hills that form part of the catchment area for the Macquarie River. The Little River drains the western side of the area, and the Buckinbah Creek drains the eastern side. These converge in the north of the area. A number of small creeks seasonally drain the central portions of the mapping area before flowing into the Buckinbah Creek.

The topography is dependent on the underlying units. The monzodiorite forms gently sloping and flat lying plains. It is surrounded on three sides by prominent, heavily timbered adamellite ridges. To the east, the volcanics and sediments of the Cudal Group outcrop very poorly in a generally flat lying terrain.

The average rainfall is 58cm per year, this being evenly distributed throughout the year. The climate is temperate and the average summer temperature is 25°-30° celsius, although the average temperature at the time of mapping was 35°C, and the area was in the grip of a serious drought.

Sheep and cattle are grazed over the flat lying areas, and various crops are grown. In the adamellite ridges there is some grazing of livestock but the terrain is too rugged and the soil too poor for the growing of crops.

1.3 Previous Work

Gold was first discovered at what is now known as the Goodrich mine in 1868. Mining of gold and copper was subsequently carried out until 1886 when a fatality during mining caused the closure of the open pit. The mine was reopened in 1903 and worked until 1909. During this period, numerous other areas around Yeoval were mined but, apart from the Goodrich deposit, production was very low. In his report on the copper mining industry of New South Wales, Carne (1908) reported the presence of copper in the Yeoval district. Some prospects were worked up until the late 1930's (e.g. Freehold Prospect), but all work ceased with the advent of World War Two.
More recently, prospecting has been carried out on a small scale around the Goodrich deposit and other old shafts by a local prospector, Mr. Kevin Barker. He was the first person to find scheelite at the Yeoval prospect in the late 1970's.

The first geological study of the area was carried out in 1945 by Basnett and Colditz. They described the regional geology between Wellington and Yeoval, and their work was followed on by Maggs (1963) in his thesis on the stratigraphy between Yeoval and Manildra. He defined the sediments and volcanics east of Yeoval as belonging to the Manildra group. The term Manildra Group was subsequently discarded by Brunker et al (1970) and the Cudal group to the east was extended to include all of the original Manildra Group. The Cudal group was then redefined by Pickett et al (1982) to include further formation that were first classified by Maggs (1963).

In the mid 1960's, the Geological Survey of New South Wales conducted four studies of the Goodrich Mine (McClatchie and Dickson (1963), Ringis and Webster (1964), Ringis and Kennedy (1964), McManus and Loudon (1966)). The most important finding of these reports was that the mineralization at the Goodrich Deposit is controlled by a steeply dipping arcuate narrow shear. This structure has been truncated by an easterly striking shear.

A Ph.D. thesis on the rocks of the Yeoval Batholith was completed by Brian Gulson of A.N.U. (1968). He was the first to delineate what he described as a dioritic phase of the Yeoval Batholith as being a separate entity from the main adamellite phase of the batholith. His isotopic studies (Gulson and Bofinger 1972), showed a clear time difference of 40 million years between the intrusion of the diorite and intrusion of the main adamellite phase of the batholith. From this he concluded that there was no genetic relationship between the adamellite and the diorite. Gulson classified the rocks of the Yeoval Batholith by their chemical composition. He found that the bulk of the diorite was actually a high-K diorite (Gulson 1972), which differs from normal diorites only in a higher potassium and related trace elements content. High-K diorites are believed to be the coarse grained equivalents of the high-K andesites (Gulson et al, 1972). However, Gulson's high-K diorites have since been identified petrologically as granodiorites (Patterson et al 1983, Ambler 1979), and as monzodiorites
Glendale Exploration conducted several studies of a number of small deposits in the monzodiorite and surrounding rocks in the early 70's (Smith 1971, Buchhorn 1972, Buchhorn 1973). Their work included a geochemical survey at Jake's Prospect (see figure 1), and reports on mineralization control at a number of deposits including the Goodrich deposit.

In the early 1970's, Hastings Exploration discovered a large, low grade, disseminated porphyry copper style deposit at the Yeoval Prospect (Wright-Smith and Gould 1973, King 1974). The results of an initial drilling program were studied by Ambler (1972) and, together with additional information from later drill holes, was published by Ambler and Facer (1975). North Broken Hill Ltd. joined Hastings Exploration in 1973 and 1974 and carried out further exploration and drilling around the Yeoval prospect. The information derived from this was published by Ambler (1976, 1979). A comprehensive study of the Yeoval prospect was the subject of Ambler's Ph.D. thesis (1979).

Disseminated copper mineralization associated with small porphyritic intrusions was discovered at the Porphyry King prospect (see figure 1) (Bowman, 1973; Bowman and Hobbs, 1974) and at the Yeoval East prospect (Rogis, 1975).

The accompanying mine data sheets for the Dubbo 1:250,000 metallogenic map lists style of mineralization and production figures for most of the old shafts and mines in the area (Matson 1974).

The Geological Survey of New South Wales conducted a detailed survey around Yeoval in the mid 1970's. Petrological reports on various rock types were prepared (Rogis 1975, Barron and Beckett 1976). Patterson et al (1977) presented a detailed report on the geology and mineralization of the area which presented the results of the survey. The work was then revised and published (Patterson et al 1983) as part of a publication dealing with the porphyry copper deposits of New South Wales. This paper discarded the old Yeoval Granite terminology which had previously been used to describe both the monzodiorite and adamellite phases of the Yeoval Batholith. They suggested the names Naringla Granodiorite and Obley Granite for the two
phases, and this terminology has been modified to Naringla Monzodiorite and Obley Adamellite for this paper.

In more recent times, scheelite has been discovered at the Yeoval prospect and at a few other localities. It has been suggested that the area may emerge as a new tungsten field (Plumridge 1984).

1.4 Geological Setting

1.41 Introduction

The Palaeozoic Lachlan Fold Belt is composed of rocks ranging from Cambrian to Carboniferous ages. It outcrops in central and eastern Victoria, and in central, western and southern New South Wales. The Lachlan Fold Belt has been subdivided into several structural zones (i.e. antclinorial and synclinorial zones), and one structural depression (see figure 1.2). The antclinorial zones generally contain the oldest rocks, together with the more deeply eroded intrusions and metamorphics. The younger rocks generally lie within the synclinorial zones.

1.42 Forbes Antclinorial Zone

The Yeoval Batholith lies at the northern end of the Forbes Anticlinorial Zone. Further to the north, the zone is covered by the Great Artesian Basin. The eastern margin is largely defined by an intrusive contact with the Cowra-Yass Synclinorial Zone. The western boundary is the faulted and unconformable contact with the Bogan Gate Synclinorial Zone (Gilligan and Scheibner 1978).

The oldest rocks within the Forbes Anticlinorial Zone are the cherts, jaspers and slates of the Hoskins Formation. These rocks are believed to be of a Cambrian to Early Ordovician age. They are overlain by dominantly andesitic rocks of Middle to Late Ordovician age. Deep water marine sediments were then deposited in the Late Ordovician to Early Silurian. These sediments were subsequently deformed and metamorphosed during the Silurian. Middle to Late Silurian sediments and volcanics rest unconformably on the Ordovician rocks. These sediments were then deformed in the
Early Devonian (Bowen Orogeny). (Gilligan and Scheibner 1978).

Orogenic granite emplacement began in the Late Silurian and continued during the Devonian. The voluminous Young Granodiorite, which covers one third of the Forbes Anticlinorial Zone, was intruded in the south of the zone during the Late Silurian to Early Devonian. In the north, the Naringla Monzodiorite was emplaced in the Early Devonian, and the Obley Adamellite during the Middle Devonian. Around this time, massive granites were also emplaced at Burrinjuck, Grenfell, Eugowra and Gumble (Gilligan & Scheibner, 1978). Shallow freshwater sediments were the last rocks deposited in the zone. These are of a Late Devonian age.

1.43 Cowra – Yass Synclinorial Zone

The Cowra-Yass Synclinorial Zone is a narrow zone trending from Dubbo to Yass. The western margin was described in the previous section. The eastern boundary lies between the Silurian and Devonian sequences belonging to the Cowra-Yass Synclinorial Zone, and Ordovician sequences which are part of the Molong-South Coast Anticlinorial Zone. This contact is commonly faulted.

The oldest rocks in the Cowra-Yass Synclinorial Zone are Late Ordovician to Early Silurian sediments that were deposited on the flanks of the Molong Volcanic Rise. Unconformably overlying these are Middle to Late Silurian acid volcanics and sediments. A similar sequence of Early Devonian age overlies the Late Silurian rocks. The volcanics in the northern part of the zone are dominantly subaerial whereas to the south they are found to be largely of a submarine nature. Several minor granitic bodies have intruded into this zone generally during the Early Devonian.

The folded sediments and volcanics that outcrop east of Yeoval (see figure 1.4) are part of the Cowra-Yass Synclinorial zone. Ryall (1966) defined them as belonging to the Cudal Group, which extends from Wellington to South of Cowra. Smith (1969) described low grade regional metamorphism affecting rocks of the Cudal Group near Canowindra (see figure 1.3). No evidence has previously been found for regional metamorphism of the Cudal Group in the Yeoval district.
Figure 1.2 - Structural Units of the Lachlan Fold Belt, New South Wales

Figure 1.3 - Metamorphic zones in the Bathurst-Wellington district (after Smith 1969)
Figure 1.4 - General geology of the Yeoval district (after Patterson et al., 1983)
Chapter 2

- Silurian Volcanics and Sediments of the Cowra-Yass Synclinorial Zone

2.0 Cudal Group

The Silurian rocks of the Cudal Group extend from about 18km south of Cowra to 10km west of Wellington. This group consists of a sequence of shale, siltstone, sandstone, volcanics and minor limestone, together with a massive porphyry unit called the Canowindra Porphyry (Gilligan 1974). Within the Cudal Group, there appears to have been a transition from shallow water conditions to the east near the Molong High, and deep water conditions to the west (Cas 1983).

The Cudal Group has been deformed into a series of synclines and anticlines after deposition ceased at the end of the Silurian (Pickett et al. 1982). These folds plunge both north and southwards, and were probably formed during the Bowning Orogeny (Pickett et al. 1982).

Three units of the Cudal Group are exposed in the area studies. These are (in ascending stratigraphic order) the Yullundry Formation, the Canowindra Porphyry and the Hanover Formation (see figure 1).

2.1 Description of Rock Units

2.11 Yullundry Formation

The Yullundry Formation consists of a sequence of chert, tuff, conglomerate, sandstone and shales. It is probably of a Late Llandovery - Early Wenlockian age (Pickett et al. 1982). The predominance of fine grained laminated cherty and shaley sediments, together with the presence of tuffaceous bands and limestone pebble conglomerates, suggest that the unit was deposited in a moderately deep water environment reasonably close to a volcanic rise. The occurrence of minor limestones suggests some shallow water deposition (Pickett, 1982).

Tuffaceous horizons of the Yullundry Formation outcrop on hills around the Suntop mine, east of Yeoval, and also east of the andesite unit in the north-eastern part of the mapping area (see figure 1).
Set C is a typical example of tuff from near the Sunset Mine (GR587738). It is flow banded and medium grained. Thin section examination reveals that phenocrysts of quartz, altered K-feldspar, chlorite and minor zeolites and malachite are set in a matrix of devitrified interstitial glass, opaques and sericite (see figure 2.1). Phenocrysts account for over 75% of the rock.

The average composition is K-feldspar (39.6%), quartz (28.4%), chlorite (14.6%), opaques (6.2%), interstitial glass (6.0%), zeolites (3.2%) and malachite (2.0%). Potassium feldspar crystals average 2mm in length and are extensively altered to sericite. The sericite is Fe rich and gives the feldspar crystals a pale green colouration in plane polarized light. Crystals of K-feldspar are aligned with long axes parallel to the flow direction. Quartz phenocrysts (average grain size 2mm) show signs of compaction, with undulose extinction being common. As for K-feldspar, the long axes of the quartz crystals tend to be aligned with the flow direction. Chlorite phenocrysts range up to 1.5mm in length. Chlorite has formed due to the breakdown of ferromagnesian minerals during the hydrothermal event associated with the intrusion of the Naringla Monzodiorite. Phenocrysts of zeolites and malachite are rare. Zeolites occur as small (average = 0.05mm) sub-rounded grains with a very low (almost isotropic) birefringence. They show a negative relief and have a pinkish tinge under plane polarized light. Rare phenocrysts of ragged green malachite (up to 0.7mm) often rimmed by iron oxide alteration have formed by supergene enrichment. Malachite is more abundant in strongly weathered samples. Devitrified interstitial glass, together with opaques and sericite, make up the matrix.

The tuffaceous outcrops east of the andesite unit differ from the outcrops around the Sunset mine in that they tend to be finer grained and massive, and malachite is absent. The mineralogy and alteration is very similar.

Contacts with other units are not exposed in the mapping area, but Pickett et al.(1982) has described a conformable contact with the Bournewood Formation underlying the Yullundry Formation to the east. The fact that the Yullundry Formation interdigitates with the Canowindra Porphyry east of Yeoval (see figure 1) suggests that the contact between
these two units is conformable as well.

2.12 Canowindra Porphyry

The Canowindra Porphyry was defined by Stevens (1951) as a sparsely garnetiferous porphyry well developed near Canowindra. Ryall (1966) observed columnar jointing at the base of the porphyry, and also spotting in the underlying shales suggestive of a low grade contact metamorphism. These features suggest an extrusive origin for the porphyry.

Pickett et al. (1982) proposed, on stratigraphic evidence, that the age of the Canowindra Porphyry is probably Early to Late Wenlockian. Maggs (1963) found that four horizons of Canowindra Porphyry interfingered with the Yullundry Formation east of Yeoval (see figure 2). The Yullundry Formation is considerably thicker at this locality than elsewhere, and the upper parts are stratigraphically equivalent to the Canowindra Porphyry. This indicates that deposition at the Yullundry Formation extended to the Late Wenlockian at this locality.

Two tracts of Canowindra Porphyry outcrop in the study area. The first lies east of Yeoval, where the Canowindra Porphyry intercalates with the Yullundry Formation. This horizon was first identified as part of the Canowindra Porphyry by Maggs (1963). The second tract outcrops south of Yeoval, roughly parallel to the south-eastern boundary of the Naringla Gonzodiorite (see figure 1). Prior to this study, this horizon had not been recognized as part of the Canowindra Porphyry. Maggs (1963) mapped it as alluvium and Gulson (1968) incorrectly mapped it as tuff. The reasons why this horizon of porphyry is suggested to be part of the Canowindra Porphyry are:

(a) The rocks of this horizon are identical petrologically and mineralogically to those that outcrop east of Yeoval that have previously been mapped (Maggs 1963) as being part of the Canowindra Porphyry.

(b) A garnet found by Gulson (1968) within the previously unidentified tract of Canowindra Porphyry was identified by electron microprobe analysis as being of the almandine-pyrope
variety. This is consistent with the composition of the garnets found within the Canowindra Porphyry elsewhere (Pickett et al. 1982).

(c) A tight syncline extends northwards through the Hanover Formation. Evidence for this can be seen 15km south of Yeoval where a horizon of the Canowindra Porphyry occurs within the Hanover Formation and is obviously folded (see figure 1.4). Also, north east of Yeoval, the Yullundry Formation outcrops on both sides of the Hanover Formation (see figure 1), indicating that the syncline is still present in the Hanover Formation to the north. The Canowindra Porphyry has been folded by the syncline and, as for the Yullundry Formation further north, is seen here to outcrop on both sides of the Hanover Formation.

Petrographically, the Canowindra Porphyry is of dacitic composition in the Yeoval district, although elsewhere it has been described as rhyodacite (Gilligan, 1974). The average composition is quartz (54.6%), plagioclase (18.2%), biotite (21.0%) K-feldspar (4.8%), opaques (0.8%), apatite (0.2%) and zircon (0.2%).

Thin section examination of sample DC37, collected 50m from the monzodiorite boundary (GR554730) revealed that quartz, plagioclase and biotite phenocrysts are set in a very fine matrix composed dominantly of quartz, with minor biotite and opaques. Quartz phenocrysts (average grain size = 0.4mm) are partially resorbed, exhibit undulose extinction, and are deeply embayed. Inclusions of small quartz and mica grains are common. Quartz also occurs in the matrix as very fine grains (< 0.01mm). Plagioclase occurs as subhedral laths (average grain size = 0.06mm) which have been extensively sericitizied. The composition of the crystals range from An25 to An30, indicating that the plagioclase is oligoclase. Multiple twinning is evident even in the most altered grains. All grains have been partially resorbed. Alteration is generally more prevalent around the rims of the grains than in the cores. Biotite (\(K = \) straw yellow, \(L = \) foxy brown) occurs as aggregates ranging from 0.1 to 0.7mm in size. The biotites are secondary, and have probably recrystallized due to contact metamorphism effects of the Naringla Monzodiorite. Inclusions of rounded apatite grains range up to 0.1mm in size and are fairly common. Zircon
inclusions are surrounded by dark pleochroic haloes. Lineations of opaque grains occasionally occur within biotite aggregates (see figure 2.2). Biotite also occurs as very fine grains in the matrix. K-feldspar is present at highly sericitized irregularly shaped phenocrysts.

The main differences between the Canowindra Porphyry close to the contact with the monzodiorite and that which outcrops further away, outside the contact aureole, is that further from the contact biotite occurs as primary flakes ($\times$ = pale yellow, $\parallel$ = brownish green) with vermiculite alteration common along cleavage traces (see figure 2.3). Also, quartz has normal extinction further from the contact, compared with the undulose extinction found close to the contact.

Xenoliths are rare in the Canowindra Porphyry. When they do occur, they are generally small ($< 3$ cm long) and foliated. These xenoliths are identical in texturally and mineralogically to the tuff horizons in the Yullundry Formation (i.e. sericitized K-feldspar, quartz, chlorite and opaques) and have mostly been derived from the underlying Yullundry Formation.

A sample of Canowindra Porphyry has been analysed for major and trace elements. This has been combined with two other analyses from Gulson (1968). The results are recorded in table A1-1.

Ryall (1966) showed that the garnets in the Canowindra Porphyry are identical to those found in the Cowra Granodiorite and, together with the similarity in chemical composition between the two units, used this to suggest that the porphyry is an extrusive equivalent of the Cowra Granodiorite. In 1973, Ashley and Basden claimed that the Cowra Granodiorite was part of the Young Granodiorite. Chemical analyses of the Young Granodiorite (including and from the body previously known as the Cowra Granodiorite) are given in table A1.8 and will be compared with the analyses for the Canowindra Porphyry in Chapter 6.

2.13 Hanover Formation

The Hanover Formation is composed of interbedded black and grey
Figure 2.1 - Green malachite and yellow chlorite together with sericitized K-feldspar and clear quartz crystals. (Tuff; Set-C)

Figure 2.2 - Brown biotite aggregates with lineations of opaques in contact metamorphosed Canowindra Porphyry (DC37).
cherts, slates and mudstones, together with rare tuff horizons. This unit overlies the Canowindra Porphyry and is conformable or slightly disconformable with it (Ryall 1966). Maggs (1963) recorded the presence of Monograptus Bohemicus and Spinograptus Spinosus from shales near the base of the formation, indicating a Ludlovian age. The dominantly fine grained shaley and cherty sediments, together with the graptolite fauna, indicate a deep water depositional environment for the Hanover Formation.

Sporadic occurrences of poorly outcropping mudstone and shale belonging to the Hanover Formation are scattered along the eastern and southern sides of the mapping area. The best occurrence is on a hill near Beulong East Homestead (GR536669) in the south of the area. The contact between the Obley Adamellite and the buff coloured mudstones of the Hanover formation is well exposed on the flanks of the hill (see figure 2.4). The mudstone usually has a conchoidal parting and is generally massive, having no discernable structures. Rare horizons are finely laminated and no cross bedding or graded bedding was apparent. Contact metamorphic effects of the adamellite are not recognizable at this locality, possibly due to the very fine grain size and the quartz rich nature of the rock.

Fine grained black siltstones outcrop at a few localities within the Hanover Formation. These consist of an interlocking matrix of quartz and biotite. The biotite indicates that the sediment has not been transported far, as biotite would break down easily during transport.

A small outcrop of alkali basalt belonging to the Hanover Formation outcrops at the Freehold Prospect south of Yeoval (GR733565). Hydrothermal activity associated with the intrusion of the monzodiorite has affected these rocks, causing epidotization of the basalts. Both porphyritic and fine grained varieties are present.

Thin section analysis of a typical sample (DC47A) from this locality reveals that the composition of the rock is: plagioclase (38.0%), sericite (25.8%), titanaugite (16.6%), opaques (10.2%), quartz (4.0%), chlorite (3.0%) and calcite (2.4%). Plagioclase (An45) phenocrysts range from 2 to 8mm in size and occur as euhedral crystals which are surrounded by alteration rims of sericite. Multiple twinning is common but compositional zoning is very rare. Plagioclase needles in the groundmass (0.1 - 0.3mm)
Figure 2.3 - Green-brown primary biotite flake with vermiculite alteration along cleavage traces in unmetamorphosed Canowindra Porphyry.

Figure 2.4 - Contact between the Obedy Adamellite and the sediments of the Hanover Formation. The sediments outcrop on the left bank of the creek, and the adamellite outcrops on the foreground of the photo and on the hill on the right.
have corroded edges and are occasionally altered to quartz and calcite. Titanaugite (2V = 55°) occurs as irregular grains in the groundmass (average grain size = 0.2mm). Alteration of titanaugite is fairly common. Due to the high dispersion, titanaugite has a pinkish tinge in plane polarized light. Sericite alteration is prevalent throughout the groundmass and around the rims of plagioclase phenocrysts. Chlorite and opaque minerals are usually associated with sericite. Sericite normally occurs as pale green needles and aggregates, and has occasionally broken down to clay minerals. This horizon is of interest because the only volcanics previously reported in the Hanover Formation were quartz bearing tuffs. However, outcrop is restricted to the one hill surrounding the Freehold Prospect (see figure 1), and the basic volcanic episode associated with the formation of this horizon appears to be very restricted in extent.

2.2 Regional Metamorphism

In his paper describing low grade regional burial metamorphism in New South Wales, Smith (1969) described his lowest grade of metamorphism in rocks of the Cudal Group near Canowindra. The characteristic assemblage for this zone of metamorphism was quartz, epidote, albite, chlorite and carbonate.

The rocks of the Cudal Group near Yeoval have undergone hydrothermal alteration, and the alteration minerals produced (as has been described previously) are quartz, albite, sericite, chlorite and carbonate. Although not described before, epidote is also present as an alteration product. Thus, if the above metamorphic assemblage is present in rocks of the Cudal Group around Yeoval, it would be indistinguishable from the hydrothermal alteration mineral assemblages developed during the intrusion of the Karingla Monzodiorite and so cannot be taken as evidence of regional metamorphism.

The presence of zeolites in the tuffs of the Yullundry Formation may indicate low grade regional metamorphism, as zeolites are usually only developed in late vein alteration stages associated with the hydrothermal system (see Chapter 4). However, many zeolites form under diagenetic conditions and are by no means characteristic of metamorphism (Winkler 1979). Thus, the presence of zeolites cannot be taken as proof of regional
metamorphism. Regional metamorphism will be discussed further in Chapter 7.

2.3 Contact Metamorphism

Gulson (1968) briefly described the contact metamorphic effects of the Naringla Monzodiorite on the surrounding country rocks. He found that metamorphism reached hornblende hornfels facies close to the contact, producing disseminated clots of biotite and minor andalusite and possibly cordierite.

This study did not reveal the presence of andalusite or cordierite. However, the presence of secondary clots of biotite were noted in the Canowindra Porphyry close to the monzodiorite contact. These clots are believed to be produced by contact metamorphism and not hydrothermal alteration because wherever hydrothermal activity is seen to have occurred, biotite is not an alteration product. In fact, biotite is usually the most readily altered mineral, commonly being completely altered to chlorite. Hence, hydrothermal activity has not affected the Canowindra Porphyry to a great extent.

The contact metamorphic affects of the Obley Adamellite are not well known. No spotting was produced in the rocks of the Hanover Formation near the contact with the adamellite. Nor could any contact metamorphic effects be discerned in the Naringla Monzodiorite near the adamellite contact. The possible reasons why no contact effects of the Obley Adamellite have been noted in the Naringla Monzodiorite or the Cudal Group are:

(1) the poor outcrop of the monzodiorite and sediments;

(2) Hydrothermal effects may have destroyed any evidence of contact metamorphism; or

(3) the contact metamorphic effects of the Obley Adamellite were minimal.

However, contact metamorphic effects on the Obley Adamellite may be evident in the gabbros and quartz-hornblende diorite. This will be
discussed further in Chapter 3.

The extent of the contact aureole surrounding the Naringla Monzodiorite is not certain but, as unaltered biotites are found in the Canowindra Porphyry 3 km from the monzodiorite contact, the aureole most probably extends for less than 3 km.

2.4 Conclusions

The sediments and volcanics of the Cudal Group were deposited under marine conditions in the Mid to Late Silurian around Yeoval. As deposition continued, input from a nearly volcanic arc decreased with increasing depth of deposition.

Deposition ceased at the end of the Devonian and the Cudal Group was deformed into a series of synclines and anticlines during the Bowing Orogeny. The regional metamorphism that affected the Cudal Group near Canowindra (Smith, 1969) is not recognizable around Yeoval.

During the Early Devonian, intrusion of the Naringla Monzodiorite resulted in a contact aureole being imposed on the country rocks. This metamorphism reached a maximum of hornblende hornfels facies adjacent to the monzodiorite contact. Hydrothermal alteration associated with the intrusion of the monzodiorite has had widespread effects on the Cudal Group.

The intrusion of the Obley Adamellite in the Middle Devonian has not produced any noticeable contact metamorphic effects on the rocks of the Cudal Group.
Chapter 3 - Intrusives and Volcanics of the Forbes Anticlinorial Zone

3.0 Introduction

Several phases of igneous activity occurred in the Forbes Anticlinorial Zone around the Yeoval district during the Devonian. The Naringla Monzodiorite and associated rocks represent the first period of igneous activity, being emplaced during the Early Devonian (see Chapter 7). The second major phase was the intrusion of the Obley Adamellite and related rocks during the Middle Devonian. A body of quartz-hornblende-diorite of uncertain age was emplaced before the intrusion of the Obley Adamellite. Rhyolite dykes of possible Devonian age are the third major phase of igneous activity, intruding the Naringla Monzodiorite along east-west joints. The final period of igneous activity in the Yeoval district was the intrusion of basic dykes into the Naringla Monzodiorite. These dykes are of possible Tertiary age.

3.1 Naringla Monzodiorite

3.11 Basaltic Andesites

Basaltic andesites outcrop at two localities in the Yeoval district. The main occurrence is north-east of Yeoval, here called the northern belt. The basaltic andesites outcrop poorly over a distance of approximately 12km² (see figure 1), and are restricted in occurrence to the flanks of low hills. Due to the paucity of outcrop and lack of continuity, individual lava flows could not be mapped.

The second belt of basaltic andesites outcrops very poorly to the south-east of Yeoval, near the Monzodiorite-Adamellite contact. This belt will be referred to as the southern belt. Apart from a large hill in the south of this belt, the basaltic andesites do not outcrop for more than 100m². As this study has concentrated on the rocks around the Goodrich deposit, the basaltic andesites of the southern belt have been studied in more detail than those of the northern belt. This complements the work of Gulson (1968), as he mainly dealt with the northern belt.
Both fine and coarse grained varieties of basaltic andesites are present in the southern belt, with the fine grained varieties being more abundant. The rock types present are porphyritic basaltic andesite, gabbroic diorite and meta-quartz monzodiorite. The compositions of these rocks are very similar, the main minerals being plagioclase, hornblende, augite, quartz and opaque minerals. The alteration minerals present are chlorite, sericite and epidote (table 3.1).

Plagioclase (An_{40-50}) phenocrysts up to 2.5mm long are sericitized to varying degrees, but noticeably more so in the cores than in the rim. Augite occurs as subrounded grains that are often twinned (see figure 3.2). Reaction rims of hornblende and opaque minerals always surround augite grains, and total replacement of augite by hornblende has occasionally occurred (see figure 3.3). The components making up the fine grained matrix are needles of twinned plagioclase crystals together with irregular hornblende and opaque crystals. The average grainsize in the groundmass is about 0.01mm. Chloritization of hornblende is not uncommon, and epidote is developed in the cores of the most sericitized plagioclase crystals.

The small body of meta-monzodiorite in the southern belt (figure 2, GR482708) outcrops about 20m from the Naringla Monzodiorite. In hand specimen, it is a dark green to black coarse grained igneous rock with small (2mm thick) aplite veins transecting it.

The meta-monzodiorite is porphyritic with phenocrysts of plagioclase (An_{20-43}) and augite set in a matrix of quartz, K-feldspar and mafic minerals (table 3.1). Quartz and K-feldspar are interstitial to all other minerals and range in grainsize from 0.1 to 0.5mm. These grains have been strongly recrystallized and now have sutured grain contacts. Triple junctions are very abundant. Quartz has a strongly undulose extinction and K-feldspar is highly sericitized. The present of sutured grain contacts and triple junctions strongly suggest that this body of monzodiorite has been contact metamorphosed during the intrusion of the Naringla Monzodiorite.

Plagioclase laths have undergone sericitization and rare epidotization. Augite crystals have been almost completely replaced by hornblende. Breakdown of hornblende has produce clots of small biotite and
Figure 3.1 - Twinned augite crystal surrounded by a reaction rim of hornblende and opaque minerals. Gabbroic diorite - southern belt (DC116).

Figure 3.2 - Secondary hornblende and opaque minerals in relict augite grain. Gabbroic diorite, southern belt (DC116).
opaque grains, and biotite has undergone partial chloritization. Biotite is also present as small (average 0.5 mm) discrete flakes in the groundmass. These grains have probably been produced by the contact metamorphic effects of the Naringla Monzodiorite, as biotite is not present in any other rocks of the northern and southern basaltic andesite belts.

The main differences between the northern and southern belts is the abundance of fine grained volcanic rocks and the total lack of coarse grained varieties in the northern belt.

Gulson (1968) has described the rock types present in the northern belt as being porphyritic basalt, meta-andesite, pyroxene andesite, orthoclase bearing andesite and associated pyroclastic rocks including fine grained tuffs, breccias and agglomerates. However, as will be discussed later, the classification scheme for andesitic rocks has changed since Gulson produced his thesis, and the rocks Gulson described are actually mainly basaltic andesites.

The basaltic andesites of the northern belt are very similar petrographically to those of the southern belt and will not be described in detail here. One rock type unique to the northern belt that Gulson did not recognize is an epidotized porphyritic basaltic andesite. Hydrothermal alteration has affected a porphyritic basaltic andesite so that half of the rock is now composed of epidote and opaque minerals (table 3.1). The intensity of the epidotization is very rare in the rocks of the Yeoval district, with the only other locality at which this has occurred is in the alkali basalts at Freehold's Prospect (GR564734). Epidote (together with minor quartz) has completely replaced the phenocrysts, and plagioclase needles in the groundmass have been epidotized to varying degrees. Tiny rounded opaque grains are very abundant in the groundmass and have probably formed after hornblende (see figure 3.4).

At one locality in the northern belt (GR591835), a small body of Naringla Monzodiorite has intruded the basaltic andesites. This, combined with the contact metamorphic effects noted in both belts indicates that the Naringla Monzodiorite intruded the basaltic andesites.
Geochemical analyses for major and trace elements have been conducted on a sample of gabbroic diorite and of meta-monzodiorite from the southern belt. These have been combined with Gulson's (1968) four analyses from the northern belt and one from the southern belt, and are presented in appendix 1, table Al-2.

Andesitic rocks have been subdivided into basaltic andesites (low-Si andesites) with 52% to 56% SiO₂ (Jakes and White 1972). They have also been subdivided into low, medium and high-K varieties (Gill 1981). These subdivisions are represented on a plot of SiO₂ vs K₂ (see figure 3.4) for the analyses given in table Al-7. The two coarse grained rocks have also been plotted on this diagram as they are the coarse grained equivalents of the andesitic rocks.

All but one of the samples plot in the high-K field of figures 3.4. The exception is Gulson's volcanic breccia which, as its name implies, is not a true igneous rock and should not have been grouped with the other rocks as it is chemically distinct from them. The remainder of the samples plot in the basaltic andesite field with two exceptions. The meta-monzodiorite is sufficiently enriched in SiO₂ to plot in the high-K andesite field, and the porphyritic basalt is too deficient in SiO₂ to be classified as an andesitic rock. However, as both of the rock types outcrop with the basaltic andesites, it is most likely that they are part of the same suite.

Patterson et al (1983) believed that the basaltic andesites are unrelated to the Naringla Monzodiorite, and that they are Ordovician in age. However, there is isotopic and geochemical evidence to suggest that the basaltic andesites are the extrusive equivalents of the Naringla Granodiorite. This suggestion will be pursued in Chapter 6.

3.12 Gabbrro

Gabbros and minor pyroxenite outcrop at the northern end of the monzodiorite. The gabbroic rocks outcrop on a flat plain over approximately 6km², with outcrop being very poor near the contact with the monzodiorite, and very good near the Obley Adamellite (see figure 1). The pyroxenite outcrops over 25m² and is surrounded by the monzodiorite. It
Figure 3.3 - Epidotized porphyritic basaltic andesite. Note abundant opaque grains in the groundmass. - Northern belt (DC92).

Figure 3.4 - Nomenclature of andesites using $K_2O$ and $SiO_2$. - (modified after Gill 1981).
was not visited by this author.

The gabbros are typically coarse grained black rocks that are extremely hard and resistant to weathering. Minerals present in the gabbros include plagioclase, hornblende, augite, biotite, orthopyroxene, olivine, chlorite and opaques (see tables 3.1 and A1-1).

Plagioclase (An$_{61}$-An$_{85}$) occurs as euhedral laths ranging from 0.2 to 1.5mm in size. Most grains are simply twinned and all are sericitized to some extent. Augite is the dominant pyroxene. Grain size is quite variable (2.20mm) and most grains are twinned. All augite crystal are surrounded by reaction rims of hornblende and opaque minerals, and alteration to hornblende has also occurred along fractures that transect augite crystals (see figure 3.5). Hornblende is present as both primary grains, and secondary after clinopyroxene. Hornblende crystals range from 0.01mm up to 6mm in size and have occasionally undergone breakdown to biotite. Small (0.1-0.4) flakes and clusters of biotite are commonly intergrown with opaque minerals and have been partially replaced by chlorite.

Olivine is not present normally in the gabbro, although some samples contain up to 8%. When present, olivine is surrounded by irregular reaction rims, and Gulson (1968) has suggested the following reaction sequence:-

olivine - orthopyroxene + clinopyroxene - amphibole + spinel - biotite.

This sequence is mostly in agreement with observations made during the course of this study, however, Gulson has not recognized that biotite breaking down to chlorite is a further stage in the reaction sequence. This sequence is not a result of hydrothermal alteration, as biotite is never a breakdown product of hornblende in the hydrothermal system. It is always the first mineral to have altered during hydrothermal alteration, and completely chloritized biotites, together with unaltered hornblendes in the same rock, are fairly common in the Yeoval region. When hornblende does break down (in the more intensely altered rocks) chlorite and opaque minerals are the products.

Contacts between the gabbro and the surrounding rock units are not
exposed. The contact with the Naringla Monzodiorite may be gradational, as rocks transitional to the two rock types (see table 3.1) outcrop between them. However, this minor outcrop is surrounded by a large area of alluvium and so the nature of the contact cannot be proven. The Boxleigh Park Adamellite rises sharply to form a steep hill adjacent to the gabbro plain, and this suggests an intrusive contact between the two bodies.

The gabbro has formed a ridge near the Obley Adamellite contact, and outcrop is much better on this ridge than elsewhere in the unit. The gabbro may be more resistant to weathering here, due to recrystallization during contact metamorphism of the gabbro by the Obley Adamellite. Hornblende alteration of pyroxene is noticeably more pronounced in the gabbros close to the adamellite contact, and this suggests that the reaction sequence described above may have been produced by heating of the gabbro during intrusion of the Obley Adamellite.

Gulson (1968) has described the presence of two small areas of pyroxenite which are composed of up to 80% pyroxene and amphibole. The rock is dark green coloured and pyroxene grains can be up to 2cms long. Alteration of augite to hornblende is common. The pyroxenite is entirely surrounded by the Naringla Monzodiorite and a complete gradation exists between the two end members (Gulson 1968).

Geochemical analyses of three gabbros and three pyroxenites from Gulson (1968) are listed in appendix 1, table A1-1).

3.13 Monzodiorite

The monzodiorite is a heterogeneous body, that ranges in composition from diorite to granodiorite. It outcrops poorly over 90km², with a length of approximately 20km and a maximum width of 9km (see figure 1). Generally small boulders and pavements of monzodiorite are sparsely distributed over low hills. The best outcrops of monzodiorite occur on hills that have been intruded by abundant rhyolite dykes NE of Yeoval.

Gulson (1968) originally classified the Naringla Monzodiorite chemically as a high-K diorite. Ambler (1979) reported that the host rock for the Yeoval porphyry copper prospect contains modal quartz ranging from
25% to 30%, so that petrographically it is a granodiorite. Barron and Beckett (1976) and Patterson et al. (1983) believed that the intrusive varied in composition from granodiorite to adamellite.

The Naringla Monzodiorite has here been classified petrographically, as the effects of hydrothermal alteration may have affected the chemical composition of the samples. Modal analyses of nine samples from the Naringla Monzodiorite (determined by conducting 500 point counts of thin sections - see table 3.1) have been combined with 46 modal analyses from Gulson (1968) (determined by conducting 2000 point counts of stained rock slabs - see appendix 1; table A1-4, and appendix 2; table A2) and are presented on a Streckeisen plot (figure 3.7). Since over half the total analyses plot in the monzodiorite field, the body is here classified as a monzodiorite.

It is noticeable from figure 3.7 that the bulk of the analyses from this study plot in the granodiorite field. This is because they have mostly been collected from around the porphyry copper deposits, where the most highly fractionated rocks of the suite occur. This means that the silica content is higher at these localities than elsewhere in the suite, and the rocks are of granodiorite composition.

Two main structural orientations are present in the monzodiorite. The first is a widespread jointing direction striking approximately east-west. McManus and Loudon (1966) suggested that there had been some movement along this jointing direction at the Goodrich Deposit. Stereoplots of poles to joints, fractures and veins for the Goodrich, Yeoval and Cyclops Mines, and for the Naringla Monzodiorite as a whole are presented on figures 3.8 to 3.11 respectively. The dominant orientation on these diagrams is the east-west jointing. Abundant alteration veins and areas of pervasive albitic alteration occur in areas of closely spaced jointing at the Yeoval and Goodrich deposits. Numerous rhyolite and basic dykes have intruded the monzodiorite along the joints.

The second structural orientation is more sporadic in nature and strikes roughly north-north-west. Movement along this direction has occurred, with the east-west joints being sheared by this movement at some localities (see figure 3.6). Also, the rhyolite dykes have been sheared
Figure 3.5 - Augite phenocryst (right) breaking down to hornblende and opaques. Gabbro (DC86).

Figure 3.6 - Joints in the Naringla Monzodiorite oriented 098/88°S disrupted by a small shear zone bearing 164/82°W (Yeoval East Prospect GR550775).
Figure 3.7 - Ternary Plot of modal quartz, K-feldspar and plagioclase for the Naringla Monzodiorite and Obley Adamellite (modified after Streickeisen; 1973).

- Granodiorite (this study)
- Monzodiorite (Gulson 1968 - Table A1 - 3)
- Monzodiorite (Gulson -968 - Table A2)
- Adamellite
- Microadamellite
Figure 3.8 - Goodrich Deposit

Figure 3.9 - Yeoval Deposit

Figure 3.10 - Cyclops Deposit

Figure 3.11 - Naringla Monzodiorite
and faulted by these structures (see figure 3.20). This indicates that the faulting occurred after intrusion of the rhyolite dykes into the east-west jointing system. As the basic dykes were not observed to be faulted, and as rare basic dykes strike approximately north-south, this indicates that the basic dykes intruded after the faulting occurred. Many of the smaller copper deposits around Yeoval lie on these faults and shear zones (see Chapter 5).

The typical monzodiorite is a medium grained equigranular grey coloured rock that weathers to an earthy brown colour. In thin section, plagioclase crystals are subhedral and range in size from 0.3 to 4mm. Compositionally zoned crystals range from An$_{48}$ in the core to An$_{17}$ in the rim. Sporadic sericitization of plagioclase laths is common (see figure 3.12) and interstitial quartz range from 0.2 to 2mm in size. Hornblende ($=$ yellow, $=$ bluish green, $=$ brown-green) is present as irregular grains that are often partially altered to chlorite and opaque minerals. Orthoclase crystals have a turbid appearance and are dusted with abundant brown sericite. They are often intergrown with quartz and range in size up to 2.5mm. Chlorite grains generally have a ragged appearance (see figure 3.12) and reach 1.5mm in diameter. Chlorite is produced from the breakdown of biotite and hornblende during hydrothermal alteration. Biotite ($=$ straw yellow, $=$ dark brown) is so susceptible to chloritization that it is rarely seen in thin section. When present, it contains abundant apatite inclusions and occasional zircon inclusions are surrounded by pleochroic haloes.

A small outcrop of leucocratic granodiorite occurs at the Yeoval East Prospect (figure 4). Mafic minerals comprise only 2% of the rock, the rest being interlocking grains of plagioclase, quartz and minor K-feldspar. The relationship between this body and the Naringla Monzodiorite is uncertain due to the poor outcrop.

Geochemical analyses of two samples of granodiorite from the Goodrich deposit have been conducted for major and trace elements. One is propylitically altered (GR49) and one is albitically altered (GR 53). The results have been combined with 28 analyses of monzodiorite (Gulson 1968) and 23 analyses of granodiorite (Ambler 1979) and are presented in appendix 4, table A1-3.
Xenoliths are fairly rare in the Naringla Monzodiorite. There are two main types recognizable, the most common type being very fine grained, with occasional phenocrysts of plagioclase and hornblende. These two minerals also dominate the groundmass, and quartz, K-feldspar and opaque minerals are only present in minor amounts. These xenoliths are normally no more than 5cm long (although some reach 20cm in length), and have a subrounded shape. The second variety of xenolith is medium grained and contains plagioclase, hornblende, quartz and rare biotite, together with very fine grained mosaics of plagioclase and hornblende. Geochemical analyses of two samples of the first type of xenoliths from Goulson (1968) are given in appendix 1, table Al-7.

3.14 Porphyritic Microgranodiorite

Small bodies of porphyritic microgranodiorite outcrop within the Naringla Monzodiorite at the Yeoval, Yeoval East and Porphyry King Prospects (see figure 1). Porphyritic microgranodiorite was first recognized in the dumps at the Goodrich mine by Patterson et al. (1983).

Outcrop varies from very poor to non-existent, with the body of microgranodiorite at the Yeoval Prospect having been delineated by drilling (see figure 4). Patterson et al. (1983) reported that the microgranodiorite reached a maximum width of 350m in drill hole Y16. This is much larger than the other porphyritic bodies, which only outcrop to a maximum extent of 20m.

The typical microgranodiorite from Goodrich is not obviously porphyritic in hand specimen, making it difficult to distinguish from the Naringla Monzodiorite. The rock is often an orange-pink colour due to albition of plagioclase, and this has led previous workers to classify it as adamellite (Ringis and Kennedy 1964). It weathers to a dark brown colour, and some samples are a greenish colour on fresh surfaces due to extensive chloritization.

In thin section, the rock is composed of phenocrysts of plagioclase, quartz, and chlorite set in a fine grained matrix of quartz, chlorite, BPl orthoclase and opaque minerals (table 3.1). Phenocrysts comprise about 80% of the rock. Quartz phenocrysts reach 2.2mm in diameter and contain
inclusions of all other minerals except orthoclase. Quartz crystals in the matrix have an average grainsize of 0.05mm. Plagioclase (An0-An9) phenocrysts are subhedral shaped and multiply twinned. Development of sericite is very common (see figure 3.13), and calcite and epidote are also fairly common alteration products of plagioclase, indicating the high degree of hydrothermal alteration that has affected the monzodiorite. Chlorite forms clusters after biotite and hornblende and is commonly intergrown with opaque minerals. Orthoclase occurs in the groundmass and is very sericitized, giving the grains a turbid appearance. The grains are less than 0.05mm in diameter, and are intergrown with quartz, Z-Zoisite is distinguished from epidote by its anomalous blue birefringence, and from clinozoisite and B-zoisite by its dispersion (\(\r > \nu\)). It is present as small crystals after plagioclase.

Ambler (1979) has recognized two types of microgranodiorite at the Yeoval Prospect. The first is a porphyritic hornblende-biotite-microgranodiorite which has often suffered intense alteration of pervasive and vein types. The composition is similar to the porphyry at Goodrich except that hornblende and biotite are present both as phenocrysts and in the groundmass, and comprise up to 5% by volume of the rock. This suggests that the microgranodiorites at Yeoval are not as intensely altered as the microgranodiorite at Goodrich. The ferromagnesian minerals have undergone partial replacement to chlorite and epidote.

The second type of microgranodiorite does not appear porphyritic in hand specimen. In thin section, it consists of phenocrysts (85%) of plagioclase, quartz, hornblende (8%), biotite (3.5%) and orthoclase set in a fine ground matrix. The higher proportion of hornblende in this rock led Ambler (1979) to call it a porphyritic hornblende microgranodiorite.

Ambler (1979) has shown from observations of intrusive contacts in drill core from the Yeoval Prospect that the hornblende-biotite microgranodiorite intruded the granodiorite, and the hornblende microgranodiorite then intruded these two bodies.

Forty three geochemical analyses of both varieties of microgranodiorite from the Yeoval Prospect (Ambler 1979) have been combined with two samples of microgranodiorite from the Goodrich Deposit (GR51-sericitized
3.12 - Sericitized plagioclase laths together with chlorite (after biotite) and unaltered quartz and hornblende. (GR49 - Goodrich Deposit)

Figure 3.13 - Phenocrysts of sericitized plagioclase (P) and chlorite (C) set in a fine grained matrix of quartz and opaque minerals. (Porphyritic Microgranodiorite, Goodrich Deposit - sample GR51)
microgranodiorite and GR54 – chloritized microgranodiorite) and these results are presented in appendix 1, table A1-4.

3.15 Porphyritic Dacite Dykes

Four small northerly trending porphyritic dacite dykes outcrop at the Yeoval Prospect (see figure 4). Outcrop is poor, consisting of a few narrow (up to 2m wide) pavements of white dacite. The rocks are similar in composition to the hornblende-biotite-microgranodiorite porphyry but have less phenocrysts (30-50% by volume – see figure 3.14). Drill core studies show that the dacite dykes have a sharp intrusive contact with the granodiorite host rock (Ambler 1979).

The typical relatively unaltered dacite is a porphyritic fine grained rock, greenish-grey coloured on fresh surfaces and white on weathered surfaces. Elongate black amygdules are also present. The modal composition of the dacite sample is given in table 3.1.

Plagioclase phenocrysts (An₁₀-An₂₅) are subhedral in shape and range from 0.2 to 2.8mm in size. Sericitization of plagioclase is extreme, and epidote is often developed in the cores of plagioclase crystals (see figure 3.14). Inclusions of opaque grains are common. Quartz occurs as sub-rounded phenocrysts (0.1 to 2.0mm) and as very fine (0.01mm) interlocking grains in the groundmass. Extinction varies from straight to weakly undulose. Chlorite is present as an alteration product together with opaque grains after mafic minerals. A ragged appearance is typical of these chlorites, and their grainsize ranges from 0.3 to 2.1mm.

Chlorite is also present as the major filling mineral in the amygdules mentioned previously (see figure 3.14). Other filling minerals are sphene, chalcopyrite, calcite, epidote and sercite (Ambler 1979). Amygdules are present in all four dacite dykes and the hornblende-biotite-microgranodiorite, and a zonation is developed in one dyke where the edge of the dyke contains no amygdules, and abundance then increases towards the centre of the dyke. Ambler (1979) believed that the amygdules developed as a result of a buildup of vapour pressure during crystallization, combined with a reduction in continuing pressure resultant from boiling episodes within the hornblende-biotite-microgranodiorite. The significance of the amygdules
will be discussed further in Chapter 8.

Ambler (1979) has suggested that the porphyritic dacite and the hornblende-biotite-microgranodiorite have a very close genetic relationship and has proposed a model for their formation. This model will be discussed in Chapter 8.

Eighteen samples of porphyritic dacite were geochemically analysed for major and trace elements by Ambler (1979). These results are presented in Appendix 1, table A1-5.

3.2 Quartz Hornblende Diorite

A fine to medium grained diorite body trends in a north-south direction at the northern end of the Naringla Monzodiorite (see figure 1). Due to poor outcrop, the relationship between the diorite and the monzodiorite is uncertain. Large angular blocks of diorite have been incorporated into the Obley Adamellite (see figure 3.15), indicating that the adamellite intruded after the formation of the diorite body.

In hand specimen, the diorite is a fine grained black igneous rock that weathers to a brown colour. Outcrop is good, particularly in the Buckenbah Creek. The model composition of the rock is 56.8% plagioclase, 15.6% hornblende, 14.2% quartz, 4.4% biotite, 2.6% opaque minerals and 1.4% sphene.

Plagioclase (An$_{41}$-An$_{55}$) occurs as subhedral laths ranging up to 1.5mm in length. In contrast to the rocks of the Naringla Monzodiorite, sericitic alteration of plagioclase is virtually non-existent. Hornblende (\(\alpha\) = clear, \(\beta\) = blue green, \(\gamma\) = pale green) is present as irregular grains ranging from 0.2 to 1.1mm in size. They are extensively broken down to biotite and opaque minerals. Quartz patches range from 0.05 to 0.8mm and have undulose extinction. Biotite (\(\alpha\) = yellow, \(\beta\) = \(\gamma\) = dark brown) is present as both secondary aggregates after hornblende, and as primary flakes (average grain size = 0.6mm) containing abundant apatite inclusions. Sphene crystals (average grain size = 0.3mm) have a subrectangular shape and are often associated with biotite.
Figure 3.14 - Blue-black spherical amygdules filled with chlorite, together with sericitized and epidotized plagioclase phenocrysts and subrounded quartz phenocrysts set in a fine grained matrix of quartz and opaques. (Porphyritic Dacite, Yeoval Prospect - YV6A).

Figure 3.15 - Angular blocks of quartz-hornblende-diorite incorporated in the Obley Adamellite. Aplite veins often transect the diorite inclusions. (GR574869).
The abundance of biotite, together with the absence of sericite indicate that the rock has not been affected by the hydrothermal system (probably due to the very hard, resistant nature of the rock). As for the gabbro described previously, the breakdown of hornblende to biotite and opaques has probably been produced by contact metamorphism during the intrusion of the Obley Adamellite.

3.3 Obley Adamellite

The bulk of the Yeoval Batholith is composed of a medium to coarse grained bright pink coloured rock with a low mafic content (see figure 3.15). This rock has previously been described as granite, but when modal analyses (see table 3.2 and A1-6) are plotted on a Streickeisen diagram (figure 3.5), the coarse grained varieties fall into the adamellite field. The outcrop is good, with tors and pavements of adamellite scattered across heavily timbered steep ridges. Gulson (1968) has classified three distinct rock types in this body. They are: (1) Two-feldspar type, (2) One-feldspar type and (3) Granophyric type (here called microadamellite). Two types of dykes are associated with the adamellite, those are aplite dykes and a microadamellite dyke.

3.3.1 Two Feldspar Adamellite

The dominant phase of adamellite in the area mapped contains both plagioclase and orthoclase. It is a pink coloured medium grained rock, although some orthoclase crystals reach a diameter of 1.5 cm. Modal composition is given in table 3.2.

Orthoclase is the dominant mineral, occurring as large irregular sericitized crystals often granophyrically intergrown with quartz. Sericitization give the grains a dusty brown colour (see figure 3.16). Patches of quartz range from 0.2 to 4mm and contain inclusions of plagioclase, biotite and opaque minerals. Plagioclase (An5-An16) is subhedral and ranges in grain size from 0.5 to 2.5mm. Sericite is well developed in plagioclase crystals, particularly in the cores. Ragged crystals of hornblende ( = pale yellow, = blue green, = dark green) have undergone extensive alteration to chlorite and opaque minerals. The grain size ranges from 0.3 to 14mm. Sphene crystals (ave. grain size = 0.3mm) are
diamond shaped and have high birefringence and relief. Flakes of biotite
( = straw yellow, = dark brown) are usually associated with opaque
minerals and contain tiny inclusions of apatite, zircon and opaque grains.
Most grains are chloritized, but even in highly altered rocks some biotite
flakes are completely unaltered (see figure 3.16).

Geochemical analysis of a sample of two-feldspar adamellite has been
conducted for major and trace elements. This has been combined with three
analyses from Gulson (1968) and are given in appendix 1, table A3-6.

3.32 One Feldspar Adamellite

No outcrops of Gulson's (1968) one feldspar type were observed in the
study area. A brief description from Gulson is given here for
completeness:

"The one feldspar granites consist mainly of quartz with minor ferro-
magnesian minerals. The feldspar is perthite in which there are equal
proportions of potassium feldspar and plagioclase. Biotite is the
usual ferromagnesian mineral".

The geochemical analysis of a sample of one-feldspar adamellite from
Gulson (1968) is listed in table A1-6, appendix 2.

3.33 Microadamellite

A fine grained zone of Obley Adamellite outcrops at the contact with
the Naringla Monzodiorite. It is usually about 300m thick although in
places it is non-existent. Outcrop is generally poor, dominantly
consisting of scattered float due to abundant fractures in the rocks.
Modal analyses are given in tables 3.2 and A1-6.

Weakly undulose quartz grains are occasionally granophyrically inter-
grown with orthoclase and range in grainsize from 0.01 to 0.8mm.
Plagioclase (An₁₀-An₂₇) is subhedral and reaches a maximum grainsize of
1.8mm. Sericitic alteration has affected all plagioclase grains to some
extent, and the most altered grains contain small grains of epidote.
Orthoclase grains are interstitial to all others and are dusted with
sericite. Extensive alteration to hornblende ( = yellow, = blue-green, = deep green) and biotite ( = straw yellow, = = dark brown) to chlorite and opaque minerals have occurred. Apatite inclusions in biotite are rounded and reach a maximum of 0.1mm in diameter. A zoned, irregularly shaped allanite crystal was observed in the microadamellite. It has pleochroism ranging from light brown to brownish yellow (pleochoric scheme not determinable). Alteration to epidote, chlorite and opaques is occurring around the edge of the crystal (see figure 3.17). Rounded apatite inclusions reach 0.5mm in grain size.

A blocky medium grained xenolith (3cm long) found in the microadamellite is composed of zoned and twinned plagioclase (An$_{20}$-An$_{30}$) crystals, chloritized hornblende ( = clear, = pale blue green, = pale green) and irregular patches of quartz and minor sericitized K-feldspar. The mineralogy is compatible with the Naringla Monzodiorite, although hornblende is more abundant.

Geochemical analysis of two samples of microadamellite from Gulson (1968) are presented in table A1-6.

3.34 Aplite

Minor aplite dykes are present in the Obley Adamellite and in the Naringla Monzodiorite. They have a sugary texture and normally do not contain mafic minerals. The dykes are normally narrow (0.3m average) and are not laterally continuous, having an average outcrop extent of 5m. The dykes have intruded the Monzodiorite along the east-west joints and only occur near the adamellite contact. A small body of aplite is present south of the Goodrick deposit (see figure 2).

The aplites are very similar minerallogically to the Obley Adamellite, and a geochemical analysis of an aplite dyke (from Gulson 1968 - see table A1-7) within the Obley Adamellite has an almost identical composition to the host rock (see table A1-6). It is most likely that the aplite formed during the intrusion of the Obley Adamellite.
Figure 3.16 - Extremely sericitized brown orthoclase crystals, together with unaltered biotite crystal and clear quartz crystals. (Obley Adamellite - DC43)

Figure 3.17 - Yellow-brown allanite crystal with clear apatite inclusions. Alteration to epidote (yellow) and chlorite (pale green) is occurring around the rims of the grain. (Microadamellite - GR50).
3.35 Microadamellite Dyke

A dyke of adamellite composition has intruded the basaltic andesites south of the Goodrich deposit (see figure 1). The dyke has intruded in an east-west direction and extends for a distance of 1 km. The dyke appears to be related to the Obley Adamellite, as it has a higher mafic mineral content than the rhyolite dykes, and has a very similar petrological composition to that of the adamellite (see table 3.2).

A xenolith present in the dyke consists of a fine grained (average 0.05mm) aggregate of hornblende, sericitized plagioclase, epidote, opaques, chlorite and minor quartz together with rare hornblende phenocrysts. The xenolith is rimmed by coarser hornblende crystals (average 0.5mm). The abundance of hornblende and plagioclase and the scarcity of quartz suggests that this xenolith originated from the basaltic andesites that are host to the dyke.

3.4 Boxleigh Park Adamellite

A small body of medium grained pink adamellite outcrops on a steep hill between the gabbro and the Naringla Monzodiorite in the north of the area. Contacts with the surrounding rocks are unexposed, but the rapid change in topography suggests an intrusive contact.

The modal composition is 33.2% K-feldspar, 32.0% quartz, 28.8% plagioclase, 8.6% hornblende, 4.4% chlorite and 2.0% opaques. Orthoclase occurs as irregular grains interstitial to all others, and often exhibits granophyric intergrowths with quartz. Orthoclase crystals are a dusty brown colour due to high degree of sericitization. Patches of quartz range from 0.2 to 3mm in size. Plagioclase (An17-An35) is often compositionally zoned, and sericitization and minor epidote alteration is most prevalent in the cores of these grains. In multiply twinned plagioclase laths, sericitic alteration is dominant along the twin planes. Plagioclase ranges from 0.9 to 3.7mm in size. Irregular grains of hornblende are often surrounded by opaque minerals and have two prominent cleavages of 120°. Chlorite ranges from 0.5 to 2.5mm and is present as ragged grains after biotite.
Table 3.1 - Modal composition of rocks from the Maringla Monzodiorite

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</table>

* - Geochemically analyzed samples.

(Modal estimates were obtained by doing 500 point counts of thin sections).

Table 3.2 - Modal composition of rocks from the Obley Adamellite

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<tr>
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<td>J-Feldspar</td>
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<td>-</td>
<td>1.6</td>
</tr>
</tbody>
</table>

* - Geochemically analysed samples

(Modal estimates were obtained by doing 500 point counts of thin sections).
The Boxleigh Park Adamellite was named after the property it outcrops on to avoid confusion with the Obley Adamellite. It is very similar petrographically to the Obley Adamellite and may in fact be related, but no geochemical data is available on the body and so the origin of the adamellite cannot be proven.

3.5 Rhyolite

West of Yeoval, a small area of dominantly silicic volcanics outcrop over approximately 1 km. The volcanics are usually flow banded, and sometimes convolutely so (see figure 3.18). Outcrop is very poor, dominantly being float strewn across the surface. Contacts between the other units are not exposed, however, Gulson (1968) has suggested that the volcanics have been contact metamorphosed by the intrusion of the Obley Adamellite. Gulson also suggested that the rhyolite is related to the abundant rhyolitic and basic dykes that have intruded the Naringla Monzodiorite. However, the rhyolite and rhyolite dykes have been affected by hydrothermal alteration whereas the basic dykes have not, indicating that the basic dykes intruded after hydrothermal alterations ceased and therefore cannot be related to the rhyolite.

Modally, the rhyolite is composed of 33.8% K-feldspar, 28.0% interstitial glass, 24.4% quartz, 6.4% plagioclase, 6.2% epidote and 1.2% opaques. K-feldspar is present as irregular interlocking grains (average grainsize = 0.1mm) together with quartz, opaque minerals and interstitial glass in the groundmass. All orthoclase grains are sericitized, and some have been partially altered to epidote. Quartz is present as rounded and partially resorbed phenocrysts (average grainsize = 1mm) as well as in the groundmass. Plagioclase phenocrysts (An0-An5) have also been partially resorbed and range in grainsize from 0.4 to 1.8mm. Sericitization of plagioclase is minimal, however, some alteration to epidote has occurred. Interstitial glass is very fine grained and isotropic.

In his thesis on the Victorian Valley Batholith, Atkinson (1976) has suggested that fold structures can be produced in banded dykes by drag effects during intrusion, due to differation in velocity between the less viscous magma in the middle of the dyke and that of the chilled margin. As the rhyolites at Yeoval are of an extrusive nature, and it is not certain
if they are from a lava dome or a rhyolite flow, the method of formation cannot be determined. However, if they were a flow, a similar mechanism to that for the formation of folds in dykes is possible, as the rocks beneath the flow would cause chilling of the base of the flow, and the resultant velocity differential would produce folds.

Geochemical analysis of a sample of rhyolite has been conducted for major and trace elements, and the results are listed in table A1-7.

3.6 Rhyolite Dykes

Numerous rhyolite dykes have intruded the Naringla Monzodiorite along the east-west jointing system. They normally are one to three metres wide, although some areas of rhyolite extend for half a kilometre in width. Since they are more resistant to erosion than the Naringla Monzodiorite, the dykes form small prominent ridges across the countryside rising up to 2m from the relatively flat plains. Vertical flow-banding is often developed (see figure 3.19) and both porphyritic and even grained varieties are present.

They are often displaced by the previously described minor faults (see figure 3.20). At some localities, shearing has occurred (see figure 5) and occasionally the dykes have suffered fault drag (see figure 4).

The typical modal composition of the rhyolite dykes is 59.2% K-feldspar, 35.0% quartz, 4.2% plagioclase, 0.6% chlorite, 0.6% epidote, 0.2% biotite and 0.2% opaques. K-feldspar is the dominant mineral, and often granophytic intergrowths of K-feldspar with quartz are so well developed that they are visible in hand specimen (see figure 3.21). Spherulites of K-feldspar are present in some samples, indicating that devitrification of the dykes has occurred. As K-feldspar is very sericitized, hydrothermal alteration has probably affected the dykes and this may have produced the observed devitrification textures. Quartz patches are interstitial to all other minerals, and range in grain size from 0.01mm up to 0.5mm. The larger grains are weakly undulose. Plagioclase (An9–An5) is present as extremely sericitized phenocrysts that have undergone partial resorption. The grain size ranges from 1 to 3mm. Epidote is present as a very fine grained alteration product of K-feldspar.
Figure 3.18 - Convoluted flow banding in rhyolite (GR500774).

Figure 3.19 - Vertical flow banding in a rhyolite dyke, Cyclops Mine (GR541793).
Figure 3.20 - Left lateral fault offsetting a rhyolite dyke, Yeoval Prospect (GR541773).

Figure 3.21 - Granophyrically intergrown quartz (white) and K-feldspar (black) transected by an epidote vein (Rhyolite - TH-A).
The rhyolite dykes at the Goodrich deposit are quartz deficient compared to the dykes further north, containing 17.8% quartz, 67.6% K-feldspar and 4.4% plagioclase (An9-An9). Previous workers have called these dykes trachytes (Ringis & Kennedy 1964, Patterson et al. 1983), however, as they contain quartz and calcium bearing plagioclase this classification is incorrect.

The rhyolite dykes at Goodrich have intruded areas of intensely veined and altered granodiorite and have not been affected. This phenomena has been observed at several other localities, including the Yeoval Prospect where Ambler (1979) observed it in drill core. Ambler also noted from his drill core studies that the rhyolites at Yeoval have intruded the Naringla Monzodiorite, porphyritic microgranodiorites and the dacite dykes. These facts indicate that the rhyolite dykes intruded after the main phase of alteration. However, epidote veins often transect rhyolite dykes (see figure 3.21) and at one locality, the groundmass of a rhyolite dyke adjacent to a fault has been completely epidotized, and rare albite phenocrysts are the only unaltered minerals (GR538772). This indicates that the rhyolite dykes have been affected by the later stages of hydrothermal alteration (see Chapter 4). This places constraints on when the rhyolites have been intruded, and these constraints will be discussed in Chapter 7.

Atkinson (1976) has proposed that flow banding in dyke rocks of the Victorian Valley Batholith, Western Victoria, is produced by flow differentiation in a highly viscous magma. If the magma was not highly viscous, destruction of the banding could occur due to magma mixing. This process has resulted in bands of feldspar-rich and mafic-rich material.

At Yeoval, the dyke rocks contain virtually no mafic material. The bands are produced by an alternating sequence of very fine grained interstitial glass, and coarser layers composed dominantly of quartz and K-feldspar. Although the composition of the layers are different at Yeoval, the same process of formation is envisaged as for that at Victoria Valley.

Geochemical analyses of a sample of rhyolite from near the Goodrich deposit has been conducted for major and trace elements, and the results are presented in table A1-7.
3.7 Basic Dykes

The final intrusive event in the Yeoval district is represented by a swarm of small, discontinuous basic dykes. These dykes are less significant than the rhyolite dykes, with the largest lateral extent being 200m although the dykes are normally no more than 5m long and 0.5m wide. Most have intruded the Naringla Monzodiorite along the east-west joints (see figure 3.22), although some have a northerly orientation, having intruded the small faults. Unlike the rhyolites, the basic dykes outcrop level with the surface of the Monzodiorite outcrops (see figure 3.22).

The typical basic dyke is a fine grained black igneous rock with occasional grey plagioclase phenocrysts. The modal composition is 54.2% plagioclase, 20.0% olivine, 18.2% interstitial glass and 7.6% opaques. Euhedral crystals of twinned plagioclase (An$_{64}$-An$_{93}$) together with sub-rounded and fractured olivine crystals and small irregular opaque grains are set in a matrix of very fine grained greenish brown interstitial glass.

The plagioclase crystals and the interstitial glass are totally unaltered and no alteration veins transect the basic dykes, even though they intrude highly altered areas of monzodiorite. Hence, it can be concluded that the dykes intruded after hydrothermal alteration ceased. Gulson (1968) has suggested that the dykes are related to the alkali basalts of tertiary age that are common in eastern Australia.

A geochemical analyses of a basic dyke from Gulson (1968) is presented in table A1-7.

3.8 Young Granodiorite

The Young Granodiorite is a massive body that outcrops over 3990km$^2$ in the southern part of the Forbes Anticlinorial zone, 200km south of Yeoval. It is the only intrusive body apart from the Yeoval Batholith that has been subjected to detailed studies. Stevens (1952) suggested that the Canowindra Porphyry is an extrusive equivalent of the Young Granodiorite.

Ashley and Basden (1972) have reported that the dominant rock type of the batholith is grey, massive to foliated biotite granodiorite grading to
adamellite, and that veins, dykes and xenoliths (in contrast to the Naringla Monzodiorite) of several types are abundant. The granodiorite is characterized by the abundance of biotite and the paucity of K-feldspar. White and Chappell (1983) have described the Young Granodiorite as an S-type (i.e. derived from a sedimentary source).

Two separate K-Ar biotite ages have been determined for the Young Granodiorite. These are 414 ± 4 Myr (recalculated after Everden and Richards, 1962), and 405 ± 16 Myr (recalculated after Thomson, 1973). This indicates that the Young Granodiorite is slightly older than the Naringla Monzodiorite (395 ± Myr - see Chapter 7).

Geochemical analyses of seven samples of Young Granodiorite (from Ahsley and Basden 1972) are given in table A1-8.

Figure 3.22 - Basic dyke intruded along east-west jointing in the Naringla Monzodiorite (Yeoval East Prospect - GR550773).
Chapter 4 - Alteration

4.0 Introduction

At most porphyry copper deposits, a crude concentric pattern of alteration types is developed. A few deposits, such as San Manuel-Kalamazoo (North America) also show vertical zonation (Lowell and Guilbert 1970). Unfortunately, classification schemes for alteration zones are not universally accepted, and a wide range of classification schemes exist.

The alteration zones of the San Manuel-Kalamazoo porphyry copper deposit defined by Lowell and Guilbert (1970) are a useful classification scheme, as they provide assemblages for both high and deep level porphyry copper system. The mineral assemblages that define the alteration zones at San Manuel-Kalamazoo are summarized in figure 4.1 (after Lowell and Guilbert, 1970) and the alteration and mineralization zones are summarized in figure 4.2.

The mineral assemblages at the Yeoval porphyry copper deposits bear some similarities to those at San Manuel-Kalamazoo. Hence, comparisons of mineral assemblages between the two deposits can be made and this is done in section 4.11. Comparisons with the alteration assemblages of Meyer and Hemley (1967) are also made in this section.

Unfortunately, the porphyry copper deposits in the Yeoval district are by no means classical systems. Alteration zones are generally not developed, and where minor variations of alteration do occur, these are of a very limited and patchy nature, and it was not practical to map them in the field. Hence it is not possible at Yeoval to classify alteration and mineralization zones in the manner of figure 4.2.

4.1 Pervasive Alteration

In his study of the Yeoval porphyry copper prospect, Ambler (1979) recognized that the first hydrothermal event resulted in a zoned assemblage consisting of an albitized core, grading outward into a phyllic zone and thence into a propylitic zone, although a high degrees of overlap exists between the phyllic and propylitic zones. These zones were determined from
Figure 4.1 - Summary of hydrothermal alteration assemblages at San Manuel-Kalamazoo.

Figure 4.2 - Concentric alteration - mineralization zones at San Manuel-Kalamazoo. (a) Schematic drawing of alteration zones. (b) Schematic drawing of mineralization zones. (c) Schematic drawing of the occurrence of sulphides (after Lowell and Guilbert 1970).
drill core studies, they are not developed on the surface of the deposit. The zones have very similar mineral assemblages, the only real differences being the development of albite in the albitic zone, and the abundance of sericite and lack of albite in Ambler's phyllic zone.

Propylitic alteration has affected nearly all the rocks in the study area, and is present at the Goodrich deposit. Albitic alteration has also been recognized at Goodrich, but phyllic alteration was not. In addition, two different types of chloritic alteration are present at Goodrich.

4.11 Propylitic Alteration

Alteration minerals have been developed in almost all rock types present in the area studied. Both plagioclase and K-feldspar are sericitized to varying degrees, and in the more extensively altered grains calcite and/or epidote are sometimes developed. Ferromagnesian minerals have invariably altered to chlorite and magnetite, and rare epidote and sphene may also be developed from alteration of these minerals. Sometimes pervasive epidotization and development of abundant magnetite have affected the basic rocks of the Cudal Group, and also the basaltic andesites (see figure 3.4). Occasionally, zoisite is the epidote group mineral developed. Copper sulphides (particularly chalcopyrite) are sometimes developed. Hence, the typical alteration assemblage developed in most of the rocks at Yeoval is:

Sericite + chlorite + magnetite + epidote (zoisite) + calcite + sphene + Cu-sulphates

The propylitic zone at San Manuel-Kalamazoo (the outermost alteration zone) consists of a poorly defined zone characterized by the development of chlorite, epidote and carbonate. Quartz is unaffected, but clay minerals, albite and pyrite may be developed (Lowell and Guilbert 1970). The majority of these minerals are also produced by low grade regional metamorphism, and surface weathering, and it is difficult to distinguish propylitic alteration from these effects.

Meyers and Hemly (1967) state that propylitic assemblages include epidote (zoisite, clinozoisite), albite, chlorite, septochlorite and
carbonate. Common accessory minerals are sericite, pyrite and iron oxides and less common accessory minerals are zeolites and montmorillonites.

The similarities between the assemblages described by Lowell and Guilbert (1970) and Meyer and Hemly (1967), and the assemblage developed at Yeoval indicate that the dominant alteration at Yeoval is propylitic in nature. One major disparity between the typical assemblages and the alteration at Yeoval is that magnetite is developed instead of pyrite. Even in the most highly altered rocks, Yeoval is unusual due to the almost total absence of pyrite. At San Manuel-Kalamazoo, the only assemblage where magnetite is developed instead of pyrite is in the outer deep level assemblage (see figure 4.1). However, a deep level of formation for the porphyry copper deposits at Yeoval is not consistent with its geological setting. This will be discussed further in Chapter 8.

Due to the often highly fractured nature of the Narinigla Monzodiorite, it is possible that even though the rocks appears fresh, movement of groundwaters through them has caused breakdown of minerals to produce the alteration minerals present in the rocks. However, epidote is not produced by surface weathering, and the presence of epidote indicates that the alteration developed in the Narinigla Monzodiorite and the Cudai Group is not a result of weathering.

There is isotopic evidence that indicates that there has been no regional metamorphism after the intrusion of the Narinigla Monzodiorite (see Chaper 7). This indicates that the alteration in the monzodiorite is not a product of regional metamorphism.

Weathering and metamorphism cannot account for the alteration in the monzodiorite, and deuteric alteration appears unlikely due to the often intense nature of the alteration. This, together with the abundant epidote veins present throughout the monzodiorite, indicates that the alteration in the monzodiorite is propylitic alteration caused by hydrothermal circulation associated with the porphyry copper deposits.

4.12 Sericitic Alteration

The assemblage Ambler (1979) described for his phyllic alteration zone
consisted of an identical mineral assemblage to that described in the previous section, and only differed in that sericite was highly developed in feldspars. As phyllic alteration is characterized by the development of sericite, pyrite and quartz (Lowell and Guilbert 1970), the alteration at the Yeoval prospect cannot be classified as phyllic. This is because pyrite is almost completely absent and quartz is unaffected by the alteration at Yeoval. The greater abundance of sericite is the only noticeable petrological difference between the propylitic alteration and the phyllic alteration of Ambler (1979). Hence, it is proposed here that the phyllic alteration be called sericitic alteration to distinguish it from the typical phyllic alteration zones at porphyry copper deposits.

On a ternary plot of CaO, Na₂O and K₂O (figure 6.6) the sericitized rocks from the Yeoval Prospect plot to the right of the major trend for the rocks of the Naringla Monzodiorite. This is due to potassium enrichment associated with the sericitic alteration phase.

4.13 Albitic Alteration

Albitization is classified by Meyer and Hemley (1967) as a subtype of propylitic alteration in which sodium metasomatism converts nearly all aluminous material to white Na-rich plagioclase, locally associated with Na-rich amphibole. Associated minerals are usually those of the propylitic assemblage, particularly epidote.

Sporadic areas of albitic alteration have developed within areas of intense veining and fracturing at the Yeoval and Goodrich deposits. These areas of albitic alteration are really pseudo-alteration zones as they are a result of overlapping albitic alteration haloes around alteration veins (see figures 4.3 and 4.4). These areas are of limited extent, usually no more than five metres in width.

The albite developed at Yeoval is a bright pink colour, unlike the typical albite described by Meyer and Hemley (1967). At other porphyry copper deposits in New South Wales, such as Copper Hill (Manini 1985) and Cargo (Weston 1984), the albite produced by hydrothermal alteration is also pink coloured, and this suggests that the development of pink albite may be characteristic of the N.S.W. porphyry deposits. Previous works
(e.g. Ambler & Facer 1975) have been misled by the pink colouration and have incorrectly stated that alteration veins are surrounded by pink K-feldspar alteration haloes.

The innermost zone of albitic alteration at the Yeoval Prospect is relatively unfractured (Ambler 1979) and this may mean that this zone has been produced by genuine pervasive albitic alteration, unlike the pseudopervasive alteration observed on the surface.

When plotted on a ternary CaO-Na₂O-K₂O diagram (see figure 6.2), the albitically altered rocks plot to the left of the trend for the Naringla Monzodiorite complex (as distinct from the sericitic alteration which plots to the right).

4.14 Chloritic Alteration

Chlorite has a wide distribution in hydrothermal systems, due to its wide range of compositions. Where chlorite is the dominant phase of alteration, there have normally been addition of large amounts of magnesium and/or iron to the alteration zone.

Two very minor occurrences of different types of chloritic alteration occur at the Goodrich deposit. The first is in rare samples of porphyritic microgranodiorite from the dumps around the Goodrich mine. Samples that have suffered chloritic alteration have a dark grey-green colour due to the abundance of chlorite. Modal analysis of a typical sample (DC54) is given in table 3.1. It contains abundant chlorite, sericite, epidote and calcite. When plotted on a diagram of total/Fe vs SiO₂ it plots well away from the normal microgranodiorite field due to the enrichment in Fe associated with the development of chlorite. This alteration is of only very minor significance, and represents local concentration of FeO + MgO in the propylitically altered rocks.

A second, more extreme type of chlorite-epidote alteration has affected a xenolith in a highly fractured outcrop of Naringla Monzodiorite south of the Goodrich deposit (GR485720). The xenolith is fine grained and has a greenish-black colour due to the abundance of chlorite and epidote. Other minerals present are quartz and minor magnetite. Numerous epidote,
Figure 4.3 - Abundant alteration veins surrounded by albitic alteration haloes. Overlap of the alteration haloes gives the rock a pinkish tinge - Goodrich Deposit (GR479729).

Figure 4.4 - Numerous chlorite-epidote alteration veins, transecting a sample of Naringla Monzodiorite. Overlapping albitic alteration haloes have given the rock a pseudo-pervasive albitic alteration. (Sample GRV - Goodrich Deposit).
calcite and quartz veins transect the rock. The xenolith is about 70cm long.

The geochemical analyses of the xenolith is given in table A1-7. It contains abundant iron, magnesium and calcium and almost no sodium or potassium. Zinc is anomalously high in this rock (1015ppm). This value is far greater than any other obtained in the Yeoval district, with the next highest value occurring in a sample of granodiorite from the Yeoval Prospect (Y20-162) which contains 284ppm zinc.

4.2 Vein Alteration

Alteration veins are widespread in the Naringla Monzodiorite, and are particularly abundant around the porphyry copper deposits. Some veins extend into the Obley Adamellite and the Cudal Group, but these are much more restricted in extent.

Epidote veins are the most common type (see figure 4.5), although calcite (figure 4.6) and quartz veins are also common. Prehnite veins are very rare (see figure 4.7). Alteration veins are often surrounded by pink albitic alteration haloes (see figures 4.5 and 4.6), and these are normally no more than 4cm wide. As described previously, overlap of alteration haloes in highly fractured areas can produce a pseudo-pervasive albitic alteration.

Several vein stages have affected the porphyry copper deposits, and these are summarized in sections 4.21 and 4.22.

4.21 Goodrich Deposit

Four stages of alteration were identified during the study of alteration at the Goodrich deposit. These stages are summarized in figure 4.9.

Sulphides are abundant in the earliest vein stage, in which quartz and magnetite are the dominant minerals. These veins reach a maximum width of 30cm, although they are more typically no more than 15cm thick. They are often transected by later epidote and calcite veins (see figure 4.8). The
Figure 4.5 - Epidote vein surrounded by albitic alteration halo 3 cm wide. (DC76).

Figure 4.6 - Calcite vein surrounded by 2 cm wide albitic alteration vein. Naringla Monzodiorite (GR519785).
quartz-magnetitite veins are concentrated in a steeply dipping semi-circular structure and were mined for gold in the late 19th century. A discussion of the formation of the quartz-magnetitite veins is presented in Chapter 8.

The most abundant vein assemblage in the rocks surrounding the Goodrich deposit is calcite, chlorite and epidote. These veins are often surrounded by pink albitic alteration haloes.

4.22 Yeoval Prospect

Ambler (1979) identified six vein stages at the Yeoval Prospect, and his findings have been summarized in figure 4.10. Noticable differences between the vein stages at Yeoval and Goodrich are:

(1) The presence of Cu-sulphides in the first five vein stages at Yeoval, compared to only one stage of Cu-sulphides at Goodrich.

(2) K-feldspar occurs in the first three vein stages at Yeoval, and is totally absent from veins at the Goodrich deposit.

(3) Epidote is present in the earliest stages at Yeoval, whereas it is present in the middle stages at Goodrich.

(4) Chlorite is present in three vein stages at Goodrich and only one at Yeoval.

(5) Late stage prehnite* and zeolite veins are present at Yeoval and absent at Goodrich.

*Prehnite veins, although rare, are present at various localities around the Naringla Monzodiorite, and are not restricted to the Yeoval Prospect.

The propylitic vein assemblages (i.e. epidote and calcite bearing) are the most common type at Yeoval, as they are for the Goodrich deposit and for the Naringla Monzodiorite as a whole. The presence of K-feldspar, sericite and zeolite, in vein assemblages, are unique to the Yeoval prospect.
Figure 4.7 - Prehnite alteration vein in Naringia Monzodiorite. (CC1 - Cyclops Mine).

Figure 4.8 - Small epidote veins transecting quartz-magnetite-chalcopyrite vein in porphyritic microgranodiorite - Goodrich Deposit (GR484726).
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Figure 4.9 - Vein stages for the Goodrich Deposit.

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Figure 4.10 - Vein stages for the Yeoval Deposit.

(Key to figures 4.9 and 4.10:

- Dominant
- Sub-dominant
- Minor
- Accessory)
4.23 Conclusions

The important conclusions that can be drawn from studies of the vein assemblages are:

(1) The earliest hydrothermal fluids at the Yeoval Prospect were enriched in potassium and sulphides, and Ambler (1979) has suggested that these fluids formed at temperatures at around 500°C.

(2) The earliest hydrothermal fluid at the Goodrich deposit was enriched in iron, copper, gold and molybdenum and totally devoid of potassium.

(3) The later vein assemblages at both deposits are rich in calcite, and probably formed at a much lower temperature than the earlier veins, indicating that hydrothermal activity has occurred over a prolonged period of time.

(4) The zeolite and prehnite vein stages at Yeoval indicate that the Yeoval deposit had a longer and more varied hydrothermal history than the Goodrich deposit.

4.3 Alteration Minerals

Electron microprobe analyses of chlorite, albite, prehnite and epidote were conducted to determine their exact chemical compositions and to compare them with published analyses. Analyses were conducted using a JOEL JX54 electron microprobe. Sericite was not analysed as the grain size was too fine, however, Ambler (1979) has analysed sericitic from hydrothermal veins at the Yeoval Prospect, and these analyses are discussed together with the other alteration minerals in the following sections.

4.31 Chlorite

Thirteen partial probe analyses of chlorite from the Yeoval prospect (Ambler 1979) have been combined with microprobe analyses of chlorite from the Goodrich and Cyclops deposits and from three general localities in the
Naringla Monzodiorite. The analyses are presented in appendix 3, table A3-1.

Most of the analyses lie in the pycnochlorite field of figure 4.11, although four from the Yeoval Prospect lie in the ripidolite field and one lies in the Brunsvigite field. The average chemical formula of the chlorites from the Yeoval district is:

\[
(Hn_{0.1}, Mg_{5.1}, Al_{2.3}, Fe_{4.5})_{12} [(Si_{5.7} Al_{2.3})_8 O_{20}] (OH)_{16}
\]

4.32 Albite

The cores of four pink albitized plagioclase crystals from vein alteration haloes in the Naringla Monzodiorite were analysed and found to range in composition from An\textsubscript{1} to An\textsubscript{5}. Three sericitized (but unalbitized) plagioclase cores were analyzed for comparative purposes. Two from the northern end of the monzodiorite were found to be labradorite (An\textsubscript{56} and An\textsubscript{58}). An unalbitized plagioclase from the Goodrich deposit (where the Naringla Monzodiorite is of granodioritic composition) was found to be andesine (An\textsubscript{48}). Analyses are presented in appendix 3, table A3-2.

4.33 Epidote

Two epidote analyses from veins at the Goodrich deposit are given in appendix 3, table A3-2. The totals are slightly low, but are comparable with other published analyses at epidote (Deer et al. 1966). They are slightly richer in Si and Al, and lacking in Fe compared to those of Deer et al. Ca is almost identical.

4.34 Prehnite

Four prehnite analyses from veins in the Naringla Monzodiorite are presented in appendix 3, table A3-2. Although the totals are low, the analyses are comparable with those in Deer et al. (1966), since water has not been analysed in this study, and H\textsubscript{2}O comprises about 4.5% of the prehnite analyses in Deer et al. Si and Al are lower than the published data. Ca is roughly equal and Fe is higher. One analysis from this study contains much higher Fe and less Al than the other three, and this may have
been due to contamination by other minerals during probing.

4.35 Sericite

Averages of five sericitcs from the dacite porphyry and four from the Naringla Monzodiorite at the Yeoval Prospect from Ambler (1979) are given in table A3-2. They are rich in K, and Mg is higher than normal sericite (Deer et al. 1966). Na is very low, indicating that they are true sericitcs and not paragonite.

Figure 4.11 - Nomenclature of chlorites and oxidized chlorites (after Hey 1954).
Chapter 5 - Mineralization

5.0 Introduction

There are three main types of mineralization in the Yeoval region. These are:

(1) Disseminated Deposits

(2) Shear Zone and Fault Deposits

(3) Vein Deposits

The disseminated deposits are the largest, and the most important economically. Examples of this type are the Yeoval and Porphyry King Prospects. Deposits that occur in small shear zones and faults (normally no wider than 1m) include the Cyclops and Al mines, and Jakes Prospect. Vein deposits are the least important economically, and include the Timby Hills Mine and the Freehold Prospect. The Goodrich Mines has characteristics of all three of the above deposit types, and will be discussed separately.

5.1 Goodrich Mine (figure 2)

The Goodrich deposit is presently poorly exposed. It is in a water filled open pit (see figure 5.1) and only minor quartz veins are exposed in the walls of the pit. There are also three underground openings (the 20, 36 and 54 metre levels), but these are currently filled with water. They were dewatered in the mid 1960's and a study undertaken at that time produced the composite plan of the mine shown in figure 5.2 (after McManus and Loudon 1966).

The main style of mineralization available at Goodrich is within quartz-magnetite veins found as fragments on the dumps surrounding the open pit. Pink albite alteration haloes often surround the veins. The host rock is normally porphyritic microgranodiorite, although some are also present in the Naringla Monzodiorite.
Figure 5.1 - Looking south-west over the Goodrich open pit. Malachite and azurite staining are present on the walls of the pit. (GR484728).

Figure 5.2 - Composite plan of the Goodrich mine, showing the 20, 36 and 54 metre levels in relation to the rim of the open cut (accuracy fair only as tape and compass used in presence of very magnetic lode).
Gold is the main ore mineral, and free gold is present as small (1mm) blebs in magnetite and quartz (see figure 5.3). No chalcopyrite was observed to be associated with gold.

Chalcopyrite is by far the most abundant sulphide mineral. It occurs as discrete grains up to 1cm in width, and as veins and rims around magnetite in quartz – magnetite veins (see figure 5.4). This indicates that magnetite formed after chalcopyrite. Chalcopyrite is also seen to be replacing rare pyrite grains (up to 0.4mm in width), indicating pyrite was one of the first minerals to form. Molybdenite is present as rosettes in quartz veins (see figure 5.5) ranging up to 6cm in diameter. Bornite occurs as sporadic small grains associated with chalcopyrite. Minor covellite is present, indicating limited supergene alteration. Malachite and azurite are very common on weathered surfaces. Alteration of magnetite has led to extensive development of hematite (see figure 5.3).

Disseminated chalcopyrite, bornite and pyrite have been observed within the microgranodiorite and the Naringla Monzodiorite at the Goodrich deposit. Disseminated mineralization is more abundant in the microgranodiorite than in the Monzodiorite.

Mining at Goodrich was carried out from 1868 to 1912, and the methods employed were open cut, shafts, drives and cross cuts. The production figures are 400t Cu, 159kg Au and 62kg Ag (Matson 1974). The estimated reserves of the Goodrich deposits are 400t at 2.1% Cu, 5.2g/t Au and 14.9g/t Ag (McManus and Loudon 1966).

McManus and Loudon (1966) have reported that mineralization at Goodrich is controlled by a steeply dipping semi-circular structure that is truncated by an east-west shear. This will be discussed in Chapter 8.

5.2 **Disseminated Deposits**

5.21 **Yeoval Prospect (figure 4)**

The Yeoval Prospect has been the most intensively studied deposit in the Yeoval Region. Ambler (1979) has reported that the copper mineralization is related to the intrusion of two microgranodiorite
Figure 5.3 - Small gold grain (G) in magnetite (M). Alteration of magnetite has produced hematite (H) - Goodrich Mine.

Figure 5.4 - Chalcopyrite (yellow) and chlorite (black) in quartz vein - Goodrich Mine.
porphyries and four dacite dykes into the Naringla Monzodiorite. These dykes have then been subjected to two Cu-bearing hydrothermal fluids, which formed the disseminated mineralization. The formation of the Yeoval Prospect will be discussed further in Chapter 8.

Chalcopyrite occurs as both disseminations in alteration envelopes and as vein filling. Pyrite occurs as disseminated grains commonly intergrown with chalcopyrite. Rare digenite, pyrite, molybdenite and galena occur as small disseminated grains. (Ambler 1979). Malachite and azurite are present on weathered surfaces and as fracture coatings. Scheelite and powellite scales up to 2cm across occur in alteration veins near the microgranodiorite (see figure 4).

The Yeoval Prospect has estimated reserves of 37 million tonnes at 0.23% Cu and 0.007% Mo (Paterson et al. 1983), making it the largest known deposit in the study area. A geochemical soil survey was carried out by the Geological survey of New South Wales (Hobbs 1977). This survey delineated three northerly trending zones containing greater than 1000ppm copper. These zones are shown on figures 3 & 4.

5.22 Porphyry King Prospect (GR 571800)

A small body of granodiorite porphyry was delineated by Bowman (1973) and Bowman and Hobbs (1974) at the Porphyry King Prospect. Chalcopyrite and bornite grains are disseminated throughout the porphyry and tend to be developed within chlorite. Minor malachite is present on weathered surfaces. A geochemical soil survey revealed that anomalous copper (maximum 270ppm) and zinc (maximum 120ppm) values occur within and to the north of the porphyry (Bowman and Hobbs 1974).

5.23 Goonoo Prospect (GR 586832)

Chalcopyrite and pyrrhotite occurs as disseminated grains in hydrothermally altered andesitic rocks and, together with minor scheelite, in quartz magnetite veins. There is no intrusive porphyry body at this locality. The disseminated mineralization is the product of the hydrothermal alteration of the andesite due to the movement of hydrothermal fluids associated with the monzodiorite. Buchhorn (1972) reported that the
highest copper value was 5.7% in one rock sample, but normally mineralization is much lower grade. A small gossan outcrop contained 3350ppm Cu and 5300ppm W.

5.24 Yeoval East Prospect (See Figure 4)

Low grade disseminated mineralization has been reported within a small body of granodiorite porphyry at the Yeoval East Prospect (Rogis 1975). Chalcopyrite and bornite occur both as disseminated grains and within alteration veins. Malachite is occasionally present on weathered surfaces.

5.3 Shear Zone Deposits

5.31 Cyclops Mine (figure 5)

Eleven small shafts (see figure 5.6) have been sunk on minor shear zones and faults within the Naringla Monzodiorite at this locality (see figure 5.67). The shear zones strike at roughly 150° and are steeply dipping to the north-west (see figure 3.10). These shear zones and faults have affected the rhyolite dykes around the mine. Some have been displaced up to 3m by the faults (see figure 5).

Small (<0.5mm) disseminated chalcopyrite grains are present within magnetite, quartz and chlorite. Pyrrhotite, bornite and pyrite are often associated with chalcopyrite. Alteration of magnetite to hematite has occurred extensively at a number of locations around the mine. Malachite and azurite have been produced on weathered surfaces (see figure 5.8).

After the Goodrich mine, the Cyclops Mine was the second largest producer in the Yeoval region. It produced 244 tonnes of ore at 10% Cu. Matson (1974) lists average grades for the mine at 10% Cu, 1.59g Au/t and 4.69g Ag/t. The formation of the Cyclops deposit will be discussed in Chapter 8.

5.32 Suntop Mine (GR 587737)

A small (0.6m) shear zone is present within tuffs of the Yullundry Formation. The most abundant mineral is magnetite with very minor chalco-
Figure 5.5 - Molybdenite rosettes in quartz - Goodrich Mine.

Figure 5.6 - Main shaft at the Cyclops Mine. Malachite is visible on weathered surfaces - Cyclops Mine.
pyrite. Malachite and azurite are common on weathered surfaces. The tuffs are hydrothermally altered and mineralization is probably associated with the hydrothermal activity associated with the intrusion of the Naringla Monzodiorite.

5.33 Southern Mineralized Belt

A group of shear zone deposits, together with the Goodrich Mine, appear to lie on a N-S trending mineralized belt south-west of Yeoval. The deposits are: Jakes Prospect (GR 482644), Mt. Rose and Viles Lode (GR 703488) (all of which occur within the Naringla Monzodiorite) and two unnamed pits (GR 485705) which occur in andesitic rocks.

At Jakes Prospect, chalcopyrite and scheelite have been observed on fracture planes in the monzodiorite. Malachite and azurite are very prominent on weathered surfaces. The highest copper value obtained at this prospect was 2.35% (Buchorn 1973).

The Viles Lode and Mt. Rose shafts lie 20m apart and the strike between the two workings is 170°. At Viles Lode, chalcopyrite, galena, bornite, chalcocite, magnetite, chlorite and quartz all occur in sheared granodiorite. The Mt. Rose shafts to the north contain chalcopyrite, bornite, chlorite, magnetite and quartz. Malachite and azurite are present on weathered surfaces. A small copper anomaly (50ppm Cu) exists between the two deposits. This anomaly also extends northwards from the Mt. Rose mine towards the Goodrich Mine, and reaches 80ppm 200m north of Mt. Rose.

5.34 Northern Mineralized Belt

Two shear zone deposits, the Al Mine and the North Buckenbah prospect, together with the North Buckinbah Gossan, define a N-S trending mineralized belt to the north of Yeoval. Abundant magnetite float occurs between the North Buckinbah Prospect and the Al Mine (see figure 3).

At the Al Mine, small blebs of chalcopyrite are disseminated within specular hematite (after magnetite). Other minerals present are chlorite, prismatic quartz (0.2 - 1mm), epidote, malachite and azurite within sheared monzodiorite. Slickensides were observed along fracture surfaces. A
shear zone trend, 155° and steeply dips to the west. Estimated grades from the three shafts at the mine are 13% Cu, 1.53g Au/E, 24.5g Ag/t (Matson 1974).

The Buckinbah Prospect is a small pit sunk into a thin (0.5m) shear zone. Magnetite, epidote, chlorite and quartz occur within sheared monzodiorite. No chalcopyrite was observed.

The North Buckinbah Gossan is the largest body of gossan in the Yeoval district. It outcrops discontinuously in a roughly N-S direction over 100m, apparently along the same shear zone as the North Buckenbah Prospect (see figure 3). The gossan reaches a maximum width of 5m. It is composed of sericite, chlorite, quartz and hematite. No copper minerals were observed.

5.4 Vein Deposits

5.41 Freehold Prospect (GR 562743)

A quartz vein up to 2.7m wide striking E-W contains gold, chalcopyrite, arsenopyrite and pyrite grains. The host rock is a small horizon of alkali basalt within the Hanover Formation. Two kilograms of gold were produced from this vein at the turn of the century. Hydrothermal alteration is extensive in the country rock, causing epidotization of the basalt. This suggests that the quartz vein is probably related to the hydrothermal activity associated with the Naringla Monzodiorite.

5.42 Timby Hills Mine (GR 582770)

A vein bearing 170/70°E contains minor chalcopyrite and gold. The vein varies from 6 to 23cm thick. Some malachite staining is present on sheared monzodiorite. The vein is probably related to the monzodiorite. Granophytic rhyolite dykes outcrop around the shaft.
Chapter 6 - Geochemistry

6.1 Geochemistry of the Unaltered Rocks

The geochemical analyses from Gulson (1968) and Ambler (1979) are combined with analyses from this study in appendix 1. These have been used to plot Harker variation diagrams in the hope of establishing any geochemical trends, and from this determining any relationship that are present between the various rock types. However, the presence of hydrothermally altered rocks complicates the matter, particularly as Gulson (1968) and Ambler (1979) have not stated which rocks are highly altered.

To distinguish between the hydrothermally altered rocks and those that are relatively unaltered, all data from Yeoval have been plotted on a CaO-Na₂O-K₂O diagram (see figure 8.1). The majority of the analyses define a linear trend from very high calcium (gabbros and pyroxenite) to rocks that contain almost no calcium, and roughly equal amounts of sodium and potassium (adamellites and rhyolites). The ablitically altered rocks are well defined, plotting to the left of the trend in the sodium rich field of the diagram. These rocks have been distinguished by the label A in tables A1-3 to 5. The sericitized rocks are less abundant than the albitized rocks, and plot to the right of the main trend in the K₂O field of the diagram. These rocks have been denoted by an S in tables A1-3 and A1-4.

In order to determine any relationships between the major rock types of the Yeoval district, certain analyses have been excluded from the silica variation diagrams to reduce the scatter and so as not to confuse the data. The analyses that have been excluded are: all albitized and sericitized rocks as determined by the method above; the chloritized microgranodiorite porphyry; xenoliths; the basic dyke and the volcanic breccia.

The Canowindra Porphyry and Young Granodiorite analyses always plot very close together. These analyses are indistinguishable from the dacite and microgranodiorite porphyry analyses on some diagrams. Hence the field for the Canowindra Porphyry and Young Granodiorite is only plotted on those diagrams where it is distinct from the rocks of the Naringla Monzodiorite.

The trends for two I-type suites from the Lachlan Fold Belt (the
Moruya and Jindabyne suites) are plotted for comparative purposes. Also plotted is the chemical analyses of a typical augite from a high-K calc-alkaline suite (from Jakes and White 1972b – see table A1-7).

6.11 Geochemical Classification

The rock types present at Yeoval can be subdivided into several fairly distinct groups on the basis of their silica content. These are: gabbro (43-47%), pyroxenite (47-50%), basaltic andesites and associated rocks (50-57%), monzodiorites and granodiorites (53-66%), microgranodiorite and dacite porphyry (65-69%) and adamellites and rhyolites (73-78%). All rock types are hornblende bearing and below 64% Si all are metaluminous (Al Na + K + Ca but Al Na+K – see appendix 1). This is characteristic of the I-type granitoids of White and Chappell (1983). Above 64% Si the rocks are often strongly peraluminous (see appendix 1), which is characteristic of the S-type granitoids. However, the presence of hornblende indicates that these rocks cannot be S-types, and the apparent peraluminosity may be a product of hydrothermal alteration.

Volcanic rocks in island areas are classified by Jakes and White (1972a) on the basis of chemical composition, in particular the K₂O vs SiO₂ relation and iron enrichment trends on AFM diagrams. Tholeiitic rocks have a high degree of iron enrichment, while calc-alkaline and shoshonitic association have virtually none. When plotted on an AFM diagram (see figure 8.2), the Yeoval rocks define a slightly curved trend, indicating there is very little iron enrichment. This, together with the high potassium content of the Yeoval rocks, indicates that they are a typical high-K calc-alkaline association.

6.12 Major Element Geochemistry

Harker variation diagrams for total Fe, TiO₂, MgO, CaO, Al₂O₃, Na₂O and K₂O have been plotted (see figures 6.3 to 6.9) and these are discussed below.

Total Fe (figure 6.3) shows a very well defined negative correlation with SiO₂, except for the gabbros which are lower in iron. The trend for the Moruya suite is identical to that of the Yeoval district. The augite
plots together with the pyroxenites at the low silica end. The Canowindra Porphyry and Young Granodiorite plot above the trend, and this is a reflection of the higher biotite content of these rocks.

TiO$_2$ (figure 6.4) has a well defined negative trend. The gabbros plot below the trend, as do the pyroxenites and augite. Scatter occurs around 60% SiO$_2$. The trend for the Jindabyne suite is identical to that for Yeoval, whereas the Moruya trend is much steeper. As for total Fe, the Canowindra Porphyry and the Young Granodiorite plot above the Yeoval rocks.

MgO (figure 6.5) is negatively correlated with SiO$_2$ particularly at the high silica end of the diagram. The linear trend is identical to that for the Moruya and Jindabyne suites. Significant divergence from the straight line trend occurs at low SiO$_2$ values. The pyroxenites plot well above the trend in an almost identical position to that of the augite analysis. The four low-silica monzodiorites sampled from near the pyroxenite also plot slightly above the trend, as to the gabbroic diorite and pyroxene basalt. All of these rocks contain augite, and together they define a steeply curved trend up to the augite composition. The gabbros plot at MgO values intermediate to that of the basaltic andesites and the pyroxenites, but at lower side values.

CaO (figure 6.6) behaves in a very similar manner to MgO. There is a good negative correlation at high silica values, although some of the porphyritic rocks have suffered loss of calcium due to hydrothermal alteration. This is consistent with the apparent peraluminosity of these rocks. The Moruya trend is identical to that for Yeoval and high values of SiO$_2$. At the low silica end, there is a divergence upwards away from the main trend, producing a second, steeply curved trend defined by the same rocks as for MgO. Augite does not plot on the diagram due to its high calcium content (19.5 wt% CaO), however, the steeply curved trend extrapolates to this point.

Al$_2$O$_3$ (figure 6.7) has a good negative trend identical to that for the Moruya suite at values greater than 55% SiO$_2$. However, the pyroxenites, basic monzodiorites and some basaltic andesites plot on a very steeply rising positive trend. Augite again plots off the diagram, this time it is due to the extremely low value of Al$_2$O$_3$ (3.8 wt%). Augite plots on the
extrapolation of the second trend.

At a first glance, there appears to be a positive trend from the gabbros to the adamellites, for Na₂O (figure 6.8) and this trend is distinctly different to that of the Moruya suite. Also, scatter is greater on this diagram than most of the others as a result of the effects of hydrothermal alteration. However, it is possible that there is a straight line trend from 68 to 53% SiO₂ parallel to, but at a lower Na₂O value than the Moruya suite. Albition (particularly of the porphyries) may have resulted in the increased Na₂O content for some of these rocks. At the low silica end, it is possible that a second, steeply curved trend extends from the monzodiorites down to the pyroxenites and augite, although the scatter of the basaltic andesites make accurate interpretation difficult. The Canowindra Porphyry and Young Granodiorite plot well below all other analyses at the high silica end.

K₂O (figure 6.9) is positively correlated with SiO₂, but is badly scattered at the high silica end, and recognition of trends is difficult. The Moruya and Jindabyne suites plot at lower K-values and these trends are not parallel. However, due to the scatter of the Yeoval rocks, it is possible to postulate that they are parallel to either trend. The steeply curved trend from the basic monzodiorites to the pyroxenites may be present, but the scatter of the data prevents any definite conclusions being made.

6.13 **Trace Element Geochemistry**

The trace elements Ba, Rb, Sr, V and Zr have been plotted against SiO₂ (figures 6.10 - 6.14). These diagrams are discussed below.

Ba (figure 6.10) shows a good positive linear trend with SiO₂ for the monzodiorite and associated rocks. A large gap of 200ppm Ba occurs between the pyroxenites, and the basaltic andesites. The higher silica rocks are rich in barium (750-900 ppm) and this is due to the higher K-feldspar content of the rock (as Ba partitions into K-feldspar). The most interesting feature of this diagram is the huge scatter for the adamellites and rhyolites (162-887 ppm Ba). The fact that the K-feldspar crystals are extremely sericitized in these rocks suggests that barium has been leached
from them. The one sample of Canowindra Porphyry analysed for barium plots lower than the trend for the Monzodiorite.

Rb (figure 6.11) preferentially enters the melt and therefore increases with fractionation. This is consistent with the positive trend obtained when Rb is plotted against SiO$_2$ for the Yeoval rocks. The trends for the Moruya and Jindabyne suites are parallel to the trend for Yeoval, but occur at lower values for Rb. This is consistent with the results for K (figure 6.9). Considerable scatter of the data occurs, and the porphyritic dacites in particular suggest that hydrothermal alteration has added Rb to the system.

Sr (figure 6.12) is widely scattered, and a negative trend can be interpreted in only the broadest sense. Many of the points cluster near the Moruya trend, but a significant number also plot below this. All rocks with the exception of the pyroxenites and the adamellites plot above the Jindabyne suite trend. Sr preferentially enters K-feldspar and plagioclase, and so the very low Sr content for the pyroxenites is explained by the high (80%) pyroxene content of these rocks. The very low Sr content of the adamellites (31 - 117 ppm) suggests that these rocks are highly fractionated.

V (figure 6.13) is not very useful due to the meagre data below 63% SiO$_2$. Varadium is found primarily in pyroxenites and micas, and the negative trend observed is consistent with the decreasing abundance of ferromagnesian minerals with increasing silica. The trend for the Moruya suite is identical to that for Yeoval. The one point that plots anomalously on the vanadium diagram is the gabbroic diorite from the southern basaltic andesite belt. The high V content (311 ppm) is explained by the abundance of augite in this rock (11.6%).

Zr (figure 6.14) plots as a flat, straight line trend from 68% down to 55% SiO$_2$. There is then a rapid decline to the pyroxenites and gabbros, consistent with the trend for most other elements. Three samples of monzodiorite have anomalously high Zr contents. There are two distinct groupings of adamellite on the Zr variation diagram. The 1-feldspar adamellite and microadamellite sampled near Obley (appendix 2, figure A2-1) have much higher Zr content than the three samples from near the southern
contact with the Monzodiorite.

6.2 Discussion

For the major elements the porphyritic dacites, microgranodiorites, granodiorites, monzodiorites and some of the basaltic andesites, together with the rhyolites and adamellites define very good linear negative correlation trends with silica for total Fe, TiO₂, MgO, CaO and Al₂O₃. This is consistent with decreasing mafic mineral and plagioclase content with increasing silica. K₂O increases, which is agreeable with increasing abundance of K-feldspar and Na₂O may increase although the scatter makes it difficult to tell.

The gabbros plot anomalously on all major element variation diagrams with the possible exceptions of the Na₂O and K₂O diagrams.

The low silica augite bearing rocks (pyroxenite, pyroxene basalt, gabbroic diorite and low Si-monzodiorite) plot on a second, very steep negative curved trend with increasing silica for Ca) and MgO, and very steep positive curved trends for TiO₂, Al₂O₃ and also possibly Na₂O and K₂O. The fact that the augite analysis plots at the end of these trends suggests that fractionation involving pyroxene has been involved.

The Moruya suite is distinguishable from the Yeoval rocks on the TiO₂ and K₂O diagrams. This is consistent with the higher abundance of biotite and lesser abundance of K-feldspar for the Moruya suite (Griffin et al. 1978).

The Canowindra Porphyry and Young Granodiorite always plot together, and have distinctly higher total Fe and TiO₂, as well as lower Na₂O than the Yeoval rocks.

For the trace elements, the adamellites and rhyolites are distinct from the rocks of the Naringla Monzodiorite on the Ba and Zr variation diagrams. Zr indicates that there may be two distinct phases of the Obley Adamellite, and this is supported on geographical grounds. The large degree of scatter for Ba indicates that the rocks have suffered loss of Ba due to alteration of K-feldspar. This diagram also indicates that the
adamellites have been substantially altered in comparison with the monzodiorites, which form a very coherent trend. The very low Sr contents and high silica values suggest that the adamellites and rhyolites are highly fractionated. Rb is consistent with this as it will be high in fractionated granitoids with low biotite since it will prefer the melt. V is very low, which is consistent with the low mafic mineral content.

Positive trends for Ba and Rb, and negative trends for Sr and V, with relatively flat Zr are the characteristics for most of the rocks of the Naringla Monzodiorite. Ba increases due to increasing K contents, since it substitutes for potassium. Since biotite is not very abundant, Rb will prefer the melt, and increasing Rb is consistent with crystal fractionation not involving biotite. Since Sr partitions into both plagioclase and K-feldspar, the steep negative trend is consistent with feldspar fractionation. V is consistent with decreasing mafic mineral abundances.

The gabbros plot anomalously on the Sr variation diagram, but lie at the end of possible extrapolation of trends for Rb, Ba and Zr.

The augite bearing rocks plot on steeply curved positive trends for V, Zr and possibly Rb and Ba. Unfortunately, data for only one pyroxene bearing rock was available for the V diagram (V partitions into pyroxene). This analysis does plot above the major trend of the Naringla Monzodiorite and suggests that V would behave in a similar manner to Mg.

The Moruya and Jindabyne suites have distinctly low Rb than the Yeoval rocks, and Jindabyne is also lower in Sr. The Moruya suite trends are identical to those on Yeoval for V and possibly Sr. Data is not available for Ba and Zr.

The Canowindra Porphry and the Young Granodiorite plot below the Yeoval trends on Ba and Sr variation diagrams, and plot above the trend on the Zr diagram.

The major points that can be made from the variation diagrams of figures 6.3 to 6.14 are:

(1) As the adamellites and rhyolites always plot together on the
variation diagrams (with the exception of Ba) it is possible that they are related. However, the high silica and low Sr content indicate that these rocks are highly fractionated, and this suggests that it may just be coincidence that they plot together on the variation diagrams.

(2) $\text{TiO}_2$, $\text{MgO}$, $\text{CaO}$, $\text{Al}_2\text{O}_3$ and Sr all suggest that the gabbros are unrelated to the monzodiorites. $\text{MgO}$ and $\text{Al}_2\text{O}_3$ strongly suggest that the gabbros and pyroxenites are unrelated.

(3) The Canowindra Porphyry and Young Granodiorite are geochemically distinct from the Naringla Monzodiorite on the variation diagrams for total Fe, $\text{TiO}_2$, $\text{Na}_2\text{O}$, Ba, Sr and Zr, and this suggests that the Canowindra Porphyry and Naringla Monzodiorite are not related. The fact that the Canowindra Porphyry and the Young Granodiorite always plot together on the variation diagrams is good evidence to support the suggestion of Ryall (1966) that the two are related.

(4) Crystal fractionation of clinopyroxene is the most likely process for the formation of the pyroxene "cumulates". Pyroxene fractionation has possibly also played a role in the formation of some of the basaltic andesites, as well as the low silica monzodiorites.

(5) The negative trends for $\text{Al}_2\text{O}_3$, total Fe, $\text{TiO}_2$, $\text{MgO}$, $\text{CaO}$ and Sr for the Naringla Monzodiorite are all consistent with the process of crystal fractionation of plagioclase, hornblende and biotite. However, other processes also could result in similar trends, and this will be discussed in Chapter 8.

(6) The Naringla Monzodiorite rocks differ from the Moruya and Jindabyne suites in that they have higher K and Rb contents. They also have higher $\text{TiO}_2$ than the Moruya suite, and higher Sr than the Jindabyne rocks.
KEY TO FIGURES 6.1 AND 6.2
- Gabbros and pyroxenites
- Basaltic andesites
- Xenoliths
- Monzodiorites and Granodiorites
- Microgranodiorite Porphyry
- Dacite Porphyry
- Adamellite
- Rhyolite
- Basic Dykes

KEY TO FIGURES 6.1 - 6.14
- Gabbros
- Pyroxenites
- Basaltic Andesites
- Monzodiorites and Granodiorites
- Microgranodiorite Porphyry
- Dacite Porphyry
- Adamellite
- Rhyolite
- Canowindra Porphyry and Young Granodiorite
- Moruya Suite Trend
- Jindabyne Suite Trend
Chapter 7 - Geochronology

7.0 Introduction

It was originally intended to recalculate the published ages of Gulson and Bofinger (1972) for the Naringla Monzodiorite and the Obley Adamellite for two reasons:—

(1) The original decay constant is now out of date.

(2) An error existed in the spike calibration at A.N.U. during the 1960's (Gray, pers.comm.).

However, upon close examination of Gulson and Bofinger's data, it became apparent that significant re-interpretation of their results is possible. The regression procedure follows McIntrye et al. (1966), modified by the removal of the t-multiplier. The decay constant used for $\text{Rb}^*_{87}$ is $14.2 \times 10^{-11} \text{yr}^{-1}$ (Steiger and Jager 1977). Analytical procedures are outlined in Gulson and Bofinger (1972). The quality of fit is estimated by the mean square of weighted deviates (MSWD). If the MSWD is not significantly greater than 1.0, then the fit is to within experimental error.

The samples were collected over considerable distances - approximately 20km for the monzodiorite, 30km for the adamellite and 3km for the basaltic andesites (see Appendix 2, figure A2 for the sample localities).

7.1 Naringla Monzodiorite

Gulson and Bofinger (1972) have regressed data for the diorites, monzodiorites, granodiorite, gabbro, and pyroxenite from the Naringla Monzodiorite. With this data they regressed a small skarn that outcrops between the contact of the gabbro and the Obley Adamellite. Their results (including the recalculated $\text{Rb}^*_{87}/\text{Sr}^*_{86}$ ratios and recalculated individual biotite ages) are presented in Appendix 1 x 4 - Table A4-1. The isochron diagram for total rocks and feldspars is given in figure 7.1. Gulson and Bofinger's findings are summarized below; note that all ages and ratios given in the summaries of Gulson and Bofinger's work are taken straight from their 1972 paper.
The recalculated data will be presented after the summaries.

Gulson and Bofinger's findings were:

(1) All data fit a single isochron to within experimental error indicating an age of $411 \pm 2$ Ma., and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of $0.7049 \pm 0.0002$. The most extensively chloritized biotite (Y235) has been excluded from the regression.

(2) The biotites alone define a single "isochron" of $414 \pm 6$ Ma.

(3) Regression of the whole rocks and feldspars produced the same age and interest within the error limits ($387 \pm 26$ Ma., $0.7051 \pm 0.0004$).

The findings from this study are:

(1) The isochron diagram for the Naringla Monzodiorite (excluding biotite) (figure 7.1) indicates that the total rock and feldspar systems are disturbed, as the points are scattered about the isochron in excess of experimental error. Since the system is disturbed, the feldspars were excluded from the regression as they are more susceptible to disturbance than the total rock systems. The skarn was excluded from the regression on geological grounds, as it has probably been produced by metasomatic action associated with the intrusion of the gabbro and/or the Obley Adamellite. The pyroxenite lies outside the experimented error range, and so was omitted from the regression. Regression of the remaining whole rock data produced the model age of $369 \pm 43$ Ma. (MSWD = 2.66) and an initial ratio of $0.7052 \pm 0.0004$.

(2) Although Gulson and Bofinger (1972) stated that only three of the four biotites analysed were sufficiently enriched in radiogenic strontium to calculate independent ages, they published independent ages for all four biotites. When recalculating the biotite ages, the biotite not sufficiently enriched in radiogenic Sr was excluded. The remaining biotite ages all lie within experimental error, and given an average age of $395 \pm 4$ Ma. Since biotite has a much higher $^{87}\text{Rb}/^{86}\text{Sr}$ Ratio than the total rock systems, a regression of total rocks and biotites will be dominated by
the biotites and will produce an age similar to the individual biotite ages (as is the case for Gulson and Bofinger). The regression has not been conducted during this study as it masks the disturbance of the total rock system.

7.2 **Obley Adamellite**

The data from Gulson and Bofinger (1972) for the fine and coarse grained varieties of the Obley Adamellite is presented in table A4-2 and figure 7.2. Their results are summarized below:

1. The coarse grained adamellites plot on a single isochron just outside of experimental error limits, equivalent to an age of 370 ± 6 Ma. and an initial ratio of 0.7057 ± 0.0007.

2. The sample of biotite analysed from a coarse grained adamellite is sufficiently enriched in radiogenic Sr to give an age (393 Ma.) independent of the initial $^{87}Sr/^{86}Sr$ ratio.

3. A single isochron can be drawn for five samples of microadamellite equivalent to an apparent age of 432 ± 16 Ma. However, this age is geologically impossible in view of the intrusive relationships. Also, two points plot below the adamellite isochron (see figure 7.2), further complicating the data.

The conclusions they drew from these results are:

1. The age obtained from the total rock systems for the adamellite (370 ± 6 Ma.) is the time of crystallization of the adamellite.

2. The age of 393 Ma. obtained from the biotite is slightly higher than the whole rock ages.

3. The most likely explanation for the scatter in the microadamellite data is weathering, particularly in relation to sample size. More than 25kg of the coarser grained adamellites were collected by blasting, whereas the microadamellites, with a
closely spaced ubiquitous jointing system, were only hand specimen size. Such small samples in areas subjected to weathering over extended periods are probably not sufficient to allow for closed chemical systems.

Everden and Richards (1962) published a K-Ar biotite age from the north-western corner of the Yeoval Batholith, 56km north-west of Yeoval. The recalculated age for this sample is 389 Ma. The significance of this age is questionable, as the distance between it and Gulson's samples suggests that it comes from a different pluton.

The results of this study are:

(1) Regression of the coarse grained adamellites gives a model four age of 356 ± 10 Ma. (MSWD = 6.21) and an initial ratio of 0.7057 ± 0.0010.

(2) The individual biotite age recalculates to 378 ± 4 Ma. It is significant that the biotite age and the total rock ages do not overlap, and this will be discussed in section 7.4.

(3) The microadamellite data is too scattered for consideration.

7.3 Basaltic Andesites

Gulson and Bofinger's data for the basaltic andesites is presented in table 4-3. From the data they obtained an age of 411 ± 227 Ma., and an initial ratio of 0.7047 ± 0.0009. The large uncertainties are due to the very limited range of $^{87}$Rb/$^{86}$Sr.

The data for the basaltic andesites was not regressed during this study as the large uncertainties make it a pointless exercise. However, it is interesting to note that the volcanics plot exactly on the Naringla Monzodiorite isochron (see figure 7.3), and this suggests that they are the extrusive equivalents of the monzodiorites.
7.4 Discussion

The biotite ages from the Naringla Monzodiorite give a well defined age of 395 ± 4 Ma. This age is consistent with a period of intense magmatic activity in the Lachlan Fold Belt as documented by Richards and Singleton (1982) and Pickett et al. (1982). The biotite age could therefore represent the age of emplacement of the Monzodiorite.

The total rock age for the Naringla Monzodiorite (369 ± 43 Ma.) overlaps the biotite age and is consistent with it. The large uncertainty in this age determination make it chronologically unreliable, but it can still be used as an indicator of the influence of other processes on the total rock system. Some possible causes of the large uncertainty are:

(1) As has been stated before, the Naringla Monzodiorite is a heterogeneous body ranging in composition from gabbro to granodiorite. Since the samples were collected over the entire length of the monzodiorite, variations in the source rock composition are likely to occur and the initial 87Sr/86Sr ratios could be different.

(2) Hydrothermal fluids have affected the bulk of the monzodiorite. As has been described in section 6.1, the Rb and Sr contents of the rocks have been affected by the passage of these fluids (see figure 6.11 and 6.12). The apparent disturbance (scatter) of the total rock system is consistent with this hypothesis. Such alteration could produce the large uncertainties in the age indicated above.

(3) The precision of age determinations were much less in the 1960's than they are today, and the larger experimental uncertainties add to the imprecision of the determination.

Two distinct ages were obtained for the Obley Adamellite; 356 ± 10 Ma. for the total rock systems and 378 ± 4 Ma. for the biotite. The fact that the two ages do not overlap was not explained by Gulson and Bofinger (1972).
The biotite age from the Obley Adamellite may possibly be the age of intrusion of the adamellite. It is consistent with a major phase of igneous activity documented by Richards and Singleton (1982) and Pickett et al. (1982). This phase is distinct from the previously described major period of igneous activity.

There are several possible explanations for the age obtained from the total rock data for the Obley Adamellite. These are:

(1) The total rock age is the primary age, and the biotite age is incorrect.

(2) The Obley Adamellite has been affected by a regional tectonic event at around 356 Ma.

(3) Weathering of the adamellite has disturbed the total rock system.

(4) Hydrothermal activity has reset the total rock system.

(5) An event unresolved in any other way has affected the total rock system.

Evidence against the first possibility is good. The biotite age is consistent with a major peak in magmatic activity in the Lachlan Fold Belt while the total rock age is not. Also, petrological examination of adamellite samples has revealed that the feldspars are invariably extremely sericitized, whereas while biotites are often chloritized to varying degrees, they are occasionally totally unaltered (see figure 3.18).

Regional deformation and metamorphism of Late Devonian/Early Carboniferous age has affected the rocks of the Hill End Trough, east of Yeoval (Powell et al. 1976). The metamorphism reached biotite grade, and K/Ar ages obtained from two of the metamorphic biotites gave ages of 338 ± 10 and 349 ± 10 Ma. (Cas, Flood and Shaw 1976). The biotite ages from the Naringla Monzodiorite and the Obley Adamellite discount the possibility of metamorphism affecting the Yeoval district at this time. This is because if biotite is heated above 200°C, it is reset, and will thereafter record the age of metamorphism since the biotite ages at Yeoval are older than the
metamorphism in the Hill End Trough, they have not been affected by this event.

Due to the highly altered nature of the Obley Adamellite, it is possible that the rocks have been severely weathered. However, this weathering would have to be remarkably uniform over a distance of 40km to produce the well defined isochron of figure 7.2. Normal weathering disrupts total rock ages, it does not reset them. Therefore, weathering can be discounted.

Hydrothermal activity has been noted in the Naringla Monzodiorite and may have been the cause for the poorly defined age of the total rock system. If hydrothermal activity has affected the Obley Adamellite, it would therefore have to be much more uniform over a larger scale than that which has affected the Naringla Monzodiorite. However, lowering of Rb-Sr total ages due to mild hydrothermal leaching has been noted in Proterozoic igneous rocks at Mt. Isa (Page 1978). This hydrothermal leaching resulted in the loss of Sr, which is consistent with the very low Sr contents of the Obley Adamellite (see table A1-6). Also important is the fact that the biotites from the rocks at Mt. Isa recorded older ages than the total rock systems, which agrees with the findings at Yeoval. Hence the effects of hydrothermal alteration may have resulted in the lowering of the total rock ages of the Obley Adamellite on a massive scale.
CHAPTER 8 : DISCUSSION

8.1 Relationships between the Yeoval Rocks

The pyroxenites, basaltic andesites, monzodiorites, granodiorites, microgranodiorites and dacite porphyry all appear to be related. Gulsen (1968) has described a gradational contact between the pyroxenite and the monzodiorite. The basaltic andesites are believed to be the extrusive equivalents of the monzodiorites as they plot on the same trends (with the exception of the pyroxene bearing basaltic andesites) on silica variation diagrams. Also, the basaltic andesites plot on the Rb-Sr isochron for the monzodiorite, and their initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are indistinguishable from the monzodiorites (see Chapter 7). The microgranodiorites and the dacite porphyry have very similar petrological and chemical composition to the granodioritic rocks, and are concluded to be late stage intrusions into the main monzodiorite mass.

The gabbros plot anomalously on the silica variation diagrams and are probably unrelated to the monzodiorite. A gradational contact may be present between the two units, although poor outcrops prevents any positive proof of the matter. Also, the gabbro plots on the total rock isochron for the Naringla Monzodiorite, although this may just be coincidence.

Although the Obley Adamellite analyses plot on the trends for the Naringla Monzodiorite the two rock types are considered to be unrelated for two reasons. These are (1) the biotite age for the Obley Adamellite is approximately 17 Ma younger than those from the Naringla Monzodiorite; and (2) although no contact was observed, the adamellite rises sharply to form steep ridges in direct contrast to the flat monzodiorite plains. This suggests that there is an intrusive (rather than gradational) contact between the two units. The presence of a fine grained intensely fractured marginal phase of the adamellite supports this hypothesis.

The rhyolite dykes are clearly younger than the Naringla Monzodiorite, having intruded along the dominant east-west jointing system. The dykes were not observed at all in the Obley Adamellite, even though they were concentrated nearly in the monzodiorite. This suggests two possible explanations (1) the rhyolite dykes intruded before the Obley Adamellite
and are unrelated, or (2) the rhyolite dykes intruded during the emplacement of the Obley Adamellite and are related. The silica variation diagrams (Chapter 6) support the latter proposal, although the highly fractionated nature of the rocks may result in the analyses plotting together even though they are unrelated.

The high abundance of biotite, together with the often anomalous positions on the silica variation diagrams indicate that the Cawndora Porphyry is unrelated to any other rock type in the Yeoval area.

8.2 Petrogenesis

Three models for the formation of the Naringla Monzodiorite will be discussed below. The petrogenesis of the other rock types will not be discussed due to the limited data available.

8.2.1 Fractional Crystallization

Fractional crystallization has long been recognized as a process which can result in straight line or (in the more extreme cases) curved trends on elemental variation diagrams. For example, Bateman and Chappell (1979) proposed that crystal fractionation was the process for the formation of the compositionally zoned Tuolumne Intrusive Series, California.

Fractional crystallization has almost certainly been a formation process for the pyroxenites of the Naringla Monzodiorite. The steeply curved trends for MgO, CaO, Al₂O₃, TiO₂ and Sr are all consistent with crystal fractionation of clinopyroxene from a primitive melt of basaltic andesite composition. The crystallization of clinopyroxene would drive silica values down to lower values, as is the case for the Yeoval rocks. Orthopyroxene cannot have been involved in the fractionation process as total Fe is unchanged. The pyroxene bearing basaltic andesites and monzodiorites also plot on the steeply curved trend and this suggests that pyroxene fractionation has also been a process of formation for these rocks. Gill (1981) proposed that plagioclase, olivine, augite and
magnetite fractionation was by far the most common process for the formation of andesites. This is consistent with the trends obtained from the augite bearing basaltic andesites.

Progressive fractionation of hornblende, plagioclase and possibly biotite could explain the linear trends obtained for the rocks above 55% SiO₂. This is consistent with the observed decreasing plagioclase, hornblende and biotite content in the more siliceous rocks, and is possibly the formation process for the Naringla Monzodiorite.

8.22 Magma Mixing

Magma mixing has been proposed as a model for the formation of andesitic rocks. This process involves the mixing of two end members (basalt and rhyolite) to produce andesite and dacite (Eichelberger 1978). It has been proposed (Gray 1984) that magma mixing is the formation process for the granitic rocks of the Lachlan Fold Belt, and the two end members are basaltic material and meta-sedimentary derived magma. The mixing of these two rock types results in the intermediate 87Sr/86Sr ratios observed in many granitoids from the Lachlan Fold Belt.

The linear trends above 55% SiO₂ suggest that magma mixing may have been occurring during the formation of the Naringla Monzodiorite, although the low silica end member would have to be a high-Al basalt. The high K and Rb contents, together with the fact that the Naringla Monzodiorite is a calc-alkaline association (section 6.1), suggests that there has been some continental input into the original magma, even though the 87Sr/86Sr initial ratios (0.7052 ± 0.0004) is distinctive of mantle derived rocks. Hence, it is possible that magma mixing may have played a role in the formation of the Naringla Monzodiorite, although continental input must have been minimal due to the low 87Sr/86Sr orital ratio.

8.23 Restite Model

Linear trends on silica variation diagrams have been explained by the process of restite unmixing for the granitic rocks of South-Eastern Australia (White and Chappell 1977). Partial melting of a source rock produces a felsic melt and a residual mafic component (restite) which will
then separate very slowly as the magma rises. This process will result in linear trends on the Harker variations diagraming.

Griffin et al. (1978) proposed that the Moruya suite was formed by the process of restite unmixing. Since the Moruya and Yeoval trends are often identical, it is possible that restite unmixing was involved in the formation of the Naringla Monzodiorite. The main problem with this proposal is that the residual phase has not been recognized in the Naringla Monzodiorite. White and Chappell (1977) have proposed that restite takes the form of xenoliths, clots or xenocrysts in I-type granifolds. The two xenoliths analysed from the Naringla Monzodiorite have similar compositions to the low silica monzodiorites and basaltic andesites, and appear to be of a cognate origin. Complexly zoned plagioclase crystals are fairly rare in the monzodiorite. The gabbros and pyroxenites cannot be the restite phases of the Naringla Monzodiorite, as they plot anomalously on most silica variation diagrams. Hence restite unmixing may have been a formation process for the Naringla Monzodiorite, although the failure to recognize a residual phase precludes any conclusions being drawn.

8.3 General Model for the formation of porphyry copper deposits

The typical porphyry copper deposit, as proposed by Sillitoe (1973), forms at depths of 1.5 - 8km beneath a comagmatic strata-volcano. A stockwork is developed above and within a small mineralized porphyritic intrusion which has generally undergone K-feldspar alteration. The porphyritic body grades down into a much larger, unmineralized, even grained pluton. An idealized cross section of a typical porphyry copper deposit is presented in figure 8.1.

Burnham (1979) has proposed that the formation of porphyry copper deposits is dependent on the abundance of water in the melt. This model is based on the fact that magmas dissolve less water at lower pressures. When a small stock of granodioritic magma rich in water (2-4wt%) is emplaced in a near-surface subvolcanic environment, the H2O undersaturated core of the stock becomes completely encased in a solidified carapace of granodiorite (see figure 8.2a). As the melt then cools, second boiling (H2O saturated melt \( \rightarrow \) crystals + "vapour") results in a very large pressure buildup within the stock due to a large volume change associated with the release of H2O
from the melt. Failure of the enclosing carapace results in the development of an extensive fracture system in the overlying rocks. Breccia pipes may also form when the fluids escape (see figure 8.2b). The sudden decrease in pressure results in rapid crystallization of the granodioritic magma, producing the porphyritic texture characteristic of these bodies. Subsequent sealing of the fractures by crystallization can cause repetition of the entire process (see figure 8.2c). Heat from the stock can cause circulation of groundwaters in the surrounding country rocks, resulting in a convection cell. The interaction of the magmatic and meteoric waters results in hydrothermal alteration of the surrounding rocks.

8.4 Formation of the Yeoval Deposits

It was originally believed (Ambler and Facer 1975) that the porphyry copper prospects in the Yeoval district were very deep level (on the order of 8km), due to the erroneous identification of the potassic alteration at the Yeoval Prospect which is characteristic of the deep level deposits.

Ambler (1979) suggested that the depth of emplacement was only 2km on the basis of: (1) the presence of the remnants of the original stratovolcano (basaltic andesites) north east of Yeoval, and (2) amygdules similar to those found in the dacite and microgranodiorite porphyries at the Yeoval prospect were found to have formed at depths of about 2.5km at the Bingham deposit, Utah (Wilson 1978).

Patterson et al. (1983) believed that the basaltic andesites and the Naringla Monzodiorite are unrelated, and the andesitic rocks are in fact of Ordovician age. However, they claimed somewhat dubiously that the Naringla Monzodiorite intruded to a depth of 2km, and this was determinable from the thickness of andesite that would have overlain it.

Smith (1969) estimated that prehnite formed due to burial metamorphism below depths of approximately 1.5km within the Cudal Group south of Yeoval. Since prehnite is not present in the Cudal Group at Yeoval, these rocks cannot have been buried much deeper than 1.5km.

On stratigraphic grounds, the Yeoval deposits are concluded to be high level deposits, having formed at a depth of approximately 2km below the
Figure 8.1 - Formation of a typical porphyry copper deposit (after Burnham 1979)

Figure 8.2
Diagrammatic representation of the proposed intrusive relationships between the four principal intrusive rock types in the Yeoval prospect. The dacite/hornblende-biotite microgranodiorite association followed vapour pressure build-up, fracturing, boiling and final crystallisation of residual melts. Hornblende microgranodiorite intruded late in the sequence, probably during the waning stages of hydrothermal activity associated with the earlier microgranodiorite. (VP: vapour pressure; CP: confining pressure). After Ambler (1979)
surface in the Early Devonian. This means that the Yeoval deposits are
unusual on two ways. The first is that the main pluton from which the
porphyries were derived has intruded to very high levels, in direct
contrast to the suggestions of Sillitoe (1973). The second anomaly is that
in the models of Sillitoe (1973), Lowell and Guilbert (1970) and Burnham
(1979), the porphyritic intrusions are not present within the host pluton,
but above it. The Yeoval deposits are in direct contrast to this.

8.41 Yeoval Prospect

Ambler (1979) believed that the formation of the porphyritic dacite
was intimately related to that of the hornblende - biotite micrograno-
diorite. These rocks formed due to vapour pressure build-up in a small,
late stage porphyritic intrusion within the monzodiorite. As a result of
second boiling, the vapour pressure within the microgranodiorite exceeded
the confining pressure, causing fracturing and final crystallization of the
residual melts in a manner similar to that described in sections 8.2. The
hornblende microgranodiorite is believed to have intruded later in the
sequence, probably during the waning stages of hydrothermal activity
associated with the earlier microgranodiorite. The model is summarized in
figure 8.2.

8.42 Goodrich Deposit

McManus and Loudon (1966) proposed from their study of the underground
openings at the Goodrich mine that the mineralization is controlled by a
narrow (3m wide) semi-circular steeply plunging structure which has been
truncated by an easterly striking shear zone which has dragged some
mineralization into the shear. They termed these two horizons the "main
lode" and the "shear lode" respectively, and believed that main lode was
formed by collapse of part of the monzodiorite. The quartz-magnetite veins
are concentrated in the shear lode, and these are the host to the high
concentrations of Cu, Au, Ag and Mo.

The presence of abundant highly altered microgranodiorite porphyry on
the dumps around the open pit (which was not recognized by McManus and
Louden (1966), together with the semi-circular shape of the main lodge)
(figure 5.2) strongly suggest that a small porphyritic body intruded the monzodiorite at this locality. This intrusion probably formed in a similar manner to that described in section 8.2. When the buildup of pressure within the porphyry resulted in the fracturing of the confining carapace, the released fluid resulted in quartz-magnetite flooding around the rim of the porphyry. This fluid was rich in Si, Fe, Cu, Au, Ag and Mo, and crystalized rapidly around the outer rim of the porphyry. The main lode is therefore the equivalent of Lowell and Guilbert's ore shell (1970 – see figure 4.2), where the highest copper values occur.

Later, east-west movement along the dominant jointing direction resulted in the displacement of half of the deposit to an unknown locality. Rhyolite dykes intruded the E-W joints. Later, north-south faulting has resulted in the displacement of the rhyolite dykes. The remobilization of Cu from the Goodrich deposit has occurred along the north-south faults to produce the minor shear zone deposits to the south. Evidence for this can be seen in the geochemically anomalous Cu zones that extend from the Mt. Rose and Viles Lode shafts towards the Goodrich deposit.

8.43 Cyclops Deposit

The narrow shear zones at the Cyclops Mine strike roughly N-S and appear to be the northerly extension of the shear zones, that are present at the Yeoval Prospect. Evidence for this is the geochemical soil anomaly (1000ppm Cu) that extends almost continuously from the Yeoval Prospect to the Cyclops Mines (see figure 3). The source of the copper is most likely the porphyritic microgranodiorite, and the faults have remobilized the Cu, which was then deposited in veinlets and on joint planes and replaced mafic mineral grains. These faults are later than the emplacement of the rhyolite dykes, as they have displaced in a number of localities (see figure 5).