



MAGMATIC AND HYDROTHERMAL EVOLUTION OF THE BROWNS CREEK INTRUSIVE COMPLEX AND ASSOCIATED GOLD MINERALISATION

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1. Introduction

Browns Creek Mine is situated eight kilometres west of the township of Blayney and 220km west of Sydney. It is located on the Bathurst 1:250,000 map sheet (SI 55-8) at latitude 33°32'S and longitude 149°10'E. The mine is seated within the Molong-Wyangala-Jerangle-Kuark Zone in the Lachlan Fold Belt. Access to the mine is via Browns Creek Road from Blayney.

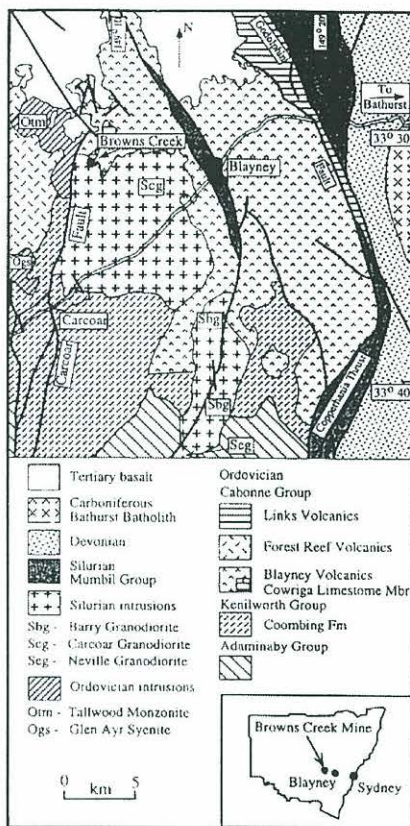


Figure 1.1 - Location of Browns Creek (Smart and Wilkins, 1997).

Browns Creek is a gold-copper deposit that has formed within skarn-altered volcanics and limestone. The mineralisation is structurally controlled and intrusive related. The deposit has formed within a structural zone, juxtaposing the Blayney Volcanics (including the Cowriga Limestone Member) to the Carcoar Granodiorite, a member of the Browns Creek Intrusive Complex. The mineralisation is hosted within calc-silicate skarn and sheeted quartz veins in this zone.

Earliest production records of the Browns Creek Mine date back to 1876 although mining is believed to have commenced in the area in 1871.

Between 1876 and 1887, a total of 55,000 ounces were recovered from about 300,000 tonnes of ore.

After this, underground mining was halted due to the workings reaching the water table. While several attempts were made to dewater the mine, it was not until 1904 that the mine became productive again with the onset of open cut mining. From 1904 to 1910, an estimated 4500 ounces of gold was recovered from 35,000 tonnes of ore. Alluvial gold was recovered during the 1920's and 1930's and yet more attempts were made to dewater the underground workings, with little success.

The ownership of the mine changed hands frequently and the workings were mostly idle, apart from exploration activities, for a period of 30 years. From 1969 to 1974, Geophoto Resources Consultants proceeded to explore the surrounding ground, dominantly for base metals. In addition, it was concluded that it would be uneconomic to continue production at the mine. In 1979, M J Hickey acquired the mine and its leases. Up to 1986, Browns Creek was a minor open cut and underground operation, with 28,233 ounces of gold being recovered from 501,995 tonnes of ore.

BHP Minerals Limited (later Newcrest Mining) acquired the mine in 1986. They extended the treatment operations and developed the majority of the open cut mine observed today. This was continued by Newcrest Mining to a total depth of 140 metres, extracting 175,394 ounces of gold from 1,569,191 tonnes of ore at an average grade of 3.48 grams per tonne.

The present owner of the Browns Creek Mine is Hargraves Resources N.L., recently acquired by Durban Roodeport Deeps. They acquired the mine and leases in 1993 and completed a drilling program to test the underground extension of the ore. This was proven, with an inferred resource of 510,000 tonnes at 8.2 g/t gold. Underground development began in November 1994 and the first production was in May 1995. Operations ceased in December 1999 due to a catastrophic hangingwall failure, resulting in a rapid influx of water from an underground reservoir of unknown size. This occurred after a routine firing of ore. Treatment of stockpiles continued at the mine to February 2000 and pumping of the incoming water continued to July 2000. At the time of writing, the mine continues to fill with water, at a rapid rate. The total amount of gold mined from the deposit by Hargraves Resources N.L. was 269,791 ounces. The remaining reserve is has been calculated at 590,000 tonnes at 6.34 g/t gold and 0.42% copper.

1.1 Previous Studies

While Browns Creek has been subject to numerous internal company reports, there has been relatively little published on the deposit. The most recent publication was by Smart and Wilkins (1997). This publication was a brief overview on the geology of the deposit. In the same year, Kjolle completed a PhD thesis on the deposit. This extensive study of the deposit focussed on the geology of the open pit, specifically the skarn alteration and mineralisation. Previous publications on the geology of the deposit include papers by Creelman *et al.* (1990) and Taylor (1983). Trzebski *et al.* (1999) compare the Carcoar Granodiorite with numerous other intrusives in the region. However, this publication focussed on the morphogenesis and tectonic setting of the granodiorite. Apart from these papers mentioned, there have been numerous other theses completed on the deposit. The most notable of these is the Honours thesis by Meldrum (1995).

1.2 Aims

The aims of the study were focused on the intrusive activity associated with the Browns Creek mineralisation. Recent suggestion has been that the mineralisation is related to magmatic events rather than pure skarn alteration events. In view of this information, the aims of the study were to:

- achieve a better understanding of the magmatic activity at Browns Creek;
- categorise the intrusive bodies associated with the Browns Creek orebody;
- determine the intrusive phase that is associated with mineralisation at Browns Creek;
- establish the age of mineralisation at Browns Creek;
- understand the structural involvement in the formation of the Browns Creek orebody;
- determine a structural history of the Browns Creek orebody;
- establish a new model of formation of the Browns Creek deposit.

1.3 Methods

The methods used in this study were dominantly detailed observations made while in the Browns Creek mine. This involved more than a year of constant observations of the geology of the mine during employment there, until its catastrophic closure in December 1999. Specifically, this included mapping of underground exposures, logging of mine exploration and mine development drill core and involvement in many detailed discussions with mine and exploration personnel of Hargraves Resources N.L. During this time, a thorough understanding of the geological relationships of the deposit was obtained.

Samples of different lithologies were collected from different levels of the underground mine. In addition, samples were also collected from drillcore. These samples were then subject to whole rock geochemical and/or petrological analysis. The whole rock analyses and thin section preparation was performed by the Geological Department at the Australian National University. Appendix 1 outlines the analytical methods for the whole-rock geochemical analyses. Other whole rock geochemical analyses were performed by A.L.S. Laboratories, courtesy of Hargraves Resources N.L.

Three samples from Browns Creek were dated on the SHRIMP at the Research School of Earth Sciences at the Australian National University. As the dates have proven to be substantially older than any previously accepted dates, they played an integral part of the understanding of the deposit. The preparation of the samples for the SHRIMP analyses was performed by the Research School and the Geology Department of the Australian National University. The analytical methods for the SHRIMP dating is outlined in Appendix 1.

2. Regional Geology

The Browns Creek gold-copper deposit is located within the Molong-Wyangala-Jerangle-Kuark Zone in the eastern portion of the Lachlan Fold Belt. This zone is an Ordovician submarine volcanic/sedimentary sequence and comprises the Adaminaby Group, Kenilworth Group, Bowan Park Group and the Cabonne Group. The area around the Browns Creek deposit forms part of the Cabonne Group. The sequence has been intruded by a variety of plutons, ranging from granodiorites to monzonites. These intrusives are of dominantly I-type affinity with some S-type and are commonly spatially associated with mineralisation. The age of these intrusives range from Late Ordovician to Early Silurian.

SILURIAN	LATE	Wyangala Batholith		Barry Granite Neville Granite	
	EARLY	Cadia Coach Shale		Carcoar Granodiorite	
	LATE	CABONNE GROUP	Forest Reefs Volcanics Tailwood Monzonite, Errowan Monzonite, Glen Ayr Syenite	Stakehill Metagabbro	
			Weemalla Formation	Byng Volcanics Blayney Volcanics Cawriga Limestone Member	
ORDOVICIAN	MIDDLE	Kenilworth Group	Mount Pleasant Basalt Member	Adaminaby Group	
			Oxart Coombing Formation		

Table 2.1 - Stratigraphic table showing the regional lithological units, modified after Pogson & Watkins (1998).

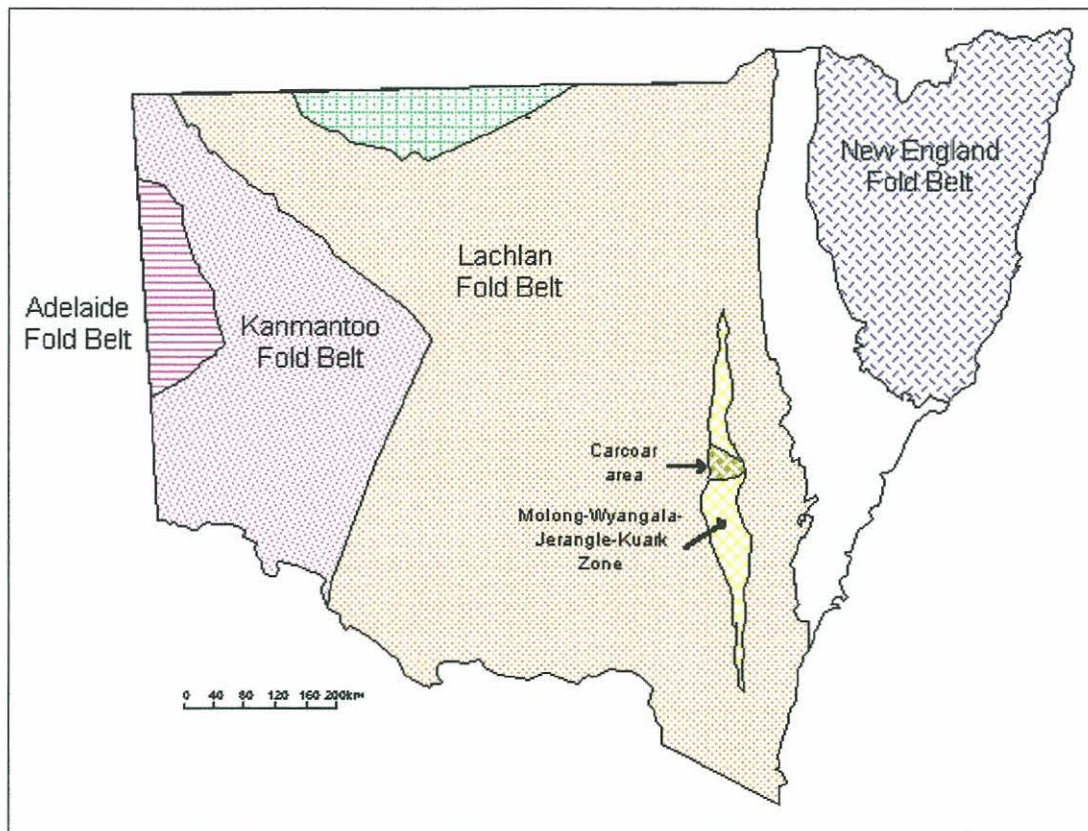


Figure 2.1 – Map of NSW showing structural zones and fold belts in outcrop and under sedimentary basins where known (modified after Scheibner & Basden, 1996).

The oldest outcropping rocks in this part of the Lachlan Fold Belt are the Middle to early Late Ordovician Adaminaby Group (see Table 2.1). This sedimentary sequence represents distal turbidite deposition. During the Middle Ordovician the Molong-Wyangala-Jerangle-Kuark Zone was formed. The Kenilworth Group is the first volcanic sequence deposited, representing a marine environment with locally emergent volcanic centres. In the late Middle Ordovician to early Early Silurian the Cabonne Group followed with extensive submarine volcanic activity, possibly as part of the Benambran Orogeny.

2.1 Regional Setting

The Lachlan Fold Belt, part of the Tasman Orogenic Zone, comprises a series of north-south oriented orogenic belts. The age of the rocks range from Early Cambrian

to Early Devonian, developed on microcontinental or oceanic basement rocks, questionably Pre-Cambrian in age (Scheibner and Basden, 1996). The component belts young eastwards and are believed to have formed from active plate margins, although this is still a contentious issue. The following description is taken from one of the most recent publications on the tectonic evolution of the Lachlan Fold Belt by Scheibner and Basden (1996).

There is little expression of Cambrian depositional history (and the Delamerian deformation) in the Lachlan Fold Belt, only facies changes. The main active plate margin development of the Lachlan region took place from the Cambrian to Early Silurian. Specifically, during the Late Ordovician to Early Silurian, most of the Lachlan Fold Belt was affected by the Benambran Orogeny, which “caused inversion of a back-arc basin resulting in a collisional thrust belt, the Wagga-Omeo Zone” (Scheibner and Basden, 1996).

Early to Middle Silurian extension followed which dominantly affected the eastern part of the Lachlan Fold Belt. This was followed by the Late Silurian to earliest Devonian Bowring-Bindi deformation, which caused extension in the western part of the belt, namely the Darling Basin. Extensive orogenic granite emplacement took place from the Silurian to Devonian. Widespread thrusting of variable intensity took place in the Middle Devonian Tabberaberan Orogeny. Diachronous volcanism and sedimentation then followed. By the Early Carboniferous Kanimblan Orogeny, the Lachlan Fold Belt was a neocraton.

The Browns Creek deposit is located within the Carcoar area of the Molong-Wyangala-Jerangle-Kuark Zone, previously known as the Molong-South Coast Anticlinorial Zone. This zone began its formation in the Early Ordovician with the deposition of mafic volcanics in a marine environment. The tectonic setting of the area was that of a volcanic arc and arc-related basin within an active plate margin. This was followed by the deposition of clastic sediments, limestone and andesitic volcanics within a volcanic arc and forearc basin in the Late Ordovician. Further

sedimentation occurred in the Early to Middle Silurian within a shelf environment in a back-arc basin. Orogenic granites intruded mostly in the Late Silurian to Early Devonian, although dating as part of this study has revealed that at least one suite of these granites (the Browns Creek Intrusive Complex) intruded in the Early Silurian. The granitic emplacement was accompanied by deposition of further volcanics and sediments. The area was then eroded and most recently covered by a thin veneer of Cainozoic sediments and basalt, representing epicratonic sedimentation and intraplate igneous activity.

2.2 Blayney Volcanics

The Blayney Volcanics (Cabonne Group) is an extensive unit that covers an area of approximately 220km², centred roughly on the township of Blayney. The unit has historically also been classified as the Blayney Andesite and the Blayney Basalt. It has been included within the Angullong Tuff and also used as a division between it and the overlying Quigley's Hill Tuff. The Blayney Volcanics also encompasses several limestone units that are collectively known as the Cowriga Limestone Member.

The Blayney Volcanics are andesitic to basaltic in composition, and are commonly brecciated. Wyborn (in Pogson and Watkins, 1998) interpreted the brecciation to be of hyaloclastic or pillow lava origin. However, there is very little evidence for either of these theories. Volcaniclastics are rare on a regional scale but have been identified near the lower contact with the underlying Coombing Formation.

The Blayney Volcanics are interpreted by Wyborn (in Pogson and Watkins, 1998) as being deposited within a shallow to moderately deep marine environment. The age of this unit is indicated by the age of the included Cowriga Limestone Member. Conodonts within the latter unit reveal an age of 450 Ma (Kjolle, 1997). The limestone units are believed to lie within the uppermost portions of the volcanics.

This geological map illustrates the Browns Creek Gold Mine and surrounding areas. The map features several labeled locations: **Browns Creek Gold Mine** (central), **Errowan Mine** (left), **Halls Road Prospect** (left-center), **Carcoar Break** (vertical line), **Carcoar Co Mine** (center-right), **Coombing Copper Mine** (right-center), **Coombing Park Iron Mine** (bottom-center), **Bald Hill** (bottom-center), **Discovery Ridge** (bottom), **Ferndale Prospect** (top), **Arsenic Shaft** (top-right), **Milners Prospect** (top-right), **Blayney Copper Mine** (top-right), and **By Mine** (top-right). The map also shows various geological units and features, including **Golden Gully** (left), **Carcoar Break** (vertical line), and **Discovery Ridge** (bottom). The map is color-coded to represent different geological units, with a legend provided in the top right corner.

Figure 2.2 - Regional geology - around Browns Creek
(After 1:250 000 Australian Basement
Geology Series - Bathurst Geology - Sheet S155-8)

Regional Geology Legend

Quaternary

-  **Qa**
Adaminaby Group undifferentiated
Quartz sandstone, siltstone, slate, phyllite, black carbonaceous slate, chert

Tertiary

-  **Qa**
Alluvium; gravel, sand, silt, clay
-  **Ti**
Silcrete, silicified gravel
-  **Tb**
Pyroxene olivine basalt, plagioclase basalt, alkali basalt, trachybasalt, trachyandesite

Silurian

-  **Smzl**
Wombiana Formation
Limestone, marble
-  **Smz**
Wombiana Formation
Siltstone, limestone

Silurian Intrusives

-  **Sl**
Leucogranite
-  **Scg**
Carcoar Granodiorite
Hornblende biotite granodiorite and tonalite
-  **Sbg**
Barry Granodiorite
Hornblende biotite granodiorite

Ordovician

-  **Ocf**
Forest Reefs Volcanics
Volcanic conglomerate
-  **Ocfb**
Forest Reefs Volcanics
Clinopyroxene basalt, agglomeratic in places, basaltic subvolcanic intrusives
-  **Ocft**
Forest Reefs Volcanics
Lafite
-  **Ocf**
Forest Reefs Volcanics
Mafic volcanics, volcanic conglomerate, siltstone

-  **Ocb**
Blayney Volcanics
Clinopyroxene basalt, agglomeratic in places; volcanic sandstone

-  **Ocbl**
Blayney Volcanics
Foliated, recrystallised, grey limestone

-  **Ocwt**
Weemalla Formation
Mafic volcanics, sandstone, conglomerate

-  **Ocws**
Weemalla Formation
Siltstone, sandstone, mudstone, chert, marble, calcareous mudstone

-  **Ocwm**
Weemalla Formation
Porphyritic trachybasalt, pillow lava

-  **Oko**
Coombing Formation
Feldspathic siltstone and sandstone, chert

-  **Oco**
Oakdale Formation
Mafic volcanic sandstone, basalt, siltstone, black shale, chert, breccia, conglomerate

-  **Ocy**
Byng Volcanics
Basalt, volcanoclastic sandstone

-  **Oas**
Carbonaceous slate, shale

Ordovician Intrusives

-  **Oi**
Diorite, leucodiorite

-  **Otm**
Tallwood Monzonite
Porphyritic clinopyroxene monzonite and monzodiorite

-  **Ofi**
Diorite, monzonite, syenite

-  **Ofd**
Fernside Monzodiorite
Clinopyroxene monzonite and diorite

-  **Om**
Monzonite, monzogabbro, quartz monzonite

-  **Osg**
Stokefield Metagabbro
Foliated plagioclase-phynic metagabbro

-  **Orm**
Errowan Monzonite
Biotite clinopyroxene monzonite, altered quartz syenite, pyritized monzonite

-  **Ogs**
Glen Ayr Syenite
Biotite syenite, biotite clinopyroxene monzonite

The base of the unit is suggested as being late Middle Ordovician, due to its conformable contact with the underlying Coombing Formation.

Mineralogically, the Blayney Volcanics are dominated by abundant phenocrysts of clinopyroxene (1-2mm). These phenocrysts are set within a dark green matrix and are typically euhedral but vary in alteration. Thin section identification shows an average composition of the volcanics as 25% augite, 5-10% olivine and 15% plagioclase (Pogson and Watkins, 1998). Olivine is variably altered to antigorite, chlorite, quartz, zeolites, hydrogarnet, calcite and pumpellyite. Plagioclase is rarely preserved and blends into the granular groundmass. Amygdales, 1-3mm across, are located throughout the unit. They are filled with orthoclase, chlorite and calcite. The magnetic signature of the Blayney Volcanics is generally low except for areas such as around the Carcoar Granodiorite where they have been recrystallised to hornfels. They are also of less oxidised nature compared with other volcanics in the area. Further mineralogic data regarding the Blayney Volcanics can be found in Chapter 3.

The overall geochemistry of the Blayney Volcanics is outlined by Wyborn (in Pogson and Watkins, 1998). He states that the Blayney Volcanics have a SiO_2 range of 49 to 52 weight percent. They have enrichments in K_2O , Ba and Sr, which may be an indication of alteration, and also enrichments in P_2O_5 . On a Le Bas diagram (SiO_2 versus $\text{K}_2\text{O} + \text{Na}_2\text{O}$) the samples plot within the fields of basalt, trachybasalt and shoshonite. It is noted that samples with abundant phenocrysts have high MgO and those with higher amount of groundmass proportions have higher K_2O . Further, it is stated that the Blayney Volcanics would fit reasonably well with the Forest Reefs Volcanics on a fractionation curve from a common magma source.

2.3 Cowriga Limestone Member

The Cowriga Limestone Member is conformable within the upper Blayney

Volcanics. The unit originally formed part of the Panuara Formation, which was downfaulted into the volcanics unit Bowman *et. al* in Pgson and Watkins, 1998). The limestone is 150 to 200m thick and is overlain with up to 190m of Blayney Volcanics (Smart and Wilkins, 1997). The majority of the mapped extent of the unit (approximately 500m across) outcrops at the Browns Creek deposit in a wedge-shaped portion. The shape of the limestone unit led Taylor (1983) and Creelman *et al.* (1990) to the belief that the unit represented a northeast trending anticlinorial zone. However, detailed mapping by Hargraves Resources N.L. has failed to prove the presence of such a structure. Other smaller units of limestone occur in the region and are believed to be fault-displaced portions of the Cowriga Limestone Member and other smaller lenses. The next largest outcrop occurs to the northeast of the deposit and smaller examples are found to the southeast further around the margins of the Carcoar Granodiorite. The outcrops to the southeast of the deposit are most likely joined to the limestone occurring at the mine. Drilling by Hargraves Resources N.L. has revealed that the limestone appears to be continuous through this area, under the cover of Blayney Volcanics.

Research undertaken by Kjolle (1997) included dating of the Cowriga Limestone Member by the conodonts that were found within several samples. This study showed that the age of the limestone is 450 ± 6 Ma, as determined by genus and species identification by the Australian Geological Survey Organisation. The limestone is thought to have been deposited in a shallow marine environment.

In the vicinity of the Browns Creek deposit, the Cowriga Limestone Member has been recrystallised to marble. However, elsewhere in the region it consists of limestone. The limestone is generally white to grey in colour and fine to medium grained. Around the mine the marble is coarser grained (grains up to 10mm). No sedimentary structures have been reported within the Cowriga Limestone Member.

Kjolle (1997) found that the recrystallisation of the Cowriga Limestone Member to marble was due to alkaline fluids that were heated to between 300 to 720°C. This has

been identified due to the discolouration by deformation of the conodonts that were found within the limestone. Subsequent to recrystallisation, the limestone has been deformed due to ductile flow.

Around the Carcoar Granodiorite, the recrystallised limestone is also altered to a calc-silicate skarn mineral assemblage. This was previously thought to be associated with the intrusion of the Carcoar Granodiorite. The skarn mineralogy is characterised by the crystallisation of such minerals as wollastonite, garnet and minor quartz, epidote and hedenbergite. This altered sequence of limestone partly hosts the mineralisation at the Browns Creek deposit.

Late mafic basaltic dykes have intruded the limestone unit within the mine. These dykes have intruded along pre-existing faults and have suffered the effects of extension. This is readily observed within the pit where such dykes are boudinaged.

2.4 Forest Reefs Volcanics

The Forest Reefs Volcanics (Cabonne Group) occurs to the west of the Carcoar Fault. The unit covers an area of approximately 65km². The volcanics are unconformably overlain by Early Silurian Cadia Coach Shale to the west and by Tertiary basalt in the north. The complex comprises a number of members, including a basal conglomerate, the Burnt Yards basalt, volcanic sediments and the Nullawonga latite.

The Forest Reefs Volcanics comprise epiclastic sediments such as volcanic siltstones, volcanic arenites and volcanic conglomerates. Lava flows ranging through basaltic, latitic and andesitic compositions are also found. Many tuffaceous sediments may also be observed. These range from aphanitic tuffs to crystal lithic tuffs. This volcanic package has been extensively intruded by mafic calc-alkalic intrusives, ranging in composition from gabbro and diorite to syenite, monzonite and

monzodiorite (Kovacs, G., pers. comm., 1999). Wyborn (in Pogson and Watkins, 1998) states that the volcanics are all shoshonitic, plotting within the fields of trachybasalt to trachyandesite.

The basaltic members of the Forest Reefs Volcanics Complex typically contain phenocrysts of pyroxene and plagioclase. The complex has been extensively hydrothermally altered, particularly in the northern parts. The alteration is typified by a demagnetisation of the volcanics and associated sericite-pyrite-epidote-carbonate alteration and veining. In some areas, alteration products consist of tourmaline-quartz (schorl rock).

There have been no fossils found within the Forest Reefs Volcanics and as such, it has yet to be formally dated. However, it is placed within the uppermost Late Ordovician as it is unconformably overlain by the Early Silurian Cadia Coach Shale. In addition, the volcanics are underlain by the Weemalla Formation that is believed to be of late Middle Ordovician to late Late Ordovician in age. This is supported by a Late Ordovician age of plutons intruding the Forest Reefs Volcanics package.

2.4.1 Intrusives Within the Forest Reefs Volcanics

The Forest Reefs Volcanics have been intruded by a series of plutons that are thought to be co-magmatic with the volcanics and would have thus intruded in the late Late Ordovician.

The Glen Ayr Syenite is an elongate, structurally emplaced (northwest-trending) body covering an area of around 7 km². It is described as a pink, medium to coarse grained, pale biotite-ferrohastingsite-ferrosilite syenite (Wyborn in Pogson and Watkins, 1998). The pink colouration is due to heavy haematitic dusting. Its whole rock geochemistry is similar to the latite unit of the Forest Reefs Volcanics. The syenite has been dated using ²⁰⁷Pb/²⁰⁶Pb dating techniques on zircons, which revealed an imprecise date of 435 ± 10Ma (op. cit.).

The Errowan Monzonite comprises several small monzonitic bodies with a total area of 6 km². It is described as a quartz-bearing, biotite-clinopyroxene monzonite (Wyborn in Pogson and Watkins, 1998). The bodies are in some cases zoned, with cumulate-rich phases present. The Errowan Monzonite has also been dated by U-Th-Pb techniques on zircons, producing another date of 450 ± 10 Ma (op. cit.).

The Tallwood Monzonite covers an area of approximately 15 km² and is a medium grained biotite-clinopyroxene monzonite. The intrusion has been selectively altered, resulting in the development of actinolite, sphene, chlorite, epidote, haematite, magnetite, pyrite and minor chalcopyrite. The Tallwood Monzonite has yet to be dated but is believed to have intruded in the late Late Ordovician with the other intrusives mentioned here (Wyborn/Krynen in Pogson and Watkins, 1998).

2.5 Stokehill Metagabbro

The Stokehill Metagabbro (referred to by Wyborn (op. cit.) as the *Stokefield Metagabbro*) is a small intrusion located to the south of the Carcoar Granodiorite. It covers an area of only 4 km² and is centred on the village of Carcoar. It is described as a plagioclase-phyric metagabbro. The gabbro has been intruded by a diorite that was previously believed by Wyborn (in Pogson and Watkins, 1998) to be a more felsic phase of the gabbro. The gabbro has not been dated due to a lack of zircons. However, it is believed to have intruded in the Middle Ordovician to Late Ordovician, as it intrudes sediments of the Kenilworth Group (Middle Ordovician in age). The gabbro also hosts rare-mineral mineralisation, including deposits with cobalt, uranium, nickel, thorium and tellurium associated with copper molybdenum and silver (Wilson, 1993).

2.6 Carcoar Granodiorite

Following magmatic activity associated with the Cabonne Group, the area surrounding the Browns Creek deposit was subject to a period of deformation, uplift and partial erosion. Part of this deformation was the formation of the Carcoar Fault and the intrusion of the Browns Creek Intrusive Complex. The latter is dominated by the Carcoar Granodiorite. This granodiorite (also known as the *Carcoar Granite*) is the main intrusive body in the vicinity of the mine, covering an area of approximately 87km² in a roughly equant body which is 9-10km across. It is of I-type affinity and ranges in composition from granodiorite to tonalite. The granodiorite has an average modal mineral composition of 45% plagioclase, 25% quartz, 10% alkali feldspar, 10% biotite, 10% hornblende and accessory apatite, zircon, pyroxene, titanite and ilmenite. It is locally altered to chlorite, clinozoisite, epidote, sericite, actinolite and calcite (Smart and Wilkins, 1997).

The amount of amphibole present in the Carcoar Granodiorite can vary greatly (up to around 25% locally). This occurs in conjunction with higher concentrations of plagioclase and lower concentrations of alkali feldspar. Such occurrences constitute cumulate-rich samples of the Carcoar Granodiorite. The present study has shown this, and it is supported by whole-rock geochemistry. Historically, the more mafic samples were termed the *Long Hill Diorite*, and were believed to represent a separate intrusive phase to the Carcoar Granodiorite (Creelman *et. al*, 1990; Kjolle, 1997 and others).

The previous evidence for the *Long Hill Diorite* as a separate intrusive was based solely on geophysics. The Hargraves Resources N.L. heliborne radiometrics survey indicates a thorium depletion near the mine. Subsequently, geologists inferred a fault, although there is no ground evidence of its existence (see figure 6.1). If the structure exists, this may explain the juxtaposition of a cumulate-rich phase next to the Carcoar Granodiorite. The *Long Hill Diorite* may represent the deeper level of the Carcoar Granodiorite that has been uplifted along such a structure. Thus, the

level of exposure today is that of two different structural levels of the same intrusive body. So, for this report, the term “Carcoar Granodiorite” will be used to describe the larger intrusive body that forms the footwall of the mineralisation at the Browns Creek deposit. The term *Long Hill Diorite* will only be used with respect to historical samples that were taken previous to this report. The new terminology of “Long Hill Phase” is introduced in this study when referring to the cumulate-rich phases of the Carcoar Granodiorite.

The Carcoar Granodiorite has long been thought to have intruded in the Silurian and the most recently accepted age is 416.2 ± 2.2 Ma acquired by $^{40}\text{Ar}/^{39}\text{Ar}$ dating on hornblende (Perkins *et al*, 1995a). As part of this study, the Carcoar Granodiorite was dated using SHRIMP (U-Th-Pb dating techniques) on zircons. This produced a date of 430.4 ± 4.7 Ma, which is 14 Ma older than previous age determinations. This places the intrusion of the Carcoar Granodiorite as occurring near the boundary between the Late Ordovician and Early Silurian.

Later intrusive phases of the Carcoar Granodiorite (the Mine Dyke Group) have been responsible for the bulk of the mineralisation at the Browns Creek deposit. The intrusives of this phase range in composition from quartz-feldspar pegmatitic dykes to granites (previously thought to be monzonites). Synonymous with the intrusion of these dykes and aiding their emplacement is a series of structural events that are important to the focussing of the intrusive activity and mineralising fluids.

2.7 Events After Intrusion of the Carcoar Granodiorite

Following the intrusion of the Carcoar Granodiorite (Early Silurian), there was a period of erosion and deposition. The Cadia Coach Shale represents the early to mid-Silurian sedimentation in a deep water, low energy environment. This unit comprises a feldspathic siltstone sequence, with an overlying massive grey mudstone (the Avon Lea Mudstone Member). The unit then grades upward to a interbedded sandstone-

siltstone sequence.

The Middle to Late Silurian is dominated by sedimentary sequences of the Cowra Trough that represents deposition in deep to shallow water. Minor lavas of Late Silurian age have also been found within the Bathurst 1:250,000 sheet. The final fill sequences of the Cowra Trough have an age of Early Devonian. An extensional phase occurred in the Late Silurian to Early Devonian, forming the Hill End Trough and facilitating the felsic volcanism and plutonism that is associated with it.

The Middle Devonian was a time of uplift, folding and fault movement, with associated volcanism and erosion (the Tabberabberan deformation). The Late Devonian consisted of deposition within a shallow marine to fluvial environment, leading to the Early Carboniferous. The Bathurst 1:250,000 sheet area was subject to metamorphism and extensive deformation including folding and faulting (the Kanimblan event).

The Bathurst Batholith intruded during the Middle to Late Carboniferous. It comprises the Icely Granite, Dunkeld Granite, Bathurst Granite, Gresham Granite, an unnamed leucogranite, Tarana Granite, Durandal Granite, Eusdale Granite and Evans Crown Granite. The batholith is the most extensive intrusive group of rocks on the Bathurst 1:250,000 sheet and covers an area of approximately 1000km². The batholith is aligned in a west-northwest orientation for a distance of 70km. It is dominated by felsic intrusives of granitic to granodioritic composition. A range of Late Carboniferous ages have been assigned to the Bathurst Batholith, from 318 ± 17 Ma for the Durandal Granite to 301 ± 6 Ma for the Bathurst Granite (Pogson and Watkins, 1998). Further, there appears to be a direction of younging towards the east. There have been no co-magmatic volcanic rocks identified in the Bathurst 1:250,000 sheet.

There are only minor amounts of deposition preserved during the Post-Carboniferous period in the region. The next period of volcanism occurred in the

Tertiary (late Eocene to Late Miocene). Mount Canobolas, located to the west-northwest of the Browns Creek deposit, is the centre for the basaltic volcanism that covers an area of 680km². The flows that were sourced from this centre are grouped under the general terminology of the Orange Province of Tertiary basaltic flows (Watkins/Warren in Pogson and Watkins, 1998). The flows from Mount Canobolas consist dominantly of trachyte. Other rock types identified include flows of olivine basalt and a porphyritic andesine basalt. These rocks were erupted in a continental intraplate setting. Age determinations have been carried out using K/Ar dating techniques. This has revealed an age of 12.7 to 10.9 Ma (Middle to Late Miocene) for the volcanic rocks of the Orange Province.

3. Mine Geology

The mine geology has been described by numerous researchers and company reports in previous years. The present study classifies the various types of intrusives in the mine, something not attempted in any detail in the past. Table 3.1 outlines the various terminologies that have been used historically compared with those in this study.

<i>Terminology Used in This Report</i>	<i>Previously Used Terminology</i>
Carcoar Granodiorite	Carcoar Granite, Carcoar Diorite
Long Hill Phase	Long Hill Diorite
Post-Mineralisation Intrusive	late diorite
Mine Dyke Group	monzonite, monzodiorite, aplite
Blayney Volcanics	Blayney Andesite, Blayney Basalt
Stokehill Metagabbro	Stokefield Metagabbro, Stokefield Diorite, Stokehill Diorite

Table 3.1 - Correlation between old and new terminology.

Information presented in this section of the study have been from the author's own observations except where referenced.

3.1 Intrusives

Three phases of intrusive activity have been identified at the Browns Creek deposit, each phase crucial in the formation of the orebody. These three phases are believed to be genetically related and represent discrete intrusive pulses from the same magmatic source. Together they are referred to as the Browns Creek Intrusive Complex. Several other sub-intrusive phases are also identified. These include a porphyritic mafic monzonite, located below the current depth of the underground workings and in the nearby Forest Reefs Volcanics. Other mafic dykes have also been identified. These generally only occur in the upper levels of the mine.

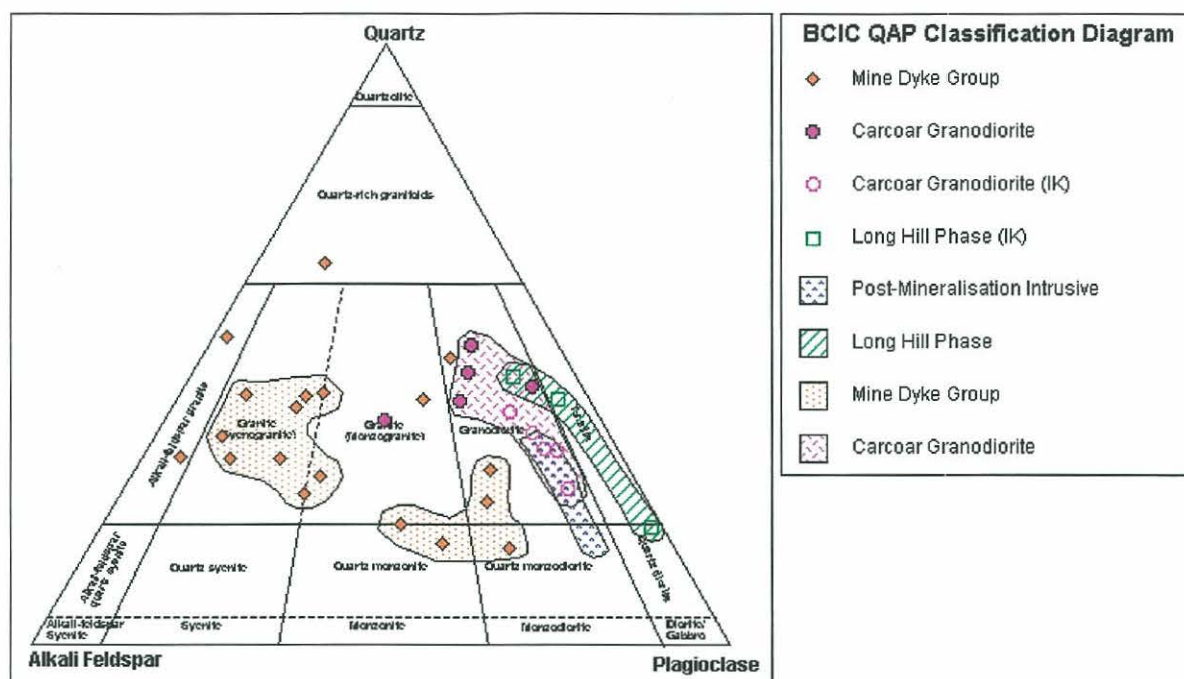


Figure 3.1 - QAP classification diagram for the Browns Creek Intrusive Complex. Region for the Post-Mineralisation Intrusive has been determined by numerous hand sample identifications. "IK" samples after Kjolle (1997). Parallel horizontal lines represent % quartz of rock volume (5, 20, 60 and 90 respectively from bottom to top); other internal lines represent % plagioclase of rock volume (10, 35, 65 and 90 respectively from left to right).

3.1.1 Phase 1 : Carcoar Granodiorite

The Carcoar Granodiorite is the dominant intrusive that lies to the west of the Browns Creek orebody (figure 3.2, plan 1). It has a partly intrusive, partly structural contact with the Blayney Volcanics and a faulted contact with the Cowriga Limestone Member. The orientation of the contact varies from the open pit to the underground workings of the mine. In the pit, the contact between the granodiorite and the other host lithologies is broadly northwest trending but swings to north-south trending in the southern limits of the pit. This trend continues in the underground workings. However, the contact swings to the northwest in the northern extremities and to the southwest in the southern extremities. This gives the Carcoar Granodiorite an arcuate contact with the country rock in the mine area.

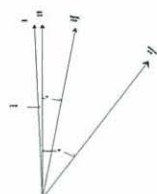
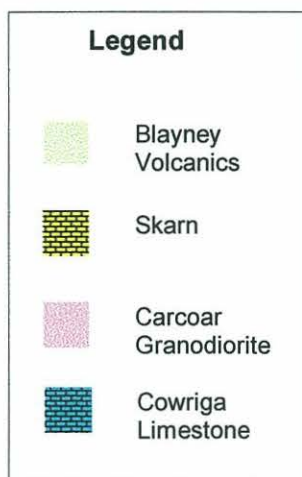
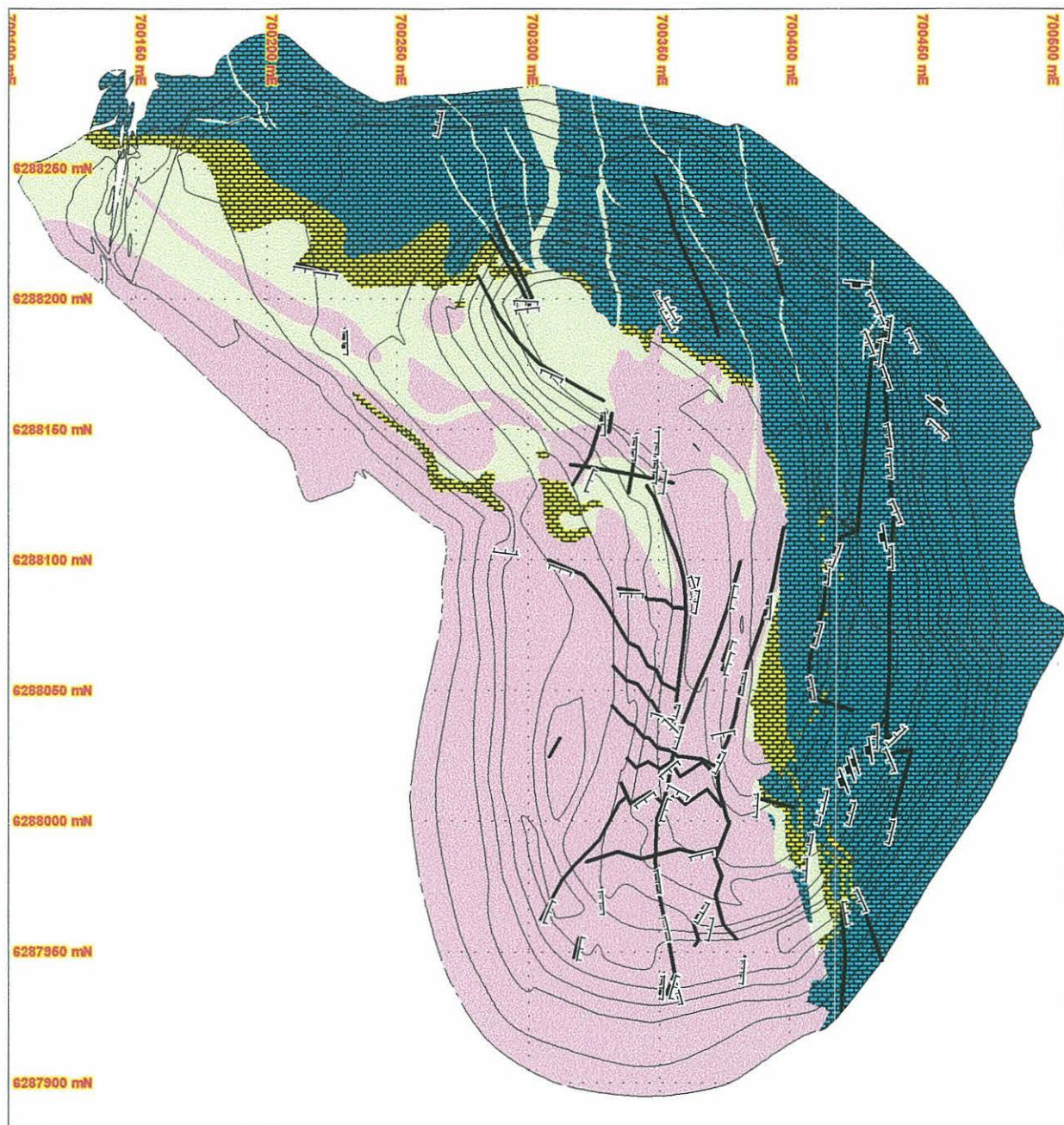
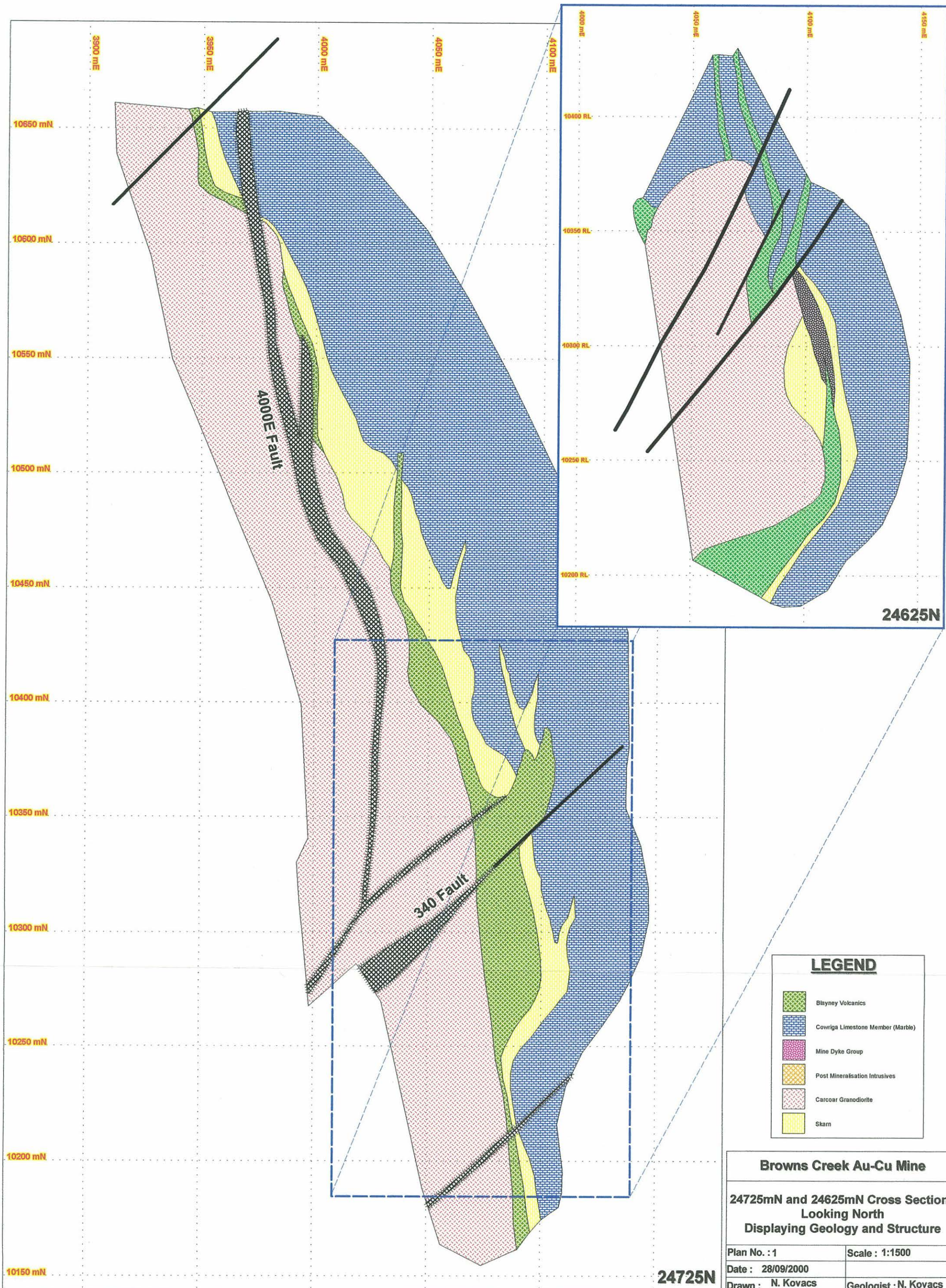


Figure 3.1 - Open pit geology and structure (data supplied by Hargraves Resources NL.). SCALE = 1:250



In recent years some researchers believed the intrusive in the mine was the “Long Hill Diorite”. The geochemical analysis of the Carcoar Granodiorite and the “Long Hill Diorite” reveals that both names refer to the same intrusive body. Samples of the “Long Hill Diorite” contain a greater amount of amphibole and less feldspars than the Carcoar Granodiorite. This is consistent with the “Long Hill Diorite” representing a cumulate-rich phase of the Carcoar Granodiorite (Chapter 6). Hence, the terminology of the Long Hill Phase is introduced when referring to the more mafic, cumulate phases of the Carcoar Granodiorite.

From the contact with the surrounding Blayney Volcanics, it is postulated that the Carcoar Granodiorite has intruded into the Blayney Volcanics. Both these lithologies were subsequently juxtaposed against the Cowriga Limestone Member. The Carcoar Granodiorite was not observed in direct contact with the Cowriga Limestone Member in the lower levels of the mine. However, previous mapping of the now inaccessible upper levels and drilling to the north and south of the orebody shows that the granodiorite is in direct contact with the Cowriga Limestone Member. The mapping in the upper levels of the underground mine is poor and lacks information about the contact between the granodiorite and limestone.

With the exception of the Long Hill Phase, the Carcoar Granodiorite is a uniform intrusive body. Through the entire mine (600 vertical metres), it sustains its uniformity. The only variation in the Carcoar Granodiorite is the degree of alteration. Deeper exposures of the granodiorite within the lower levels of the mine are less altered than in the upper levels.

The Carcoar Granodiorite is a mottled grey/white, medium grained, equigranular to slightly porphyritic intrusive body (figure 3.3). Plagioclase crystals up to 5mm are readily seen. Quartz is interstitial in its occurrence and is usually found with potassium feldspar. Biotite comprises up to 5% of total mineral composition in altered samples and <1% in the unaltered samples located further underground. Other mafic minerals (black amphiboles) are readily observed, accounting for 30%

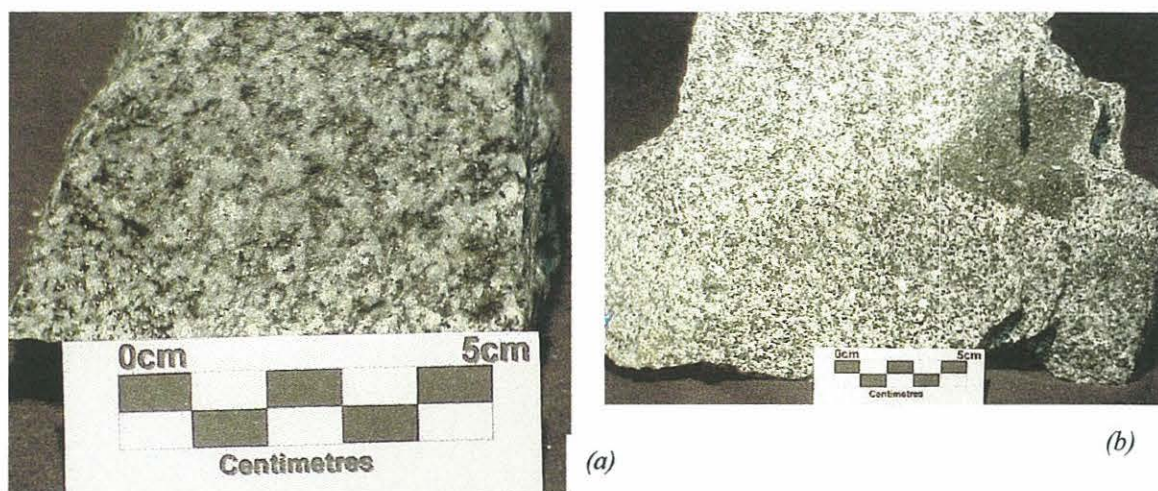


Figure 3.3 – Hand samples of Carcoar Granodiorite. Note mafic xenolith in (b). (a) Sample # NH31. (b) Sample # NH87.

to 35%. They have indistinct grain boundaries, giving them a blurred appearance. A weak planar fabric is observable in weathered/altered samples. This may provide a plane of weakness in the granodiorite, making it susceptible to post-emplacement deformation. Samples observed in drill core highlight that this intrusive appears to be more readily deformed than other intrusives observed in the mine, such as the Mine Dyke Group.

Petrological observation reveals that the Carcoar Granodiorite (samples NH37, NH39 and NH48) is quite distinct from the other members of the Browns Creek Intrusive Complex. Texturally, the majority of minerals are anhedral to subhedral, accounting for a granitic texture. The average crystal size was 1mm but ranged up to a maximum of 3mm. These larger grains are the feldspars. The mafic mineral content is considerably higher than the Mine Dyke Group. Alteration of the Carcoar Granodiorite samples is generally mineral specific and can be classified as minor to moderate. The original texture of the rock has been preserved.



Figure 3.4 – Photomicrograph of Carcoar Granodiorite (sample #NH37) to show general texture. (Crossed polars, width of photo is 2.45mm).

Quartz present in the Carcoar Granodiorite occurs interstitially, indicating that it crystallised latest from the melt. The crystals have stable grain boundaries and are associated with all other minerals. The grains display undulose extinction indicating that they have been affected by heat and/or pressure, possibly due to post-emplacement deformation (Chapter 4). The modal quartz content varies from 30-35% by volume of the total rock.

The plagioclase content of the Carcoar Granodiorite varies considerably between samples (40% in NH37 to 25% in NH48). Subhedral primary plagioclase crystals up to 3mm are readily observed. They tend to have only a slight dusting of sericite alteration, starting at the core of the grains and progressing towards the rim. In plane light observation, this takes the appearance of a brown coloured overprint. They display compositional zonation, which may imply that the melt has become progressively more sodic during crystallisation.



Figure 3.5 – Photomicrograph of zoned plagioclase in Carcoar Granodiorite (sample #NH30). (Crossed polars, width of photo is 2.45mm).

Some samples of Carcoar Granodiorite display larger potassium feldspar grains relative to plagioclase (up to 3mm). The grains display a minor amount of compositional zoning towards the rim of the grains. The abundance of such grains varies quite considerably between samples. Sample NH37 and NH39 contain 5-10% while NH48 contains up to 25%. This is the dominant reason for classifying the latter sample as a monzo-granite while the others are classified as granodiorite. The potassium feldspars tend to be more altered than plagioclase. This alteration comprises sericite and fine grained opaques (of unknown identity), giving the grains a dark, turbid appearance.

Mafic mineral sites comprise 15-20% of the Carcoar Granodiorite samples. These mafic mineral sites are invariably altered and the primary mineral can rarely be identified. There are rare subhedral cross-sectional grains of hornblende, indicating that they are primary minerals. However, the majority of amphibole has formed at the expense of primary clinopyroxene. Such grains tend to be anhedral with irregular grain boundaries. The altered mafic mineral sites can reach up to 3mm in size, but the primary hornblendes tend to be much smaller, generally around 0.5mm in size.

The breakdown of clinopyroxene has formed actinolitic amphibole that mostly occurs as fine-grained masses overprinting the clinopyroxene grains. Spatially related to this form of amphibole is the presence of fine-grained opaques. Reflected light observation has revealed these to be magnetite grains.

Primary biotite is rarely preserved in the Carcoar Granodiorite. The small amount that is present (up to 5%) is dominantly altered to chlorite. Secondary unaltered biotite varies in abundance but is generally pervasive throughout the rock. Rare accessory minerals, including apatite and zircon, have been observed in the granodiorite. These usually occur as small euhedral grains, less than 0.1mm in size.

The Carcoar Granodiorite has experienced relatively little alteration of its primary mineralogy. The alteration present tends to be selective thus relic intrusive textures are preserved. As previously stated, the degree of alteration has a tendency to decrease with increasing depth. This is particularly evident with biotite alteration. The biotite flakes have since been altered to chlorite. The other common alteration product is epidote group minerals (particularly epidote and clinozoisite). These have usually formed at the expense of the mafic silicate minerals of clinopyroxene and hornblende. Other alteration products of these minerals are actinolitic amphibole and hornblende. Primary alkali feldspars have generally suffered selective alteration to a fine grained mass of sericite, observed as turbid cores. Primary plagioclase grains have altered to illite. The initial alteration appears to have been potassic in nature due to the presence of biotite and actinolite. However, the other alteration

assemblages are propylitic, which is much more widespread throughout the vicinity of the mine. The timing of alteration was most likely late in relation to the intrusives observed, as the Mine Dyke Group has also been affected (section 3.1.2).

Mineralisation within the Carcoar Granodiorite is minor. The majority of sulfides occur as very fine grained, disseminated specks that appear to have a primary origin. Some of the magnetite present is secondary and has formed due to the breakdown of clinopyroxene. Other opaque minerals that were identified are pyrite and chalcopyrite. This is also observed on a hand specimen scale particularly in the lower levels of the mine, where these two sulfides occur in rare patches within the Carcoar Granodiorite.

The Carcoar Granodiorite has been responsible for the contact metamorphic effects experienced by the Cowriga Limestone Member and the Blayney Volcanics. The limestone has been transformed to marble and the volcanics have been hornfelsed. This has occurred due to heat transfer from the intrusive as it has been emplaced into the crust. The contact metamorphic hornfels of the volcanics is characterised by an assemblage of biotite, fibrous amphibole and chlorite. The marble has most likely been heated to a temperature of 300°C to 720°C (Kjolle, 1997), as determined using a colour index on the deformed conodonts present in the primary limestone

3.1.2 Phase 2 : The Mine Dyke Group

A network of dykes cuts the main ore zone of the Browns Creek deposit. While mostly granitic, their composition can range from monzonitic to monzodioritic to granodioritic (figure 3.1). Their textures are variable, from porphyritic to aplitic and pegmatitic. Commonly this variation can be observed within a single dyke (figure 3.6). This research has shown that these dykes are genetically related to the Carcoar Granodiorite and are a later phase of the Browns Creek Intrusive Complex (Chapter 6). Historically, the dykes have been loosely termed *monzonitic* and *aplitic dykes* in

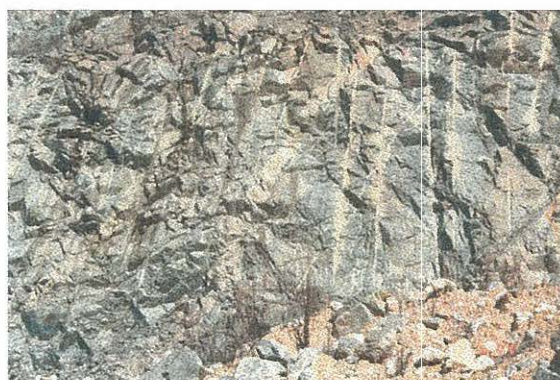
local mine terminology. However, the vast majority of samples that were petrographically and geochemically analysed in this research were classified as granitic in composition, from monzo-granitic to syeno-granitic (see figure 3.1). Thus, for the purpose of this report the terminology of the Mine Dyke Group is used as this is a more appropriate description than *monzonite*.



Figure 3.6 – Photo of the Mine Dyke Group (10592mRL) showing textural and compositional variation. Width between red markers is one metre.

Narrow monzonite, monzodiorite and aplite dykes were mapped in the open cut walls by Rangott and Bird (1994). Such dykes are vertically continuous and appear to have intruded along pre-existing fractures, faults and joints. Apart from this, there is little surface expression of the Mine Dyke Group in the local vicinity of the mine. However, there are numerous other intrusives in the region. Some of the closer bodies are the Tallwood Monzonite, Errowan Monzonite, Glen Ayr Syenite and Stokehill Metagabbro. These have been used in this study to compare and contrast the intrusives observed in the mine with others in the area. This aspect is investigated in the Chapter 6.

Figure 3.7 – Photo of Mine Dyke Group in open pit (Rangott & Bird, 1994).



Previous underground mapping of the Mine Dyke Group was conducted with poor lithological identification. Regardless of composition, the dykes were either misinterpreted as granodiorite or as monzonite, despite the relative abundance of quartz. They were originally thought to be apophyses of the Carcoar Granodiorite and were often mapped as part of this larger granitic body. While the aplitic ‘end members’ of the Mine Dyke Group are easily identified, the granitic ‘end members’ are difficult to distinguish from the Carcoar Granodiorite in hand specimen. This has led to poor information being collected in underground mapping and drill hole logging, making the vertical extent of these dykes difficult to determine. More recent, accurate mapping and logging has shown that the dykes are extensive for tens of metres laterally and vertically, and vary in thickness from 3cm to 1m. However, the historical records of the now inaccessible upper mine levels have to be relied upon.



Figure 3.8 (a), (b) – Photos of two separate dykes underground with intrusive contacts (both from 10450mRL). Length of pen is 15cm.

The location of the Mine Dyke Group is the key to their importance. The dykes are most abundant within the ore zone at the Browns Creek deposit. Some of the dykes have clearly intruded post-mineralisation and zircon dating suggests that they may have intruded after the Carcoar Granodiorite (Chapter 7). Their contacts are mostly intrusive (figure 3.8) however, one example of the Mine Dyke Group has sheared contacts (the “Ore Zone Package”). The dykes can be found within the Blayney Volcanics that have not been skarn-altered, and have been identified within drillcore through the Carcoar Granodiorite both as part of this research and in previously logged diamond drill holes. In the volcanics and the granodiorite, the dykes have intrusive contacts. To the east of the ore zone, the dykes have yet to be observed within the marble, despite numerous deep diamond drill holes from surface and short production holes from underground.

Hand specimens of the Mine Dyke Group have a cleaner appearance than the Carcoar Granodiorite, due to distinct grain boundaries. This may also be due to a higher abundance of groundmass in the granite compared to the granodiorite. Their colour varies from mottled grey/white in the granitic ‘end members’ to white and rarely pink in the aplitic and pegmatitic ‘end members’. Quartz varies in abundance from 10% to 30+%, thus explaining the range in composition. The quartz fraction tends to be seen as small distinct grains found within feldspar masses. The dominant constituent of the samples is feldspar, which varies from 30% to 50%. Plagioclase tends to occur as laths up to 8mm in length. There is frequently a pink colouration of the feldspar content. Some of the pink colouration is due to the crystallisation of pink coloured alkali feldspar. The rest is due to haematitic dusting of the plagioclase. The mafic minerals present occur as distinct phenocrysts, particularly the amphiboles. There is frequently cores of another mineral within some of the larger, more anhedral amphibole grains, possibly pyroxene. This is observed as a green coloured core with a dark green-black rim.

The Mine Dyke Group rocks commonly have a micro-porphyritic texture. This indicates a high level of intrusion, consistent with the location of these samples. The

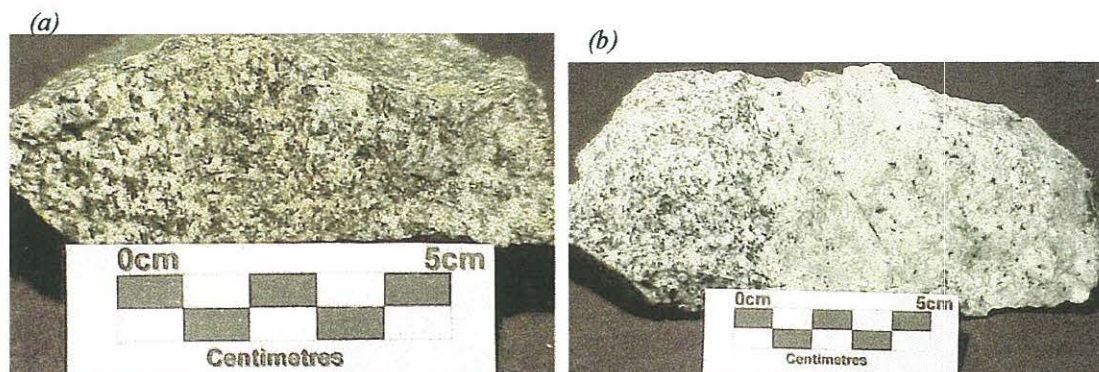


Figure 3.9 – Photos of hand samples of Mine Dyke Group. (a) Sample #NH25. (b) Sample #NH84.

larger grains in the samples studied ranged up to 4mm across and are generally subhedral, while the smaller interstitial fraction is generally around 0.5-1mm in grain size. However, the samples of the Mine Dyke Group that were sourced to the west of the ore zone tend to display a more granitic texture than the other dykes from within the ore zone.

A common textural feature of the Mine Dyke Group observable in petrographic observation is the presence of a graphic/granophyric and myrmekitic intergrowth between quartz and feldspars (figure 3.10). This feature ranges from small patches of up to 3mm, to slightly larger zones up to 20mm in size. The presence of the graphic/granophyric texture is indicative of a late stage crystallisation of a high-level magma. This is consistent with the sub-porphyritic texture discussed above.

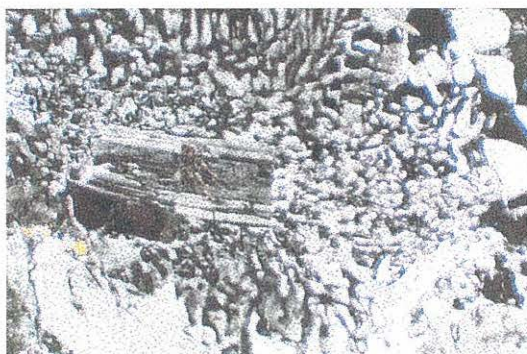


Figure 3.10 – Photomicrograph of myrmekitic intergrowth in Mine Dyke Group (sample #NH14, crossed polars, width of photo 1.22mm).

Petrographic observation shows that the quartz content varies up to 40% of the modal mineralogy of the Mine Dyke Group. This has a dramatic effect on the compositional classification of these intrusives. The quartz content of the majority of

samples places the dykes in the granite compositional field. The quartz grains that are observed are very similar to those found within the Carcoar Granodiorite samples. They are located interstitially indicating late-stage crystallisation. The grains typically show some degree of undulose extinction.

The majority of dykes have roughly equal amounts of plagioclase and alkali feldspar. However, the proportions can vary giving compositions from monzogranite to syeno-granite. Sample NH9 contained an unusually high amount of alkali feldspar, resulting in a classification of alkali feldspar granite. The composition of plagioclase remains consistent throughout the samples (oligoclase – determined by extinction angles), with rare examples of andesine. The grains are mostly lath-like and subhedral in form. They generally constitute the phenocrysts observed in the thin sections. The grains commonly display a compositional variation, becoming progressively more sodic from core to rim. The dyke samples from west of the orebody have distinctly different feldspar grains than those from the ore zone. These feldspars show zones of impurities that outline their crystal shape. This is in addition to the more distinct compositional zoning that is readily observed. These features of the feldspars are more akin to the Carcoar Granodiorite than the other members of the Mine Dyke Group.

The alkali feldspar grains are of a similar size and form to the plagioclase grains. In the dykes sourced from the mine, these feldspars typically display perthitic textures. This may indicate that the magma was hypersolvus. It is noted that there is a distinct lack of perthitic alkali feldspars in the Mine Dyke Group samples that were sourced from west of the orebody within the Carcoar Granodiorite. This may indicate the varying states of hydration of each individual magmatic phase during crystallisation. It may also indicate that the dykes that were sourced from drillcore west of the ore zone are actually samples of Carcoar Granodiorite and not the Mine Dyke Group.

Clinopyroxene is the most dominant primary mafic mineral. These grains are typically ragged and mostly altered. Alteration to hornblende and actinolitic

amphibole are the most common products. A common feature of the Mine Dyke Group is the presence of mafic mineral sites that comprise cores of clinopyroxene and rims of hornblende. This can also be observed in hand specimen. Rare subhedral to euhedral cross-sectional grains of primary hornblende can also be found. Hornblende has most commonly altered to epidote group minerals but is also found to be associated with the late growth of uraltite. The uraltite may have formed during late-stage crystallisation or is related to post-consolidation processes that may have occurred in the area such as regional, contact or metasomatic metamorphism.



Figure 3.11 – Photomicrograph of Mine Dyke Group showing mafic silicates (sample #NH38, crossed polars, width of photo 2.45mm).

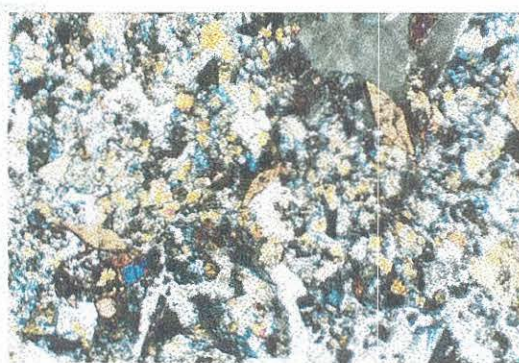


Figure 3.12 – Photomicrograph of altered Mine Dyke Group with titanite (sample #NH20, crossed polars, width of photo 2.45mm).

Biotite is generally rare in the Mine Dyke Group. The only samples that contain an appreciable amount of biotite are NH13, NH15a and NH15b. The dykes that were sourced from drillcore west of the orebody all contain biotite. Like other factors already mentioned, this points to the interpretation that these samples may be part of the Carcoar Granodiorite and are not members of the Mine Dyke Group phase.

There is a high amount of titanite present within the granites (up to 1%) (figure 3.12). One of the aplitic end members of the Mine Dyke Group (sample NH20) contained a few crystals of monazite. Other accessory minerals, such as apatite and rarely zircon, are also observed.

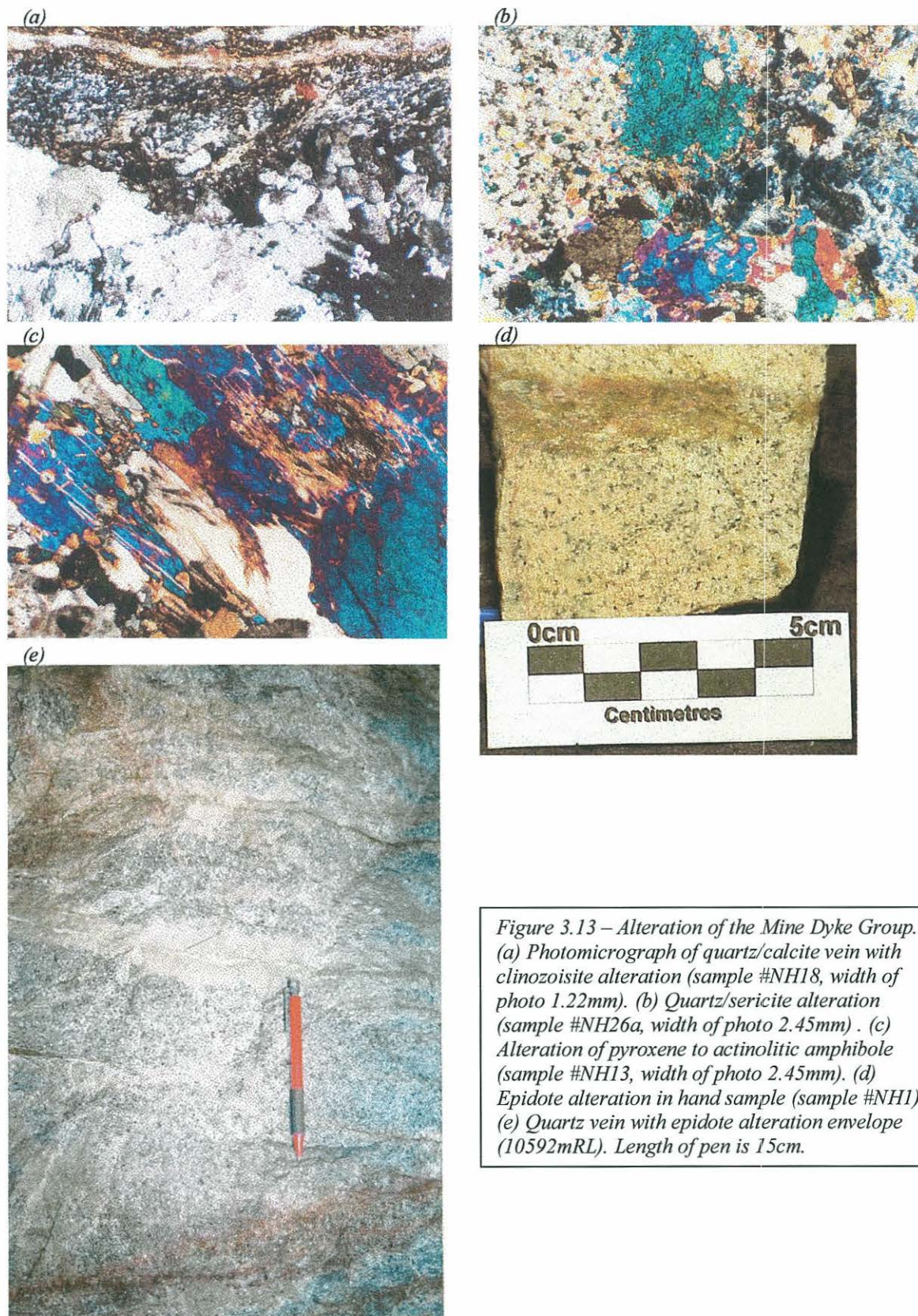


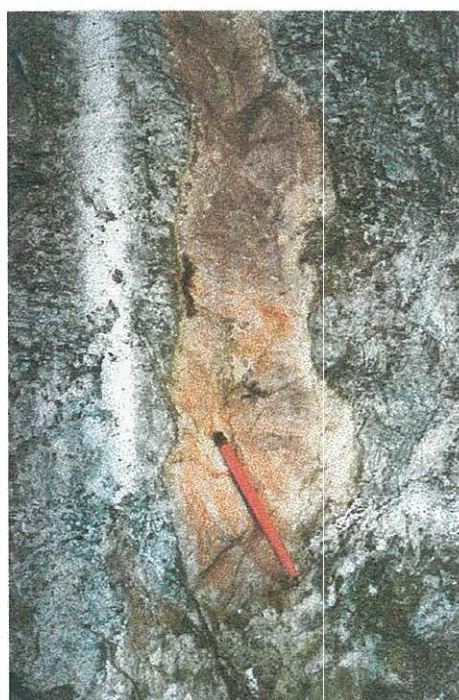
Figure 3.13 – Alteration of the Mine Dyke Group. (a) Photomicrograph of quartz/calcite vein with clinozoisite alteration (sample #NH18, width of photo 1.22mm). (b) Quartz/sericite alteration (sample #NH26a, width of photo 2.45mm). (c) Alteration of pyroxene to actinolitic amphibole (sample #NH13, width of photo 2.45mm). (d) Epidote alteration in hand sample (sample #NH1). (e) Quartz vein with epidote alteration envelope (10592mRL). Length of pen is 15cm.

The Mine Dyke Group has a similar alteration type and degree as the Carcoar Granodiorite. The dominant alteration style is selective replacement of individual minerals. Plagioclase grains are altered to illite and some have been affected by haematitic dusting. Alkali feldspar is overprinted by a dusting of fine grained sericite. The few clinopyroxene grains observed have mostly altered to hornblende and actinolitic amphibole (figure 3.12 (c)). There has been secondary growth of alkali feldspar and quartz, mostly in the form of the graphic/granophyric and myrmekitic textures as described previously. However, they are mostly devoid of any biotite alteration. Minor amounts of skarn alteration have affected the Mine Dyke Group. This is discussed later in section 3.5. Silica and quartz/sericite alteration is also sporadically observed throughout the underground mine.

The Mine Dyke Group contains only rare mineralisation in the form of bornite, chalcopyrite $\pm$ pyrite. The mineralisation occurs within the more altered dykes, particularly those altered by epidote group minerals. There is no evidence of mineralisation within more pegmatitic and aplitic 'end members' of this phase of intrusive activity. There appears to be a direct correlation between alteration and mineralisation and the timing of the Mine Dyke Group. Samples observed in the



Figure 3.14 – Photos of mineralisation within the Mine Dyke Group. Both dykes from 10450mRL. Length of pen is 15cm.



upper levels of the mine (for example 10592mRL) show mineralisation located within late jointing through the dykes. This may be related to remobilisation of the sulfides coincident with the formation of the structure. Fine-grained bornite occurs along dyke selvages giving them a dark appearance.

3.1.3 Phase 3 : Post-Mineralisation Intrusive

In the latter part of this study, a late intrusive phase was observed in the lower levels of the mine. It was first identified on the 10285mRL level (plan 2), where it cuts through the ore zone. This intrusive was termed the 'late diorite' in mine terminology and its extent has been difficult to determine due to several reasons. The greatest problem was the previously mentioned lack of accurate identification of intrusive phases. The quartz content was commonly underestimated, leading to the poor nomenclature and misinterpretation of the mine intrusives. In addition, the texture of the late intrusive phase is very similar to both the Carcoar Granodiorite and the granitic members of the Mine Dyke Group. Thus, its distinction from these earlier two phases is difficult. Hand specimen identification gives this intrusive a range of classifications from quartz monzodiorite to granodiorite (figure 3.1). One sample was geochemically analysed. This gave a classification of quartz diorite to diorite. The hand sample classification is the preferred option here as not enough samples were analysed for a geochemical classification.

The Post-Mineralisation Intrusive has not been observed to cross-cut the Carcoar Granodiorite or the Mine Dyke Group. Thus, it is difficult to place it in context with these other two phases of intrusive activity. A timing relationship has been identified between the Carcoar Granodiorite, the Mine Dyke Group and the ore formation. As the Post-Mineralisation Intrusive clearly cross-cuts the ore, it is assumed to be the latest phase of the Browns Creek Intrusive Complex observable at present.

The Post-Mineralisation Intrusive cross-cuts the ore zone on the 10285mRL level,



where the ore is banded. The banding is terminated by the intrusive and does not continue through it, thus ruling out a possible late stage structural fabric. The contact is intrusive in nature and thus the body has not been faulted into place. A very narrow zone ($\leq 5\text{cm}$) of prograde garnet skarn forms along the contact. There has been a remetasomatising effect of the already skarn altered country rock, in this case the ore zone. This effect is minimal and constitutes a contact metamorphic effect and is not regional in its nature.

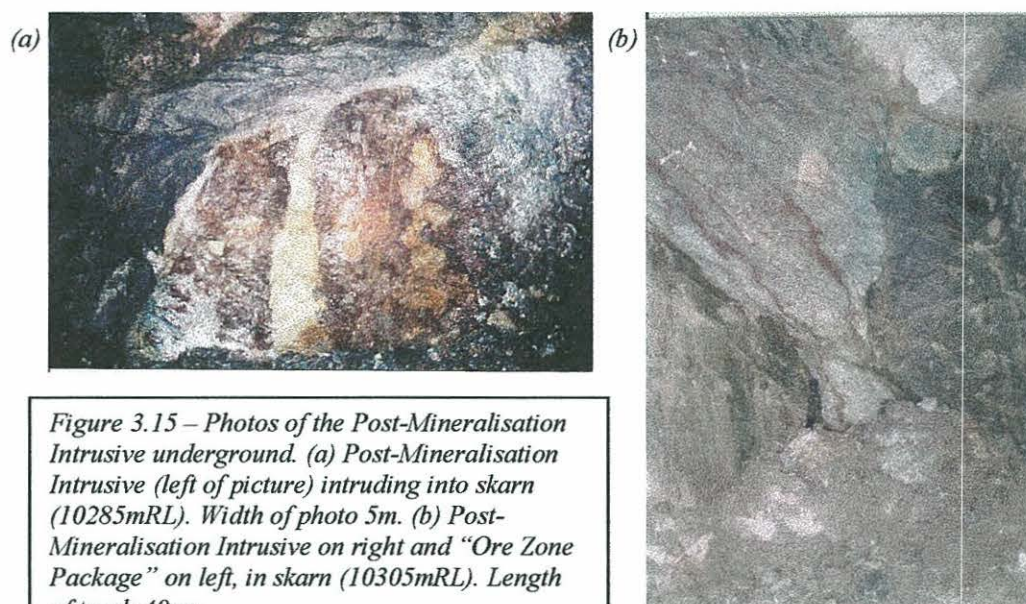


Figure 3.15 – Photos of the Post-Mineralisation Intrusive underground. (a) Post-Mineralisation Intrusive (left of picture) intruding into skarn (10285mRL). Width of photo 5m. (b) Post-Mineralisation Intrusive on right and “Ore Zone Package” on left, in skarn (10305mRL). Length of torch 40cm.

The Post-Mineralisation Intrusive is very similar in appearance to the Carcoar Granodiorite being mottled grey/white in colour. It is also of medium grainsize, equigranular and displays a typical intrusive texture. It is slightly darker in appearance than the other two intrusive phases, indicating a greater abundance of mafic minerals. These mafic silicates are amphibole and comprise 30% of the hand sample. The sites show some variation in colour that may indicate mineral specific alteration. Quartz grains (10-25%) are anhedral and occur throughout the rock. They typically occur with feldspar grains, which are dominantly plagioclase laths (30-40%). Minor alkali feldspar is also present (5%) and these grains often show alteration to epidote group minerals. Biotite is also readily observed, as this intrusive has suffered late biotite alteration.



Figure 3.16 – Photo of the Post-Mineralisation Intrusive hand sample (sample #NH81).

The Post-Mineralisation Intrusive was not uncovered until the final stages of research. As a result, no thin sections were able to be obtained for this lithology. However, a whole-rock geochemical analysis was performed by Hargraves Resources N.L. and is included in Chapter 6 and the Appendix 2 for comparison with the Carcoar Granodiorite and the Mine Dyke Group. Essentially, the intrusive does not deviate away from the rest of the Browns Creek Intrusive Complex.

There has been no mineralisation identified that appears to be associated with the Post-Mineralisation Intrusive. It may be argued that there were hydrothermal fluids preceding the intrusion of this quartz monzodiorite, which were essentially sourced from the same parent magma, and that these fluids were the source of the mineralisation. This will be discussed further in Chapter 5.

Biotite alteration is pervasive in the Post-Mineralisation Intrusive, which can be readily seen in hand sample observation. There is also minor epidote group crystallisation that appears to be replacing the feldspar fraction of the intrusive. This is consistent with the alteration observed within the other members of the Browns Creek Intrusive Complex. The lack of petrographic observation limits the knowledge of the alteration suffered by this intrusive.

3.1.4 Correlation of the Three Main Phases of Intrusive Activity

Due to the strong similarity in appearance, petrography and geochemistry of the three main phases of the Browns Creek Intrusive Complex, it is proposed that the Carcoar Granodiorite, Mine Dyke Group and the Post-Mineralisation Intrusive are likely to have been sourced from the same parent magma. The first two intrusive phases are relatively close in their age of emplacement, 430.4 ± 4.7 Ma for the Carcoar Granodiorite versus 432.3 ± 4.9 Ma and 430.0 ± 5.4 Ma for the Mine Dyke Group (Chapter 7). The Post-Mineralisation Intrusive has yet to be dated but due to its cross-cutting relationship with the ore zone, it appears to be later than the Carcoar Granodiorite and the Mine Dyke Group.

The intrusive bodies observed at the Browns Creek deposit show geochemical similarities (Chapter 6), suggesting a common source material. Together they are referred to as the Browns Creek Intrusive Complex. In numerous Harker diagrams, the plots of the major elements show that the three phases are closely related. Plots such as barium, rubidium and strontium show that the magma source has evolved. Two differentiation processes could have helped control the compositional variation observable within the phases of the Browns Creek Intrusive Complex. The first is a cumulate differentiation process, of which the Long Hill Phase is evidence. The second is fractional crystallisation, observable as the Mine Dyke Group. As little is known about the Post-Mineralisation Intrusive, it is difficult to infer any details about the magma source at the time of its emplacement.

3.2 Porphyritic Monzonite

A mafic porphyritic monzonite was intersected in deep exploration drill holes under the deepest known ore and to the southwest of the mine within the Forest Reefs Volcanics. This is a very distinct intrusive body and shows little correlation with the Browns Creek Intrusive Complex. This body has been described as a feldspar-

pyroxene megacrystic mafic monzonite from petrographic observation (Barron, 1999). The feldspar phenocrysts (plagioclase) are up to 8mm in length. However, other examples of this lithology show feldspar megacrysts up to 15mm in length. The dominant constituent of the megacryst and phenocryst fraction is glomerophorphyritic aggregates of clinopyroxene (up to 8mm in size). These sites have been selectively altered to actinolitic amphibole $\pm$ chlorite.

Figure 3.17 – Photo of porphyritic monzonite hand sample (sample #CMRX207, Hargraves Resources N.L.).



The phenocrysts and megacrysts are set within a dark groundmass comprising dominantly feldspars and mafic mineral sites. The feldspars have sodic (plagioclase) cores and alkali feldspar rims. The mafic mineral sites have mostly been converted to actinolitic amphibole $\pm$ biotite $\pm$ titanite-leucoxene.

Whole-rock geochemical analysis was conducted on this lithology by Hargraves Resources N.L. (Appendix 2 and Chapter 6). This has been included in this report for the purposes of correlating this unit with the other intrusives in the mine environment. However, there is no geochemical relation between the monzonite and the Browns Creek Intrusive Complex. The monzonite has a similar geochemical signature to the Blayney Volcanics and the Tallwood Monzonite. If so, the intrusion of this mafic monzonite occurred prior to the intrusion of the Browns Creek Intrusive Complex as both the Blayney Volcanics and Tallwood Monzonite are older than the latter intrusives.

3.3 Blayney Volcanics

The Carcoar Granodiorite intruded the Blayney Volcanics and its constituent, the Cowriga Limestone Member. This group is the host rock sequence of the Browns Creek orebody. The Blayney Volcanics have previously been given the term *andesite* in mine terminology however, the majority of occurrences are volcaniclastic, basaltic and rarely andesitic.

The open-pit mapping by Rangott and Bird (1994) revealed that the Blayney Volcanics was thin (10-30m wide), separating the Carcoar Granodiorite from the Cowriga Limestone Member. While the spatial relation of the Blayney Volcanics with the Carcoar Granodiorite and the Cowriga Limestone Member has not changed in the underground mine, the extent of the package has. The horizontal thickness of the volcanics unit varies from five metres to more than 50m. The broadest zone of volcanics interpreted from diamond drill core is located from approximately 10250mRL to 10050mRL. This area also coincides with a large embayment in the Carcoar Granodiorite contact.

The Blayney Volcanics are observed underground to be in direct contact with both the Carcoar Granodiorite and the Cowriga Limestone Member. The intrusive contact with the Carcoar Granodiorite has been previously discussed. The contact with the Cowriga Limestone Member is often difficult to determine as it is overprinted by skarn and mineralisation. However, it is probably fault-controlled, due to the presence of mylonite in the Cowriga Limestone Member. The contact between the two units within the mine has been interpreted from drillcore by past researchers and mine employees to be conformable. This is unlikely to be the case, as stressed, boudinaged blocks of volcanics appear in the ore zone. These bodies display pressure shadows and mylonite banding surrounding them (see figure 4.3).

The Mine Dyke Group and the Post-Mineralisation Intrusive were not observed in direct contact with the Blayney Volcanics. These were identified within the ore

zone. However, as they both post-date the skarn, they would be expected to also post-date the Blayney Volcanics. Some of the Mine Dyke Group would also have structural contacts with the Blayney Volcanics, as they have intruded along north-south oriented structures. This is covered in more detail in Chapter 4.

In general, unaltered Blayney Volcanics are dark coloured, ranging from black to dark green and dark grey. Their texture is quite varied from volcaniclastic to sub-intrusive. The volcaniclastic samples contain clasts that can range up to 30-40mm in size. The clasts are typically rounded to sub-rounded and their origin is indeterminate as they have suffered skarn alteration. Rangott and Bird (1994) noted during their detailed mapping of the open pit that due to pervasive epidote alteration and localised skarn alteration, the Blayney Volcanics appear to have a pseudo-brecciated texture. This feature is also common throughout underground exposures, particularly within the central skarn zone.

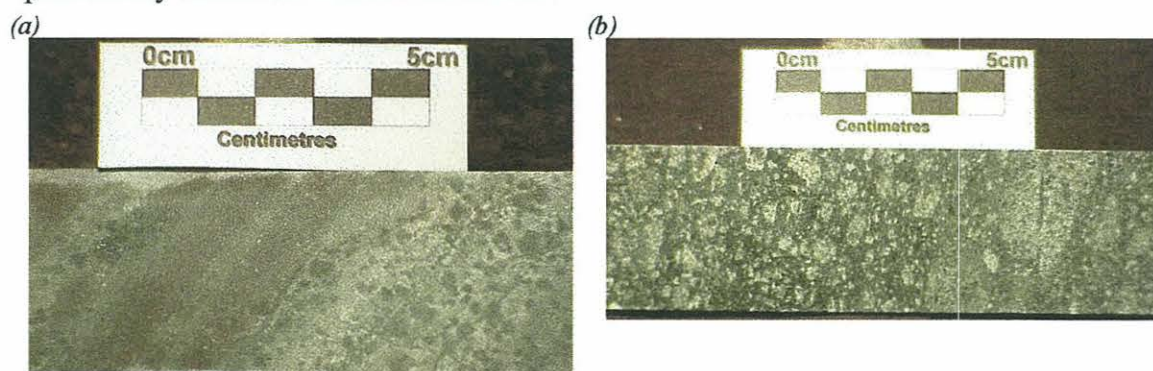


Figure 3.18 – Photos of Blayney Volcanics hand samples. (a) Sample #BCDX0010 (Hargraves Resources N.L.). (b) Sample #BCDX0008 (Hargraves Resources N.L.).

The Blayney Volcanics was not a focus of this study. So, the petrographic study by Barron (1998) was utilised, in conjunction with other reports, to obtain an overview of the unit. Barron identifies two different types of volcanics observed at the mine. This grouping is based on the relict textures observed in the samples. The first of these sub-groups are the porphyritic volcanic flows that are characterised by clinopyroxene and subordinate feldspar phenocrysts. The second sub-group is the lithic/crystal fragmental volcaniclastic group, whereby lithic fragments of

clinopyroxene, plagioclase and porphyritic andesitic fragments are set within an aphanitic, possibly andesitic volcanic groundmass.

The Blayney Volcanics are dominated by clinopyroxene phenocrysts (up to 25%), with varying amounts of plagioclase phenocrysts (up to 15%) (Pogson and Watkins, 1998). The groundmass fraction of these rocks was most likely of a similar composition to the phenocryst fraction. However, it has suffered quite substantially by fine-grained contact metamorphic processes and skarn alteration. The groundmass now consists of secondary clinopyroxene, epidote and titanite.

All of the volcanic/volcaniclastic samples of the Blayney Volcanics have experienced varying degrees of alteration, from skarnification to pervasive epidote alteration. However, prior to this, the Blayney Volcanics were hornfelsed to produce an assemblage high in biotite. This was a widespread event that has affected a large amount of the Blayney Volcanics unit, specifically around the Carcoar Granodiorite. It is postulated that the cause of this large scale hornfelsing was the intrusion of the Carcoar Granodiorite. Minor amounts of silica alteration are sporadically observed.

After the hornfelsing event, the Blayney Volcanics were altered by a prograde skarning event. This produced the garnet-clinopyroxene-wollastonite-vesuvianite-quartz-calcite assemblage that is evident today and hosts part of the mineralisation. While this assemblage is similar to that of the prograde skarn of the Cowriga Limestone Member, there is a greater abundance of garnet and clinopyroxene in the skarn altered Blayney Volcanics. The garnet and clinopyroxene have been analysed by electron microprobe (Kjolle, 1991). The garnet is aluminium-rich (grossular). Clinopyroxene has been identified as a species that is intermediate between diopside and hedenbergite, being slightly more iron-rich (Kjolle, op. cit.).

Pervasive epidote alteration followed the prograde skarn, thought to be synchronous with the mineralising event. This can be observed by epidote veinlets, the formation



Figure 3.19 – Photo of skarned Blayney Volcanics (sample #NH59). Note predominance of garnet over wollastonite.

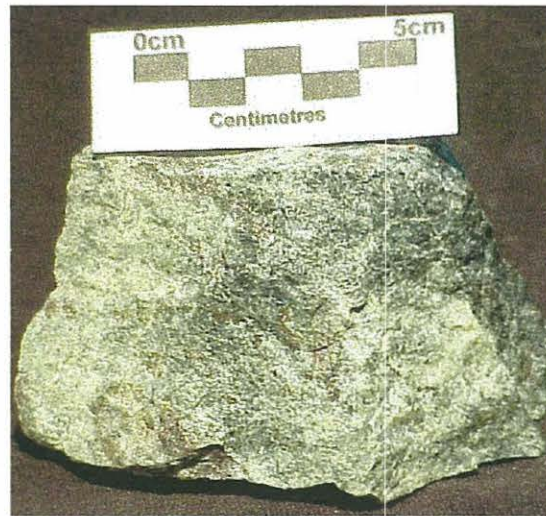


Figure 3.20 – Photo of pyroxene-garnet skarned Blayney Volcanics with epidote alteration (sample #NH60).

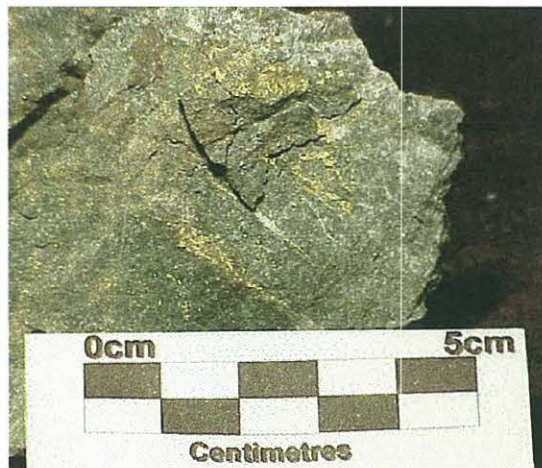


Figure 3.21 – Photos of mineralisation in Blayney Volcanics. (a) Massive bornite and chalcopyrite (sample #NH77). (b) Chalcopyrite occurring as late fracture infill and veinlets (sample #NH71).

of actinolite at the expense of primary clinopyroxene and albitisation of primary feldspars.

Mineralisation within the volcanics/volcaniclastics consists of abundant chalcopyrite and bornite with minor sphalerite, pyrite, pyrrhotite and arsenopyrite within the mine area. Detailed thin section observation has revealed that the mineralisation is contained within quartz veins that cut through the prograde skarn altered host rock.

Sulfides that are located within these veins comprise bornite and arsenopyrite with minor amounts of electrum and rare native gold. While there may have been some minor mineralisation associated with a retrograde skarn event, the vast majority of mineralisation is related to a later hydrothermal event. This is also responsible for the epidote alteration and has occurred after the skarn has formed. This is discussed further in Chapter 5.

In underground exposures, there are areas of the mine that contain massive pyrrhotite and magnetite within the Blayney Volcanics. These areas are a form of skarn. There is little mention of these skarns by the previous researchers, perhaps indicating they did not occur in the upper levels of the underground mine and the open-pit. These skarns are discussed in more detail in Chapter 5

3.4 Cowriga Limestone Member

The Cowriga Limestone Member is a concordant unit of the Blayney Volcanics. It has been metamorphosed to the grade of marble, due to the intrusion of the Carcoar Granodiorite that was also responsible for the hornfelsing of the Blayney Volcanics. The marble unit is far more extensive than surface exposure reveals (Chapter 2). It consistently lies to the east of the ore zone, forming the hangingwall to mineralisation.

The marble within the mine environment is generally white to grey in colour and is medium to coarse grained. Exposures in the open pit indicate that the marble is relatively uniform in its appearance, showing no banding/layering. However, this differs from the majority of underground exposures of the marble. The contact between the skarn altered ore zone and the marble is characterised by the formation of a mylonite zone. This gives the marble a banded appearance where the foliations are spaced at less than ten centimetres apart. The banding is caused by the alternation of light and dark grey coloured bands that are north-south trending. The

darker bands may represent more silty depositions within the original Cowriga Limestone Member. The mylonite zones of the marble are typically finer grained than the majority of the marble. The zone is discussed further in Chapter 4.

The petrography of the Cowriga Limestone Member is based upon the findings of previous researchers in the area. Kjolle (1991) performed petrographic observations on the Cowriga Limestone Member. Her research revealed that it was 98.7% CaCO_3 , with minor amounts of MgCO_3 and trace amounts of Al_2O_3 and SiO_2 . The recrystallisation of the calcite to large grains (up to 10mm in size) was the first event. The variation in the twinning of the calcite grains reveals that the marble has been subject to further events of deformation and recrystallisation.

The most notable form of alteration is the prograde skarnification of the already metamorphosed Cowriga Limestone Member. In most cases, the protolith of skarn can be identified as marble or volcanic except in the zones where the most intense skarnification processes have taken place along the contact between the Blayney Volcanics and the Cowriga Limestone Member. However, skarning of the marble is characterised by the formation of a wollastonite-garnet $\pm$ diopside $\pm$ quartz $\pm$ epidote. The garnet is of the composition of grossulite to andradite and occurs as porphyroblasts (up to 10mm). The wollastonite occurs as bladed crystals that have

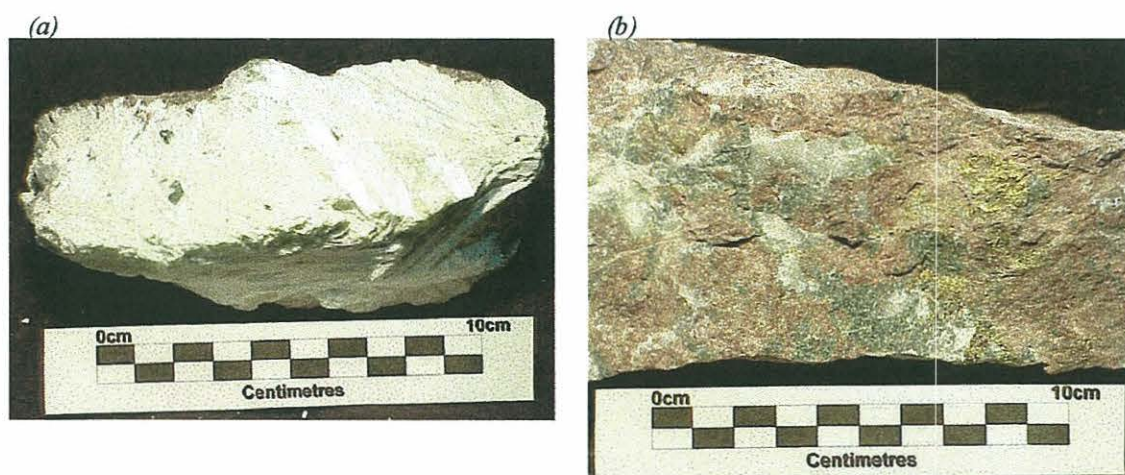


Figure 3.22 – Photos of skarned marble. (a) Bladed wollastonite (sample #NH53). (b) Contact between skarned volcanics (right) and marble (left) (sample #NH64).

been observed up to more than 10cm.

The fluids responsible for the skarn formation appear to have infiltrated via a series of fractures and joints that previously cut the marble. On the edges of the orebody where the skarn is less well developed, the skarn has the form of 'wrigg lite'. This term describes the worm-like patches throughout the marble, as used by Wilkins (1998). These patches are somewhat planar and represent northeast-trending fracture and joint sets that were dilatant at the time of infiltration.

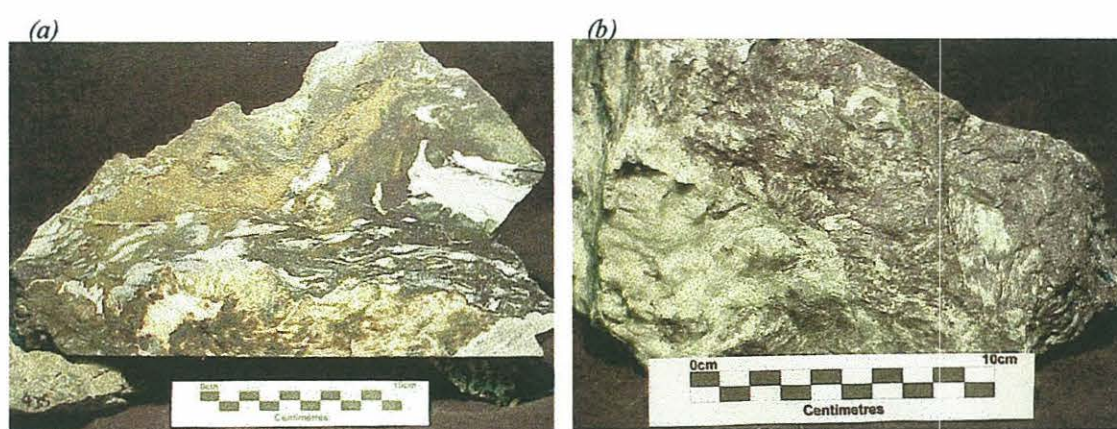


Figure 3.23 – Photos displaying mineralisation within skarned marble. (a) Massive chalcopyrite with bornite (sample courtesy of G. Kovacs). (b) Bornite within bladed wolastonite (sample #NH65).

Mineralisation of the Cowriga Limestone Member is restricted to the skarn altered areas only. The most abundant examples are bornite and chalcopyrite, with gold and minor pyrrhotite and arsenopyrite. Rare examples of hessite, gersdorffite, glaucodot and ?niccolite were also reported by Kjolle (1991). However, these sightings should be treated with extreme caution as nickel-bearing minerals may have been sourced from the mullock around the Arsenic Shaft, north of the mine (G. Kovacs, pers. comm., 1999). The crushing plant that operated there in the 19th century processed ore from both the Browns Creek and the Carcoar Cobalt Mine. Glaucodot and niccolite were primary ore minerals at Carcoar, and have never been previously reported at the Browns Creek deposit. However, hessite has also been reported by Creelman *et al.* (1990) from open-pit observations. The sulfides represent a mineralising event that has occurred post-skarn formation. The gold has deposited

after the copper-bearing sulfides and the whole system is one of hydrothermal mineralisation. Thin section observation and underground exposures reveal that the fluids responsible for skarn formation have infiltrated the host rock sequence through fractures and joints. The sulfides have mostly deposited along microfractures through the prograde marble skarn. Corbett (1997) reports gold being located along fractures through prograde garnet and as open-space infill in wollastonite (Chapter 5).

3.5 Skarn Alteration

Although a significant study on the skarn alteration was performed by Kjolle (1997), more recent studies by Barron (1999) are utilised in this study. They are consistent with Kjolle's findings but contain advanced understanding of the skarn alteration due to the deeper exposure of the deposit, unavailable during Kjolle's study.

The ore at the Browns Creek deposit is hosted within the calc-silicate metasomatised Blayney Volcanics and Cowriga Limestone Member. This skarn alteration forms a zone that is oriented approximately northwest in the open pit and north-south in the underground exposures of the mine. In both cases, the skarn zone parallels the contact of the Carcoar Granodiorite with the volcanics/marble package. This can be observed underground whereby the northern and southern extremities of the deposit follow the granodiorite contact giving the skarn zone an arcuate shape. This alone suggests that the intrusive is in some way responsible for the metasomatising event.

The skarn zone comprises a mineral assemblage of varying proportions of garnet, wollastonite and pyroxene. The proportions of these minerals is dependent on the host lithology. The resulting appearance of the skarn in hand specimen ranges from white bladed masses of wollastonite, through to red-brown masses of garnet to darker green pyroxene-rich rocks with red-brown patches of garnet. The grain size of the minerals can range from sporadic wollastonite blades up to 10cm in length to a

fine-grained aphanitic mass. Large euhedral garnet porphyroblasts have also been identified (particularly within the open pit but also rarely in underground exposures).

There is a broad zoning within the skarn. The zoning is dependent on the primary lithology of the skarn. The skarn in the open pit was previously described as stratabound skarn and was believed to have developed along the contact between the limestone and the volcanics. Taylor (1983) gives a detailed description of the stratabound skarn, however, he misidentified the volcanics as mudstone. He outlines three different assemblages within the stratabound skarn (Table 3.2).

	LITHOLOGY	GANGUE	SULFIDES
Assemblage 1	limestone skarn volcanics	Cc Wo-Qz-Cc-Cz Qz-Cc-Cz	Py-Cp
Assemblage 2	limestone skarn volcanics	Cc-Qz-Pm Qz-Cc-Ac-(Wo-Pm-Bi) Tr-Wo-Qz-Cc	Po-Py-Cp (retrograde Py-Mc)
Assemblage 3	limestone skarn volcanics	Cc-Qz-Ep Qz-Cc-Id-Ep-Ch-(Ga-Wo-Di-Sid) Wo-Cz-Bi-Di	Banded Asp-Cp-Po-(Tenn-Au)

Table 3.2 - Stratabound skarn in open pit (after Taylor, 1983). *Key:* Ac - actinolite, Asp - arsenopyrite, Au - gold, Bi - biotite, Bo - bornite, Cc - calcite, Ccc - chalcocite, Ch - chlorite, Cl - clays, Co - covellite, Cu - native copper, Cx - copper oxides, Cz - clinozoisite, Cp - chalcopyrite, Di - diopside, Ep - epidote, Ga - garnet, Id - idocrase, Mc - marcasite, Pm - phlogopite, Po - pyrrhotite, Py - pyrite, Qz - quartz, Sid - siderite, Tenn - tennantite Tet - tetrahedrite, Tr - tremolite, Wo - wollastonite. Abbreviations used for Table 3.2 and Table 3.3.

In addition to the stratabound skarn, Taylor and others also report vein skarns. These are classified as sub-vertical mineralised fractures. It is suggested by Taylor that the mineralisation associated with these veins may post-date the main period of skarn formation. An envelope of skarn development extends for up to 6m from the edge of the vein while sulfide crystallisation is limited to only 2m. Two assemblages have been identified within the vein skarns. These are listed, along with supergene assemblages, in Table 3.3.

Skarn development underground has been investigated by Barron (1998). She states that the calc-silicate skarn rocks are characterised by an assemblage of garnet,

	LITHOLOGY	GANGUE	SULFIDES
Assemblage 1	limestone skarn	Cc Wo-(Ep-Ga) retrograde Ch-Cl	Bo-Cp-Py-Ccc-Co
Assemblage 2	limestone skarn	Cc-Id Ga-Di-Id-Wo retrograde Ch-Cl	Cp-Bo-Ccc-Py-Au
Supergene	fault gouge	Qz, Cc-Ep	Py-Ccc-Cp-Bo-Co-Cx-Cu-Au

Table 3.3 - Vein skarn in open pit (after Taylor, 1983). Key as for Table 3.2.

wollastonite, clinopyroxene, vesuvianite, quartz and calcite. It is noted that this assemblage is similar to that of the skarn rocks in the open pit. This assemblage is indicative of temperatures greater than 650°C (Barron, 1998), which is consistent with other determinations made by previous researchers (500 to 650°C in Taylor, 1983; 600°C or higher in Creelman *et al.*, 1990; greater than 540°C in Meldrum, 1995). Corbett (1997) states that the fluid responsible for the skarn alteration has sourced its calcium from the adjacent marble and the water and silica has been derived from the magmatic source of the fluid. The iron, aluminium and magnesium also contained within the fluids is stated as being sourced from both the host volcanics and the magmatic source.

The array of differing skarn assemblages that were identified by Taylor have not been reported by other researchers of the underground skarn. However, some discrimination can be made regarding the proportions of the skarn minerals within the ore zone. The skarn that has formed from the marble contains greater proportions of wollastonite and calcite in its prograde skarn assemblage. The skarn that has formed from the volcanics is characterised by a greater abundance of clinopyroxene and garnet. Thus, the two primary lithologies can be broadly identified within the ore zone. The contact between the two units is no longer discernible as it has been obscured by strong development of prograde skarn.

The skarn in the ore zone has been overprinted by a later alteration event. This is described by Barron (1998) as a propylitic zone assemblage, characterised by albite,

epidote, actinolite, illite, calcite and alkali feldspar. This event is associated with the bulk of the mineralisation. It clearly overprints and in places replaces the prograde skarn. This event is discussed within Chapter 5. It is not associated with the formation of the prograde skarn and is postulated as being a purely hydrothermal event.

A feature that is often overlooked is the amount of skarn alteration of various intrusives associated with the ore zone. These examples of endoskarn are characterised by a garnet-rich assemblage. Rangott and Bird (1994) made brief mention of the weak garnet alteration of the Carcoar Granodiorite within the open pit. Kjolle (1997) frequently mentions the skarn alteration of the *Long Hill Diorite* and more felsic dykes observed within the open pit. The skarn alteration is typified by a narrow zone (several centimetres) of garnet, found along the margins of the intrusives. She adds that the skarn observed within the Carcoar Granodiorite is of garnet-pyroxene assemblage and usually occurs at the granodiorite/limestone contact. As this is a structural contact, it is presumed that the fluids responsible for the skarn alteration of the granodiorite has been sourced from depth and has been focussed along this structure.

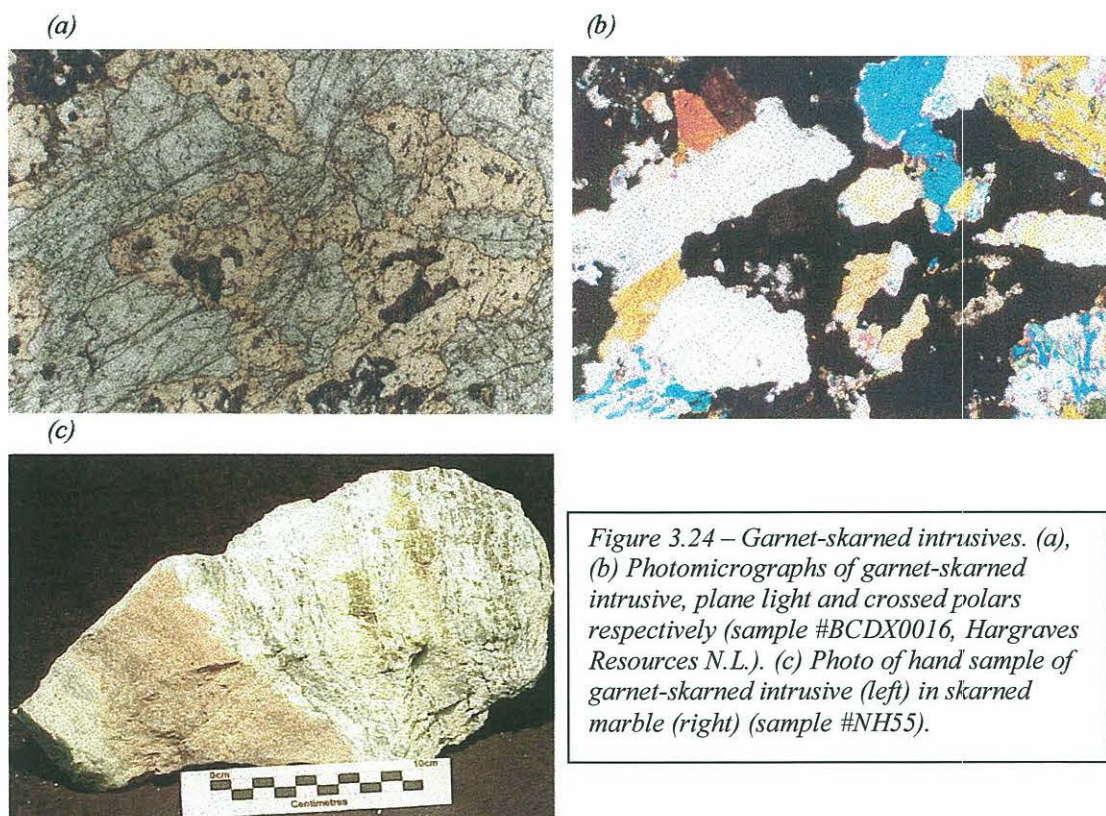


Figure 3.24 – Garnet-skarned intrusives. (a), (b) Photomicrographs of garnet-skarned intrusive, plane light and crossed polars respectively (sample #BCDX0016, Hargraves Resources N.L.). (c) Photo of hand sample of garnet-skarned intrusive (left) in skarned marble (right) (sample #NH55).

The extent of skarn alteration of intrusives in the open pit is unknown as it is rarely recorded. However, in underground exposures barren zones were intersected within the ore zone that were characterised by a mineralogy that was dominated by skarn alteration. These zones contain no economic minerals or grades. Petrography on several samples of this barren skarn feature were performed by Barron (1999). She revealed that the assemblage was dominated by garnet and mafic sites that had been replaced by clinopyroxene. These were stated to have had either an intrusive or volcanoclastic origin. The uncertainty is due to the destruction of primary minerals by the calc-silicate skarn formation. One theory is that if these zones were once intrusives, they may represent intrusives similar to the Post-Mineralisation Intrusive as the barren skarn zones cross-cut the orebody in a similar orientation to this intrusive. However, they could also be related to the later members of the Mine Dyke Group. To support this idea, several cases were found where members of the Mine Dyke Group were surrounded by an envelope of garnet alteration. It is believed that each pulse of intrusive activity within the Browns Creek Intrusive Complex had associated fluids that caused prograde skarn. This event forming the skarn overprints any others that had previously formed, including the main skarn development by the intrusion of the Carcoar Granodiorite. This may explain the differing skarn assemblages that were identified by Taylor (1983) in the open pit.

The barren skarn zones are likely to have formed after the mineralisation event. This could be coincident with either the latest members of the Mine Dyke Group or the Post-Mineralisation Intrusive. Regardless, this phase of skarn alteration has not been formed by the intrusion of the Carcoar Granodiorite unlike the rest of the skarn alteration observed at the Browns Creek deposit.

3.6 Basaltic Dykes

Late basaltic dykes intruded the Browns Creek orebody after the mineralising and skarn-forming events. These dykes vary in width up to 1m but are laterally and

vertically extensive. They can be traced along strike and dip for several tens of metres. Open-pit mapping by Rangott and Bird (1994) shows that the emplacement of these dykes has occurred along major fault and joint set orientations. The dip along these planes is sub-vertical and the stereographic analyses show two controlling orientations - north-south and the northwest trends. The importance of these two structural trends is discussed further in Chapter 4.

The basaltic dykes have intruded into a variety of the host lithologies. However, they are most readily observed within the marble in the open pit. Here they display planar structural contacts with the surrounding marble. Rangott and Bird (1994) also mention that the dykes intruded along pre-existing structures that have reactivated post-emplacement. This has resulted in post-emplacement deformation, such as shearing and boudinaging.

Figure 3.25 – Photos of basaltic dykes in the open pit (Rangott & Bird, 1994). Width of dykes 1-2m.



The relative timing of the dykes can be identified as they are also found to intrude the Carcoar Granodiorite in the open-pit. In such cases, the edges of the dykes display a bleached chill margin, clearly indicating its later emplacement. In underground exposures, the basaltic dykes also display late emplacement. They are readily observed to cut through the ore zone, commonly displaying chill margins. In these cases, they show no signs of having been altered by skarn processes.

The basaltic dykes are relatively common within the open-pit and the upper levels of the mine. However, in the lower levels of the mine, the basaltic dykes disappear. At depth, the dykes are possibly located within either the marble to the east or the Carcoar Granodiorite to the west. Rangott and Bird (1994) make brief mention of a large mafic dyke or stock that separates the Carcoar Granodiorite from the marble in the western end of the pit. The location of this stock may indicate that the source for the basaltic dykes may lie within the Carcoar Granodiorite. The mining underground has moved progressively eastwards and development has not intersected such a body.

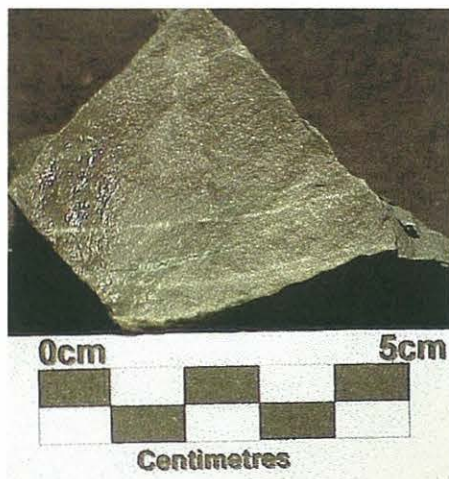


Figure 3.26 – Photo of basaltic dyke hand sample (sample #NH12).

Thin section observation of one of the underground dykes (NH11, NH12) reveals that their composition is basaltic. They are sub-porphyritic with an aphanitic groundmass, indicating a high level intrusive. Samples of basaltic dykes from the open-pit reveal a basaltic to trachybasaltic composition (Rangott and Bird, 1994). Any alignment of feldspars that were observed in the underground samples were along the margin of the dyke that was sampled, consistent with intrusive emplacement.

Thin sections were collected to reveal the reason for the bleaching of the margins of the basaltic dykes. The margins are finer grained than the centre of the dykes and show an alignment of the feldspar laths. This indicates that the bleaching is due to the chill margin and not subsequent alteration of the dyke.

The dykes have suffered alteration to an assemblage of iron-titanium oxides, clays, ?chlorite and ?carbonate. Several fractures have been infilled with epidote group minerals however, these have not affected the minerals immediately surrounding the fracture. Sample NH12 is part of the contact between a basaltic dyke and the marble host rock. The marble has been recrystallised to epidote and clinozoisite, only 0.5mm into the contact. In the pit samples, Rangott and Bird (1994) found that where the mafic dykes have intruded the marble, garnet $\pm$ pyroxene alteration was common. Higher up in the pit, they found that the basaltic dykes were ?hydrothermally affected by clay and silica alteration.

3.7 Clay Zones

Brief mention is made here of the clay alteration zones that occur in the pit. The high grades of gold that were located within these zones, led to the use of the term “clay ore zones”. This is the location of the mining of the Browns Creek orebody in the 19th century. The clay zones occur in the northern end of the pit, above 10760mRL. The detailed mapping report of Rangott and Bird (1994) states that the clay zones are typically associated with cave systems within the marble and the late mafic/basaltic dykes. The marble that the clay zones are found within is also strongly fractured. It is suggested that this created the passage for the hydrothermal



Figure 3.27 – Photo of clay zone in open pit (Rangott & Bird, 1994).

fluids to pass through to thus form the clay zones. They are also enriched in copper, arsenic, tin, tungsten, vanadium, antimony and barium.

Creelman *et al.* (1990) state that there are three types of clay ore recognised:-

(a) Nontronite zones : This is described as a retrograde alteration of the skarn, hosting anomalously high gold grades (more than 10g/t gold) that were targeted by mining in the 19th century. XRD analyses of this material by Rangott and Bird (1994) reveal that it comprises smectite-illite, with minor chlorite. The zones also contain boulders and nodular accumulations of jasperoid material or chalcedonic silica. Rangott and Bird (1994) give details of the petrographic observation of such material. It revealed that the jasperoid is hydrothermally silicified garnet $\pm$ pyroxene skarn altered marble.

(b) Massive clay zones : These zones occur in the uppermost level of the pit and are believed to have formed by in situ weathering of skarn.

(c) Clay breccias : Such clay zones are found above the Cowriga Limestone Member. The karst-like material consists of angular fragments of strongly weathered volcanics, granodiorite, skarn, limestone and jasperoid. The breccia is believed to have formed as a result of karst collapse during intense weathering.

Rangott and Bird (1994) conclude that there were two hydrothermal alteration events that were involved in the formation of the clay zones. They state that the first was a high temperature skarn-altering event that also introduced sulfides and gold. They add that this may have been the result of the intrusion of the mafic/basaltic dykes as they are also affected. The second event a lower temperature event that deposited silica and further gold. The gold from the first event may have been remobilised by this event. This second event has resulted in the intense clay alteration of the mafic material and the silicification of the dyke and skarn material. An alternative to this is that the clay zones have a supergene origin. This would be consistent with the presence of oxidate copper assemblages (including native copper) and clays, including nontronite.