Chapter One – Introduction

1.0 Introduction

The Nifty Cu deposit is located approximately 450km east of Port Hedland, Western Australia (Fig. 1.1) in the Proterozoic Paterson Orogen (Williams and Myers, 1990). The deposit consists of a secondary oxide resource of 12.2 Mt @ 1.52% and a primary sulphide ore body of 26.3Mt @ 4.6% with a 2% cut-off (WMC Resources Ltd. company reports). The deposit was owned, and the secondary oxide mined using open cut methods, by WMC Resources Pty. Ltd until September 1998 when it was sold to Steinl Resources Ltd. Steinl Resources Ltd redefined the Cu resource during 1999 as 98Mt @ 1.63% Cu with a 0.5% cutoff.

Figure 1.1: The Nifty Cu deposit is located on the edge of the Great Sandy Desert approximately 450km south-east of Port Hedland in Western Australia. This figure also shows the location of major population centres in the area of the Nifty Deposit and the inset shows the location within Australia.
1.1 Exploration History

In the 1970's descriptions of the Paterson Province by the Geological Survey of Western Australia (Chin and Hicksman, 1977) led WMC Resources Pty Ltd to develop a conceptual model for the exploration of sediment-hosted stratiform copper deposits (Haynes et al., 1993). Subsequent field investigations noted that the coarse-grained lithics of the Coolbro Sandstone could have acted as a favourable source rock and the halde of dolomitic silstone and pyritic shale of the Broadhurst Formation could have acted as a possible host for sediment-hosted stratiform copper (Haynes et al., 1993).

In 1979, geophysical surveys, further geological mapping and systematic ironstone and outcrop sampling commenced near the western margin of the basin. Interpretation of aeromagnetic data defined a Pb-Zn-Cu target in the region of Nifty and other possible targets for stratiform Cu along the western margin of the basin (Haynes et al., 1993). Follow up geological mapping and sampling in 1980 confirmed the existence of a large Cu-Pb-Zn soil anomaly at Nifty and subsequent follow-up drilling intersected mahlrite of the secondary ore body. The discovery of anomalous Pb and Zn associated with a distinctive pyritic marl bed and deeper chalcopyrite of the primary mineralisation occurred in May 1982 (Haynes et al., 1993).

After initial exploration, a programme of resource definition drilling was conducted, during which 25 diamond drill holes were drilled. A further six holes were drilled in 1991 as part of a major pre-feasibility study and the aim of drilling these holes was to delineate the edges of the primary deposit. Open pit mining operations of the secondary oxide ore body began in 1992.

Although not the largest copper deposit in the Yeneena Basin, the Nifty Cu deposit is the only one presently being mined. The largest Cu ore body is the Broadhurst Formation-hosted Maroochydore disseminated Cu deposit (Reed, 1990). Numerous other deposits and prospects occur throughout the Yeneena Basin and these include; the Kintyre unconformity-associated, vein-type U deposit, Teller Au-Cu deposit, and the following prospects; Warrabahy carbonate-hosted Pb-Zn, Rainbow stratiform Cu, Fuch Cu, Goosewacker Pb-Cu-Au vein, Moses Chair Pb-Zn, Grevilles massive pyrite, and Citadel Cu. Regional metallogeny, with a brief description of each deposit and prospect, is outlined in Chapter Two.

1.2 Previous Studies

1.2.1 Regional Studies

The earliest geological investigations in the area were conducted by H.W.B Talbot between 1912 and 1914 (Talbot, 1920). Talbot (1920) recognised two sedimentary units, the Nullagine Series and the Paterson Range Series. It was not until 1949 that the next geological study was undertaken (Reeves, 1947). Reeves (1947) examined the Permian rocks in the Paterson Range during a geological and oil prospecting investigation of the southwestern margin of the Canning Basin. This was followed by the first geological map for the area (Traves et al., 1956) produced by the Bureau of Mineral Resources in 1956. In 1966 and 1969 L.E. de la Huary and J.G. Blockley of the Geological Survey of Western Australia
made reconnaissance visits to the area in preparation for the 1966 and 1973 editions of the State Geological Map (Hickman and Clarke, 1994). In the early 1970's the discovery and delineation of the Telfer Au-Cu deposit spurred on a sudden increase in mineral exploration in the area.

1.2.2  Nifty Cu Deposit

Previous studies on the Nifty Cu deposit are mostly restricted to mine and local exploration programs conducted by WMC Resources Pty. Ltd. Early studies on the Nifty Cu deposit were conducted by M. Norris, a company exploration geologist involved in the reconnaissance exploration of the Yeneena Basin. In 1987, Norris completed a M.Sc at the University of Western Ontario on the geology of the Nifty carbonate member, Broadhurst Formation, Paterson Province, Western Australia (Norris, 1987a). The focus of Norris's study was to document the stratigraphy and sedimentology of the Nifty carbonate member and to determine the deposits geological setting (Norris, 1987a). In addition to the thesis, Norris generated several company progress reports, a series of 1:5000 outcrop map sheets and an expanded thesis summary (Norris, 1985; Norris 1987a; Norris, 1987b).

A second major contribution to early research on the Nifty Cu deposit was the work of another WMC Resources Ltd geologist, A. Carmichael. Carmichael (1990) re-examined the work of Norris (1987a) in light of data obtained during an extensive resource definition diamond drilling on the deposit in 1985. A further company report (Carmichael, 1992) detailed a geophysical and geological re-interpretation of the Throssell Range after integrating a considerable amount of new diamond drill core, RC drilling and infill SECTEML data. Once mining operations commenced, Carmichael (1993) reported on stratigraphic and structural observation in the Nifty open cut and presented a summary of evidence that he considered in interpreting a syn-tectonic timing for the deposition of Cu at Nifty.

1.2.3  Other Broadhurst Formation Deposits and Prospects

Two Ph.D studies have been completed on other mineralised occurrences in the Throssell Group. These studies are Smith (1996), who examined the geology and geochemistry of the Warranyu carbonate-hosted Zn-Pb Prospect, and Reed (1996), who examined the structural, stratigraphic and temporal setting of the Maroonychore Cu deposit. A B.Sc. (Hons) project (McKnight, 1992) also examined Maroonychore to determine the stratigraphic and sedimentary setting of mineralisation. The most recent completed work on a prospect within the Broadhurst Formation is a B.Sc (Hons) thesis (Proud, 1997) on the mineralisation and alteration of the Goosewacker Pb-Zn-Cu vein deposit.

1.2.4  Lamit Group

Within the Yeneena Supergroup, but stratigraphically above the Throssell Group, is the Lamit Group that is host to the Telfer Au-Cu deposit and numerous satellite prospects. Telfer Au-Cu mine is owned by Newman Mining Corporation and was the largest single producing gold mine in Western Australia (Dimo, 1990) in the late 1980's. The major studies on Telfer mineralisation are Goellnicht et al. (1987),
Goellnicht et al. (1989), Dimo (1990), McNaughton and Goellnicht (1990), Goellnicht et al. (1991); Goellnicht (1992); Rowins (1994); Inglis (1995), and Rowins et al. (1997).

1.2.5 Potential Analogues

Ward et al. (1998) suggested that the Nifty Cu deposit is an analogue of the mid-Proterozoic, silica-dolomite hosted Mount Isa Cu deposit of Queensland, Australia and that together they form a class of Proterozoic metamorphic Cu deposits. Other deposits listed as potential analogues are the Middle to Upper Devonian carbonate-hosted Ruby Creek deposit of Alaska (Rumels, 1963, 1969; Hitzman, 1983, 1986; Bernstein and Cox, 1986) and the Sheep Creek prospect of the Belt Supergroup, Canada. In the following chapters, details on the deposits of Mount Isa and Ruby Creek are present and compared to Nifty.

1.3 Aims

The objective of this thesis is to characterise the spatial and temporal setting of mineralisation and alteration at the Nifty Cu deposit. The aims of this thesis are:

- Characterize the geologic and structural setting of the deposit.
- Document alteration assemblages and zonation.
- Document the geochemical signatures of the Nifty mineralisation and associated alteration halo.
- Construct a model of mineral, metal, and alteration zonation.
- Investigate the physio-chemical conditions of the hydrothermal fluid.
- Propose an ore genesis model for the deposit.

The focus of this study is the genesis of the primary sulphide ore body however some of the research has relied on observations from the open pit and secondary oxide deposit.

1.4 Methods

Both field based and analytical methods were used in this investigation of Nifty Cu deposit. These methods consist of:

1. Detailed bench mapping of lithologies and structures within the Nifty open pit.
2. Logging and sampling of diamond drill core, concentrating on two cross sections (102080mE and 102240mE local mine grid). Additional diamond drill core from the edges of the ore body were also logged and sampled.
3. Outcrop mapping in the mine area (1.5km radius).
4. Petrographic studies of host rock, sulphide mineralisation and gangue minerals.
5. Pb isotope studies on galena, pyrite and K-feldspar separates.
7. Analysis of host carbonates, gangue, vein stages and mineralisation for the stable isotopes of carbon, oxygen, and sulphur in order to determine the physio-chemical conditions of hydrothermal fluids.

4
8. Fluid inclusion studies were carried out on vein material in order to obtain estimates of temperature, salinity and constrain the fluid compositions.

9. Fluid modelling using the physio- and thermo-chemical data to model the conditions of ore precipitation.

1.6 Data

Data generated by WMC Resources Ltd. has been used in this research and where appropriate the author of that data has been duly acknowledged. Examples of company data include 1) exploration assay database; 2) 1:500 geology facs maps, 3) diamond drill hole logs and interpretative cross-sections, and 4) internal company exploration reports on regional prospects, sample petrology, and XRD results. In addition to company data, extensive use has been made of data contained in recent Paterson Orogen PhD theses (Goellnicht, 1992; Rowins, 1994; Reed, 1996; Smith, 1996). Data from three BSc (Hons) theses has also been used (McKnight, 1992; Inglis, 1995; Froud, 1997).

1.5 Thesis Outline

The chapters in this thesis can be grouped into three overlapping themes. The first theme provides the general geological setting of the Paterson Orogen and the Nifty Cu deposit. These early chapters provide a framework on which chapters with a descriptive theme are presented on the structure, alteration assemblages, vein stages, and mineralisation textures. The next theme that is addressed is the presentation of analytical results from studies of 1) whole rock geochemistry, 2) Pb isotopes, 3) stable isotopes of carbon, oxygen and sulphur, and 4) fluid inclusions. These four chapters examine the spatial distribution of elements and isotopes, and characterise the metal source and hydrothermal fluid composition. The results from these themes are integrated in the final chapter where a genetic model on the formation of the Nifty Cu deposit is presented.
Chapter Two - Regional Geology

2.0 introduction

This chapter outlines the regional geological setting of the Palaeoproterozoic to Neoproterozoic Paterson Orogen. The Paterson Orogen is bounded to the west by Archaean rocks of the Pilbara Craton and from the north through to east are marine and terrestrial sedimentary rocks of the late Carboniferous to early Permian Canning Basin. From east through to the south are Proterozoic siliciclastic sedimentary and evaporite rocks of the Officer Basin, and from the south to the west are sandstone, siltstone, shale, and diamictite of the Neoproterozoic Savory Basin (Fig. 2.1).

Geologists of the Geological Survey of Western Australia established and refined the stratigraphic and tectonic relationships to the surrounding basins. One of the earliest terms for the region was the Paterson Province (Blockley and de la Hunty, 1975). The term Paterson Province was applied to an area of poorly exposed rocks consisting mainly of Archaean and Proterozoic metamorphic and igneous rocks of uncertain relationship. The Paterson Province was divided into a two-fold tectonic sub-division of a western block and the remaining area. The western block consisted of mainly older rocks running in a narrow north-south belt (now known as the Gregory Granitic Complex). The remaining area is composed of 1) igneous and high-grade metamorphic rock that appears to have experienced younger metamorphism than the stable block, and 2) widespread Precambrian sediments and relatively low-grade rocks (Blockley and de la Hunty, 1975). Two formations were recognised (Blockley and de la Hunty, 1975) within the Precambrian sediments as the Googahanna Conglomerate and the overlying Bocobble Sandstone. The lower formation consists of red conglomerate grading from boulders to pebbles and the upper formation composed of pink sandstone, siltstone and shale.

A series of Geological Survey of Western Australia mapping projects (Chin et al., 1978; Chin et al., 1980; Chin et al., 1982; Chin and Hickman, 1977; Hickman and Clarke, 1994) were undertaken during the late 1970’s and early 1980’s and these projects saw a further development of the basin stratigraphy.

Williams and Myers (1990) redefined the Paterson Province to the Paterson Orogen and used this term to describe a belt of metamorphic, sedimentary and igneous rocks that have a common tectonic history. Williams and Myers (1990) recognised two separate areas in the Paterson Orogeny, a north-western area divided into the Yeneena Basin and Rudall Complex and a south-eastern area formerly referred to as the Musgrave Block. The link between these two areas was provided by the Anketell Regional Gravity Ridge (Fraser, 1976). From 1:250 000 mapping, Williams (1990) further divided the Yeneena Basin into three zones, the western, central and north-eastern. Stratigraphic names were given for each of these zones and are presented in Table 2.1.
<table>
<thead>
<tr>
<th>Western Zone</th>
<th>Central Zone</th>
<th>Northeastern Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalbarri Beds</td>
<td>Wilki Quartzite</td>
<td>Male Quartzite</td>
</tr>
<tr>
<td></td>
<td>Pantapunta Formation</td>
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<td></td>
<td>Teller formation</td>
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<td>Indell Formation</td>
<td>Indell Formation</td>
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<tr>
<td>Choornu Formation</td>
<td>Choornu Formation</td>
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<tr>
<td>Yandamunyah Formation</td>
<td>Broadbache Formation</td>
<td></td>
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<tr>
<td>Brooweering Sandstone</td>
<td>Wacegoonyah Formation</td>
<td></td>
</tr>
<tr>
<td>Googphurna Formation</td>
<td>Coolero Sandstone</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: Early stratigraphic correlations of the Yeneena Group divided the basin into three zones (Williams and Myers, 1990). The zone classification has now been superseded (Williams et al., 1996) and the Central and North-eastern zones form the Yeneena Supergroup and the Western zone the Tarcunyah Group. The Tarcunyah Group is considered to unconformably overlie the Yeneena Supergroup.

The most recent reappraisal of the Paterson Orogen has followed Geological Survey of Western Australia 1:250,000 and 1:100,000 scale regional mapping (Bagas and Smithies, 1995; Williams et al., 1996; Bagas et al, in press) and has resulted in the following major changes:

- The redefinition of the Paterson Orogen so that the Orogen now consists of the Rudall Complex, Yeneena Supergroup, and Tarcunyah Group.
- The Throsell and Lamli Groups have been combined to form the Yeneena Supergroup.
- The Western Succession (Zone) has been redefined as the Tarcunyah Group and is now considered to unconformably overlie the Throsell Group.
- The inclusion of the Tarcunyah Group as part of the Officer Basin succession.

2.1 *The Paterson Orogen*

The full definition of Paterson Orogen (William and Myers, 1990) describes the Yeneena Basin and Rudall Complex along with the Mungarve block of central Australia. However, general usage of the term Paterson Orogen has become confined to the Rudall Complex, the Yeneena Supergroup and the Tarcunyah Group (Williams and Bagas, 1996). In this thesis the general usage of the term Paterson Orogen is followed and the term Yeneena Basin will be restricted to rocks of the Yeneena Supergroup.

2.2 *The Rudall Complex*

The Rudall Complex (Figs. 2.1 and 2.2) is the oldest unit (Palaeoproterozoic) in the Paterson Orogeny sequence and consists of a sequence of metasedimentary rocks that were intruded by pre- to syn-orogenic granitoids (Hickman et al., 1994). Two distinguishable units have been recognised in the Rudall Complex, an older banded orthogneiss and paragneiss and a younger quartzite and schist (Hickman et al., 1994). The Rudall Complex has been metamorphosed to amphibolite facies and overprinted by a highly variable retrograde greenschist facies metamorphism (Bagas and Smithies, 1995).
Figure 2.1: A simplified geological map of the Archean to Neoproterozoic Paterson Orogen that includes the locations of mineralized occurrences discussed in this thesis. The Paterson Orogen is bounded to the east by Archean rocks of the Pilbara Craton and from the north through to east are late Carboniferous to early Permian marine and terrestrial sedimentary rocks of the Canning Basin. From east through to the south the Paterson Orogen is bounded by late Proterozoic siliciclastic sedimentary and evaporitic rocks of the Officer Basin, and from the south to the west are Neoproterozoic sandstone, siltstone, shale, and diamictite of the Savory Basin.
Figure 2.2: Stratigraphic column for the Paterson Orogen. This column is a compilation of Bags and Williams (1995); Smithies and Bags (1996); Williams and Bagas (1996); and Williams et al. (1996). Yeneena Supergroup is from Bags and Williams (1995). Locations of ore deposits are indicated by numbers: 1- Kespre unconformity, 2- Rainbow Cu, 3- Nifty Cu, 4- Maroochydore Cu, 5- Warrabahy Zn-Pb, 6- Teller Au-Cu.
Bagas and Smithies (1995) recognised the Rudall Complex as being composed of two, or possibly three, tectonically juxtaposed terranes (Fig. 2.1 and 2.2); the Talbot and Connaughton Terranes and a third exotic block of uncertain affinities they called the Tabletop Terrane. The Talbot Terrane is composed of two major successions with an older succession composed of metamorphosed turbidites and pelites and the younger consisting of quartzite units. Both successions appear to predate some orthogneiss (Bagas and Williams, 1995). The Connaughton Terrane consists of mafic volcanics, banded iron formation, pelite, chert, felsic gneiss, minor quartzite, and ultramafic intrusives. The Talbot and Connaughton Terranes have common deformation and metamorphic histories (Bagas and Smithies, 1995) and both areas have a foliated K-feldspar augen orthogneiss. The Tabletop Terrane is poorly exposed group of rocks found to the east of the Comet/Tabletop Fault Zone. Geophysical data and fieldwork by Geological Survey of Western Australia geologists suggest that the Tabletop Terrane may be distinct from the Rudall Complex.

2.3 Yeneena Supergroup

Unconformably overlying the Rudall Complex are rocks of the Yeneena Supergroup (Figs. 2.1-2.3): The Yeneena Supergroup is composed of the Throssell and Lanyil Groups but the relationship between these two groups is unclear (Bagas and Smithies, 1995).

2.3.1 Throssell Group

The best exposure of the Throssell Group occurs in the Sunday Creek-Broadhurst Range area which is about 70km south of the Nifty deposit. The accurate estimation the stratigraphic thickness of the Throssell Group is hindered by deformation. The basal unit of the Throssell Group is the Coolbro Sandstone (Figs. 2.2 and 2.3), a massive, commonly planar or trough cross-beded sandstone with interbedded shale and siltstone. Stratigraphic thickness estimates for the Coolbro Sandstone ranges between 1000-4000m (Hickman et al., 1994; Hickman and Clarke, 1994). A conglomerate of well-rounded quartzite, vein quartz, orthogneiss, chert and schists occurs near the base (Hickman et al., 1994). Shale units, 10-30m thick units, with abrupt upper and lower sandstone contacts, are restricted to the south-east of the Broadhurst map sheet (Hickman and Clarke, 1994). Interbedded sandstone, siltstone and shale occur as isolated thin (< 50m) units within sandstone (Hickman and Clarke, 1994). The upper contact with the overlying shale-dominated Broadhurst Formation occurs as a 100m thick gradational sandstone-shale sequence. The Coolbro Sandstone is interpreted as representing a fluvial-deltaic succession deposited in a dominantly trans-tensional basin, elongate north-west, south-east and deepening toward the north-east (Hickman et al., 1994).

Conformably overlying the Coolbro Sandstone is the 1000m - 2000m thick Broadhurst Formation (Figs. 2.1-2.3), host of the Nifty Cu deposit. The Broadhurst Formation is a succession of carbonateous shale, turbiditic sandstone and shale beds, minor sandstone, dolomite, and limestone units (Hickman et al., 1994). The dominant rock type observed in the Broadhurst Formation occurs as very fine-grained, carbonateous, pyrite- and pyrrhotite-bearing shale (Hickman and Clarke, 1994).
Figure 2.3: Generalised stratigraphic column of the Throssell Group, Yeneena Supergroup, Paterson Orogen (after Hickman and Clarke, 1994).
Minor sandstone units are intercalated with shale in the lower parts of the Broadhurst Formation and carbonate rocks, usually dolomitic, are found in the central and upper parts. Sandstone units are 10-50m thick while the carbonates are commonly 100m thick. The Broadhurst Formation is interpreted to represent rapid basin subsidence and pelagic deposition (Hickman and Clarke, 1994). Norris (1987) summarized the environment of deposition of the Nifty Carbonate Member as a low-energy, low gradient shelf/subtidal conditions.

Unconformably overlain by, or in sequence contact with, the Broadhurst Formation is the Isdell Formation (Figs. 2.1-2.3). This Isdell Formation consists of approximately 1000m of carbonate rocks intercalated with relatively thin units of calcareous siltstone and shale. This formation is the most widespread of the Yeneena Supergroup and also occurs as the basal unit of the Lamill Group.

In the southern area of the 1:100,000 Connaughton map sheet the Talwiwanya Formation (Fig. 2.1) unconformably overlies the Rudall Complex. The Talwiwanya Formation comprises 70-150m of arkitic sandstone with rare heavy mineral bands. This sandstone is interbedded with rare thin beds of feldspar-rich wacke (Bagas and Smithies, 1995). A transitional contact occurs with the overlying, 900m thick, Punngkull Formation (Fig. 2.1 and 2.2) that consists of interbedded shale, carbonaceous shale, carbonate, and thin units of sulphide-bearing shale and sandstone (Bagas and Smithies, 1995). As shown in Figure 2.2 the Talwiwanya and Punngkull Formations may be correlatives respectively of the Coolbro Sandstone and Broadhurst Formation (Bagas and Smithies, 1995).

The age of the Throssell Group has not been determined, however the maximum depositional age is constrained as post-Rudall D3 and pre-Rudall D4. A maximum depositional age of 1132±21 (Smithies and Bagas, 1995) is provided by a Rb-Sr isochron from pegmatite veins that intrude the Rudall Complex. These veins cut Rudall D3 fabrics constraining the maximum depositional age of the Throssell Group to ~1132Ma. A minimum age is defined by a SHRIMP zircon age of 816±6Ma (Reed, 1996) on the Eva Well Intrusive. The Eva Well Intrusive is a sill-like, intermediate to mafic body that intrudes the Broadhurst Formation immediately to the north-east of the Maroochydore diapir.

2.3.2 Lamill Group

The lowest formation of the Lamill Group (Fig. 2.2) is the Isdell Formation which consists of thinly bedded dolomite and dolostone with minor sandstone, shale and conglomerate (Hickman et al., 1994). Overlying the Isdell Formation is the lenticular Malu Quartzite that consists of massive to thick-bedded quartzite, quartz sandstone with minor interbedded argillaceous siltstone and mudstone. Transitional between the Malu Quartzite and the Pustapunta Formation is the Teller Formation, a sequence of 600-700m thick sandstone, shale and dolomite. The Pustapunta Formation consists of a 2000m thick sequence of dolomite, limestone, calcarenite with minor sandstone, siltstone and shale. The uppermost unit in the Lamill Group is the massive quartzite and minor shale of the Wilki Quartzite.
2.4 The Tarcoory Group

In fault contact with, or unconformably overlying both the Rudall Complex and the Throssell Group is the Tarcoory Group (Bagas and Smithies, 1995). The Tarcoory Group was formerly known as the Western Succession of the Yeneena Group (Williams, 1990). Three sequences are recognised for the Tarcoory Group (Table 2.2 and Fig. 2.2).

<table>
<thead>
<tr>
<th>Curran Curran Rock Hole to Choorun Soak</th>
<th>Western margin of the Paterson Orogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choorun Formation</td>
<td>Noofoo Formation</td>
</tr>
<tr>
<td></td>
<td>Wongarlong Formation</td>
</tr>
<tr>
<td></td>
<td>Yandamunyah Formation</td>
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<tr>
<td></td>
<td>Browningg Sandstone</td>
</tr>
<tr>
<td></td>
<td>Waringganyah Formation</td>
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<tr>
<td></td>
<td>Googhanama Formation</td>
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<tr>
<td>Gunanya Sandstone</td>
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</tbody>
</table>

Table 2.2: Three correlated stratigraphic sequences of the Tarcoory Group.

Early definitions of the Tarcoory Group consisted of a single unit, the Choorun Formation, and described this as 2000m thick interbedded sandstone and micaceous siltstone, and quartz pebble conglomerate with minor shale (Williams et al., 1976; Chin et al., 1980). The Choorun Formation has not been identified in the central Yeneena Basin area but was described by Chin et al. (1980) as conformably overlying the Broadhurst Formation in the Western Zone (now Tarcoory Group). Recent mapping of the regional extent of the Choorun Formation (Williams et al., 1996) has resulted in redefinition of the formation and its distribution (Table 2.2). The Choorun Formation is now restricted to exposures in the Curran Curran Rock Hole to Choorun Soak areas (approximately 25 km south-west of the Kooroora U deposit). Other regions previously considered to be Choorun Formation have been renamed (Williams et al., 1996). A correlative of the Gunanya Sandstone is the Karara Formation that unconformably overlies both the Rudall Complex and the Throssell Group. The third Tarcoory Group sequence (Williams et al., 1996) is found on the western margin of the Paterson Orogen (Table 2.2). The lithologic description of this sequence of alternating sandstone and dolomite formations (Table 2.2) is taken from Williams et al. (1996).

Noofoo Formation
- thin-beded to massive dolomite and limestone; minor thin bended, fine- to coarse-grained sandstone and siltstone.

Wongarlong Formation
- fine- to coarse-grained sandstone and orthoquartzite; minor shale and siltstone.

Yandamunyah Formation
- laminated to thin-beded dolomite interbedded with minor stromatolitic dolomite, dolomitic siltstone, shale, and siltstone.

Browningg Sandstone
- white to grey fine- to medium-grained quartz sandstone.

Waringganyah Formation
- dolomites and stromatolitic dolomites.

Googhanama Formation
- medium- to coarse-grained sandstone and polymictic pebble to cobble conglomerate.

The Googhanama Formation rests unconformably on the Throssell Group.
The Tarcoola Group has not been subjected to greenschist metamorphism or the penetrative foliation that characterises the Throssell Group (Bagas and Smithies, 1995). Preliminary palaeontological evidence from stromatolites and stromatoporoids suggest an age younger than the Throssell Group (Grey, written communications). The relationship between the Tarcoola Group and the Yeneena Supergroup is unclear. Bagas and Williams (1995) suggest that the Tarcoola Group is a correlative of the Supersequence 1 of the Centralian Supergroup. The Tarcoola Group is unconformably overlain by younger units of the Savory Group.

2.5 Phanerozoic Geology

The majority of the Paterson Province is covered with:

1) Fine- to coarse-grained sandstone, siltstone and mudstone, fluvo-glacial rocks and tills of the Permian Paterson Formation (Hickman et al., 1994), and
2) Recent deposits consisting of laterite, gravel and boulder beds, colluvium, calcrite, and alluvium (Hickman and Clarke, 1994).

2.6 Intrusive Rocks

Intrusive rocks are poorly represented in the Throssell Group and occur as 1) an isolated occurrence of outcropping basalt west of Mt Judell (Hickman et al., 1994), 2) a sill-like body, the Eva Well Intrusive (Reed, 1996), in the Maroochydore area, and 3) regionally extensive dolerite dykes (Hickman and Clarke, 1994). These three intrusive types are described below. Geophysical images of a deformed circular body in the area of the Grevillea prospect suggests the potential for an unexposed intrusive body (Carnichael, 1992).

2.6.1 Throssell Group Intrusives

Basalt has been reported 12 km west of the Mount Judell (Hickman et al., 1994). The rocks are described as containing acicular pyroxene, indicative of quenching, but a volcanic, as opposed to an intrusive origin, has not been established (Hickman et al., 1994).

2.6.3 Eva Well intrusive

Ground magnetics, gravity surveys and diamond drilling in the Maroochydore area have defined a sill-like body sub-concordant to bedding (Reed, 1996). Reed (1996) describes the texture of the basal Eva Well Intrusive as medium-grained and equigranular and consisting of up to 60% olivine in a cumulate texture with interstitial hornblende (10%), diopside (10%), and plagioclase (5%). Traces of sulphides including chalcopyrite, pyrrhotite, pyrite and pentlandite are reported (Reed, 1996). Above the basal section, the Eva Well Intrusive has an optically holocrystalline texture with an assemblage of fibrous acicular amphibole, saussuritized plagioclase, diopside, albite, chlorite, magnetite, leucoxene, and minor
quartz (Reed, 1996). The Eva Well Intrusive has been deformed and foliated. A U-Pb SHRIMP age of 816±6 Ma was derived for the Eva Well Intrusive from two analyses on zircons (Reed, 1996). This radiometric date was interpreted as the age of crystallization.

2.6.3* Dolerite
Goellnicht (1992) reported two generations of dolerites in the Tellier district, an older phase that has been affected by regional, lower greenshist facies metamorphism and a younger dolerite unaffected by regional metamorphism. A dolerite dyke has been exposed in the open-pit at Nifty and is described in the following chapter on deposit geology. Mafic dykes have been intersected in Warraburty diamond drill holes (THRD54, 189.2m, 199.3m and THRD50, 349.0m, 387.7m) (Smith, 1996). Smith (1996) described these intrusives as equigranular, mid-green, with chilled margins and noted that the intrusives cross-cut Throssell Group D3 cleavage. Smith (1996) interpreted the dykes as post-D3 and similar to dolerite dykes found at Nifty. Poor Rb-Sr isochron of 700-750 Ma have been obtained from dolerite sills that intrude the Throssell Group (Williams, 1990). However, as the dolerite is poorly exposed, the origin and age remains uncertain (Hickman et al., 1994).

2.6.4 Dukes Skarn
Dukes skarn is an exploration prospect that was identified from a geophysical anomaly. Diamond drilling of the anomaly resulting in Dukes skarn being described as an auto-metasomatized, basic, alkaline lamprophyre in a diatreme, possibly a monchiquite (WMC Resources Ltd. written comm., 1993). A preliminary Rb-Sr age reported for Dukes skarn is 737±48 Ma (Norris, 1987b).

2.6.5 Intrusive in the Lamul Group
In contrast to the Throssell Group, the Lamul Group is intruded by large volumes of granite and Goellnicht (1992) suggested that interpretations of geophysical data showed up to 20% of the area in the Tellier district is composed of granites and a further 5% dolerite. None of the granites discussed below have been observed in contact with Throssell Group sedimentary rocks. Two main granite intrusive groups (Goellnicht, 1993) are exposed in Lamul Group rocks, the Minyari and Mount Crofton Groups. Titanite SHRIMP age dating of the Minyari and Mount Crofton Suites (Dunphy and McNaughton, 1998) suggest that the granites are coeval at 654-632 Ma.

1) A late syn-tectonic Minyari Suite consists of the Minyari Granite, Minyari Gneiss and O'Callaghans Granites. The Minyari granitoids consist of variably deformed, syn-tectonic biotite monzogranite and syenogranite, with mafic microgranodiorite cognate enclaves. It has a higher proportion of biotite than the Mt Crofton granitoids and contains accessory ilmenite and hornblende (Goellnicht, 1992).

2) A late to post-tectonic Mt Crofton Suite consists of the Mt Crofton Granite, Desert's Revenge Granite, and the Wilki Granite. The three phases of the Mt Crofton Suite are described as biotite syenogranites with accessory zircon and apatite, all phases have similar mineralogy but can be distinguished by the proportion of biotite (Goellnicht, 1992).
2.7 Regional Structure

Six deformation events have been recognised in Paterson Orogen rocks (Hickman and Clarke, 1994; Hickman et al., 1994; Bagas and Smithies, 1995; Smithies and Bagas, 1997). Of these events the first two are restricted to the Rudall Complex. Table 2.3 provides a summary of the regional structural evolution.

<table>
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<tr>
<td>D2</td>
<td>Mesoscopic to macroscopic, tight to isoclinal F2 folds.</td>
<td>Large scale isoclinal folds, N-S to NWW-ESW trending, and penetrative schistosity.</td>
<td>Tight to isoclinal F2 folds and D1 thrust zones.</td>
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<tr>
<td>D3</td>
<td>Local recumbent folding.</td>
<td>Local recumbent folding affecting the Thongsel group, deformation is in response to SW-directed compression.</td>
<td>Local W- and NW- directed isoclinal recumbent folding.</td>
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<tr>
<td>D4</td>
<td>Regional deformation in response to SW-directed compression.</td>
<td>Regional deformation in response to SW-directed compression.</td>
<td>Regional deformation in response to SW-directed compression.</td>
</tr>
<tr>
<td>D5</td>
<td>Local deformation; NE-directed thrusts released after D3.</td>
<td>Local deformation; NNW-SSW directed compression.</td>
<td>Local deformation; NNW-directed extension, strain release after D4.</td>
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Table 2.3: A summary of the regional structural evolution recognised in Paterson Orogen rocks. D1 and D2 are only observed in Rudall Complex rocks and are defined as the Yapangka Orogeny (Bagas and Smithies, 1995).

Three orogenic events have been defined as having deformed and metamorphosed Paterson Orogen rocks (Bagas and Smithies, 1995). In order of oldest to youngest, these events are the Yapangka, Miles, and Paterson Orogenies. The Yapangka Orogeny includes D1 and D2 and occurred between approximately 2000 and 1760 Ma, prior to the deposition of the Yeneena Supergroup and Taecunyah Group (Bagas and Smithies, 1995). Yapangka Orogeny deformation takes the form of an early penetrative schistosity followed by tight to isoclinal folding. The Miles Orogeny consists of D3 and D4 and is a regional folding and cleavage development event that occurred in response to north-east, south-west compression between 1300 and 717Ma (Bagas and Smithies, 1995). The D3 event is considered to be a local folding and faulting event with variable orientations and styles. Paterson Orogeny (D4) occurred after 610Ma and was a brittle deformation in response to north-east, south-west compression. Similarities in the deformation style and timing have been noted for the Paterson Orogeny and the Petermann Orogeny of central Australia (Bagas and Smithies, 1995). Only minor deformation is observed in the Taecunyah Group and the penetrative cleavage of the Miles Orogeny is absent (Bagas and Smithies, 1995).
2.8 Regional Metamorphism

Two main metamorphic events have been recognised in Paterson Orogen rocks. The earlier event is associated with the Yapungku Orogeny and only affects Rudall Complex rocks while the later event is associated with the Miles Orogeny and has a widespread development.

Rudall Complex metamorphism has been defined in two major studies (Clarke, 1991; Smithies and Bagas, 1997). Clarke (1991) examined amphibolite assemblages in the north-western part of the Rudall Complex. He calculated peak metamorphic conditions as 600±100 °C and 650±50 °C, and concluded that the metamorphic evolution was a fairly steep, clockwise P-T-t decompressive path typical of crustal overthickening subsequent to continental collision. The second study defined the peak metamorphic grade as amphibolite-granulite facies (Smithies and Bagas, 1997). Peak temperature was calculated using thermobarometry on minerals in amphibolites and mafic granulites from the eastern portion of the Rudall Complex and this defined peak temperatures of ~800°C and pressures of 1200 MPa (Smithies and Bagas, 1997). Smithies and Bagas (1997) went further and interpreted a steeply decompressive clockwise P-T-t path based on a late timing for peak temperature together with the presence, in some amphibolites, of amphibole-plagioclase symplectic coronas around garnet. Smithies and Bagas (1997) also suggested that the deformation and metamorphism associated with the Yapungku event recorded the collision between the Pilbara Craton and a continent to the north-east.

Paterson Orogen rocks were subject to a second major metamorphic event during the Miles Orogeny between 1300-717 Ma. This event is recognised as a retrogressive greenschist facies metamorphism in Rudall Complex rocks and as greenschist facies in the Yeneena Supergroup rocks (Hickman and Clarke, 1994; Bagas and Smithies, 1995). Hickman and Clarke (1994) conclude that metamorphism was synchronous with D3 and did not exceed greenschist facies. Bagas and Smithies (1995) observed that the main metamorphic feature in the Connaughton map sheet area was the growth of sericite/muscovite parallel to Rudall Complex S2 schistosity. Bagas and Smithies (1995) reported Throssell Group metamorphic grade as greenschist facies. The Tarcunyah Group is unmetamorphosed (sub-greenschist facies) (Bagas and Smithies, 1995).

2.9 Regional Metallogeny

The Yeneena Supergroup is anomalously mineralised with high concentrations of base metals in the Throssell Group and a combination of gold and base-metals in the Lamill Group (Fig. 2.1). Within the Yeneena Basin, Telfer Au-Cu and Nifty Cu deposits are currently being mined, and Kintyre U and Macrochydore Cu prospects are currently (1999) in pre-feasibility. All other mineralised occurrences are considered as prospects.
2.9.1 Maroochydore Cu Deposit

The largest copper ore body is the Throssell Group is Maroochydore Cu prospect (Fig. 2.1), a disseminated copper deposit with a resource of 140 Mt @ 0.5% Cu (Reed, 1996). The Maroochydore Cu prospect is located approximately 70 km south-east of Nifty in carbonaceous and dolomitic shale of the Neoprotoreozoic Broadhurst Formation (Fig. 2.1). Primary chalcopyrite mineralisation rims and replaces framboidal pyrite, and forms preferentially in D4 pressure shadows to pre-existing sulphides and in the hinge zones of F1 folds (Reed et al., 1995), Reed (1996) interpreted a syn-deformational timing for Cu mineralisation at Maroochydore.

2.9.2 Warrabarty Pb-Zn Prospect

Warrabarty is a sub-economic, Pb-Zn carbonate-replacement prospect located in the northern region of the Paterson Orogen, approximately 55 km north-north-west of the Nifty Cu deposit (Fig. 2.1). The deposit occurs in upper Broadhurst Formation dolostones over a strike length of about 2.5 km and under 50-150 m of cover. Sphalerite and galena occurs as breccias, veins and zones of disseminated to massive sulphide (Smith, 1996). The timing of Warrabarty mineralisation was interpreted by Smith (1996) to have occurred after late diagnostic dolomitisation and bedding parallel pressure solution but before regional D5 deformation (Smith, 1996).

2.9.3 Kintyre U Deposit

The Kintyre U deposit is an unconformity-associated, vein-type mineralisation (Jackson and Andrew, 1990) that is located approximately 100 km south-east of Nifty (Fig. 2.1). The estimated resource is 36,000 tonnes of contained U3O8 with grades averaging between 1.5 and 4.0 kg/t U3O8. The Kintyre deposit is hosted in RADHALL Complex chlorite-quartz schists, chlorite-carbonate-quartz schists and variably chloritic and quartzofeldspathic quartzite (metachert) of an open plunging synclinorium (Jackson and Andrew, 1990). Within the synclinorium Coolbro Sandstone unconformably overlies rocks of the RADHALL Complex. Dominant mineralisation occurs as F1 cleavage controlled veining (Jackson and Andrew, 1990).

2.9.4 Rainbow Cu Prospect

The Rainbow copper prospect is located approximately 25 km north-west of the Nifty deposit (Fig. 2.1) and was intersected during regional drill traverses as a thin (15 cm) but extensive sheet-like body of disseminated and massive chalcopyrite (Haynes et al., 1995). The prospect occurs at the contact between quartz arenites of the Coolbro Sandstone and pyrophilite-pyrite bearing siltstones of the basal Broadhurst formation (Carmichael, 1992).

2.9.5 Citadel Cu Prospect

Citadel is a Cu prospect located 10 km north-north-east of the main mineralisation at Nifty. Anomalous, patchy Cu and lesser Zn-Pb were intersected in pyritic and carbonaceous shale during regional
exploration drilling traverses. Followed up with diamond drilling failed to identify economic concentrations of base metals (WMC Resources Ltd., written comms., 1991).

2.9.6 Goosewacker Pb-Cu-Au Vein Prospect

Goosewacker is a sub-economic Pb-Cu-Au vein prospect that outcrops as a small group of low isolated hills geographically midway between the Maroochydore copper prospect and Nifty copper deposit (Fig. 2.1). The Goosewacker prospect mineralisation occurs as disseminations and veins in shale that is interpreted to be part of the Broadhurst Formation (Froud, 1997).

Froud (1997) recognised five vein stages of which stage 4, and to a lesser extent stage 3, are the most important with respect to mineralisation. Stage 3 veins consist of sulphide-quartz ± carbonate veins and stage 4 veins sulphide - carbonate ± quartz veins. Hydrothermal sericitic alteration is restricted to stage 4 veins. Froud (1997) concluded that the Goosewacker prospect formed as a result of pre- (to syn-) deformation intrusive activity, although there was no direct evidence of magmatic fluids or elevated temperatures. Froud (1997) suggested that the magmatic fluids were modified by passage through sedimentary rocks.

2.9.7 Grevillesa Massive Pyrite Prospect

Grevillesa is a massive pyrite prospect located about 10km north of Rainbow and 30 kilometers north north-west of Nifty (Fig. 2.1). On the basis of geophysical data, Grevillesa is interpreted to be hosted in the lower to middle Broadhurst Formation. The pyrite body is hosted at the contact between weakly carbonaceous siltstone with pyrobitite and massive crystalline carbonate (Carmichael, 1992). Two phases of pyrite are observed in thin-section. Early colloform and framboidal pyrite phases have been overgrown by massive/aggregated pyrite and discrete euhedral pyrite grains up to 2mm. Minor sphalerite and galena inclusions, less than 20 microns across, are seen in both pyrite phases (WMC Resources Ltd., written comms., 1988).

2.9.7 Lamill Group and the Telfer Au-Cu Deposit

The largest deposit in the Lamill Group is the Telfer Au-Cu deposit (Fig. 2.1). The Telfer gold mine is one of Australia’s largest gold deposits and has produced in excess of 400,000 Moz of gold since the start of production in 1977 (Rowins et al., 1997). Detailed descriptions of the Telfer deposit, surrounding Lamill Group mineralised prospects and interpretations of the genesis of this mineralisation have been presented by Goellnicht (1987, 1989, 1992), McNaughton & Goellnicht (1990), Goellnicht et al. (1991), Rowins (1994), and Rowins et al. (1997, 1998).
Chapter Three - Deposit Geology

3.0 Introduction

This chapter outlines the deposit stratigraphy at the Nifty Cu deposit and places that stratigraphy into a regional framework. The Nifty Cu deposit consists of a primary sulphide and secondary oxide ore bodies that are hosted by folded and altered carbonaceous shale and dolomitic mudstone of the Broadhurst Formation. The secondary oxide ore body is restricted to the northern limb of a syncline and consists of a zoned sequence of malachite, azurite ± cuprite ± native copper ± chalcolite. The primary ore body is located in the syncline keel and the main economic mineral is chalcocite with lesser, sub-economic sphalerite and galena. Deposit stratigraphy was established from diamond drilling and local outcrop mapping during exploration by WMC Resources Ltd. and was broadly divided into footwall beds, Nifty carbonate member and hangingwall beds (Norris, 1987a; Norris, 1987b). The Nifty carbonate member is further sub-divided into the footwall interbedded zone, lower massive carbonate, intermediate shale, upper massive carbonate, hangingwall interbedded zone, upper shale, and the pyrite marker bed (Fig. 3.1). The term “principal carbonate bed” is no longer used by Nifty mine geologists and the pyrite marker bed is included as part of the Nifty carbonate member. No formal stratigraphic names have been defined for the stratigraphy therefore unit names are in lower case.

This chapter first outlines the stratigraphy as established by WMC Resources Ltd. personnel and then discusses that stratigraphy in light of new data from additional diamond drill holes, exposures in the open pit and the distribution of alteration textures from detailed logging of open pit and diamond drill holes. A comparison of the WMC Resources Ltd. stratigraphy to that of observed away from the main Nifty mineralisation is conducted before presenting a reinterpretation of the stratigraphic succession at Nifty.

3.1 Footwall beds

Footwall beds are seen in diamond drill core, local outcrop (Fig. 3.2, in map pocket) and in the open pit (Fig. 3.3A-3B). Obtaining a complete stratigraphic sequence through the footwall beds is complicated by: 1) limited drilling that has penetrated the footwall, 2) the majority of interval between the outcropping footwall beds and Nifty carbonate member is covered by undrilled other Recent deposits, and 3) faulting in the open pit that has obscured marker horizons making identification of footwall and hangingwall beds difficult.

3.1.1 Footwall beds in Diamond Drill Holes

The majority of diamond drilling has intersected only short intervals of the footwall beds. The most complete footwall sequences were drilled in diamond drill holes TND780, TND2, TND3, TND4 and TND6 (Fig. 3.2). The deepest diamond drill hole at Nifty is TND780, which was drilled on cross-section 102240mE to a depth of 814m. In TND780 the footwall sequence is a grey to bluish-black,
Figure 3.1: Mine sequence stratigraphy as established by WMC Resources exploration geologists. The Nifty deposit is hosted in the Nifty carbonate member which consists of the principal carbonate bed and overlying pyrite marker bed. The principal carbonate bed is divided into, from oldest to youngest unit, the footwall interbedded zone, lower massive carbonate, intermediate shale, upper carbonate, hangingwall interbedded zone, and upper shale.
Figure 3.3A-D: A. Location map showing the extent of outcropping footwall beds to the north and south of the open pit. These outcrops act as a series of low, roughly strike ridges. B. Outcropping footwall bed from the northern series of outcrops (GJ001mL; 51150mN). Note hammer for scale. C. Very fine-grained, graded dolomitic silt-mud beds with concentrations of carbonaceous material along laminae contacts (THRD780, 455.0m). D. Uneven-grained, micaceous sandstone beds are common in the lower footwall beds (TN36, 452.5m). Abbreviations: qp-quartz, bi-biotite, cc-carbonaceous matter.
thinly laminated, carbonaceous, frambooidal pyritic shale with micaceous and chloritic siltstone and minor light grey dolomitic mudstone (Fig. 3.3C). The main variable in the footwall beds is the concentration of pyrite, which reaches a maximum close to the contact with the Nifty member. Pyrite occurs as medium-grained clots and blebs, and as bedding parallel trains of disseminated frambooids. Silicified pyritic shale similar to that observed in the pyrite marker bed occurs at the uppermost footwall beds. Minor traces of chalcopyrite occur in cross-cutting veins at depth.

TND3 is a vertical diamond drill hole collared close to the inferred outcrop of the pyritic marker bed on the southern limb (50270mN, 101720mE) and drilled to a depth of 201.4m. Diamond drill core from this hole has weathered in the trays making relogging impossible, however diamond drill logs prepared by M. Norris in 1985 suggest that variably oxidised carbonaceous shale occurs between the surface and ~128m. At 128m a two-metre thick gossanous bed marks a change to interbedded pyritic shale and dolomitic mudstone. Below the gossanous bed are minor siliceous and hydrothermal dolomite intervals with an increase in pyrite and minor trace of chalcopyrite. Only one diamond drill hole, TND3, has been drilled into rocks on the northern limb of the deposit and this vertical diamond drill hole was collared 150m north of the northern wall of the open pit (Fig. 3.2). The lithology in TND3 is dominated by banded sequences of black, carbonaceous shale with abundant 2.5cm thick beds of evaporite pseudomorphed by quartz and dolomite (after gypsum).

3.1.2 Outcropping Footwall Beds

Steeply dipping footwall beds outcrop to the north and south of the Nifty open pit (Fig. 3.3A). The relationship between these outcrops and the Nifty deposit is unclear because the interval between is covered by sand dunes and other Recent deposits. The northern limb outcrops about 1 kilometre north of the open pit and consists of low, linear, rubble strike ridges trending approximately north-west south-east and with an extent of about two kilometres (Fig. 3.3A). Surface weathering has resulted in a dark orange-brown colour on the outcrop surface and a light grey colour when fresh (Fig. 3.3B).

The northern limb typically consists of fine- to medium-grained micaceous sandstone interbedded with laminated shale with numerous cubic halite hopper (approximately 2mm). Laminated shale occur as 3-20mm thick beds with the finer-grained material weathered out leaving a rusty, bedding parallel set of outcrops. In the western-most outcrops the strike of cleavage and bedding are coincident (north-east) with the bedding dipping steeply north and cleavage approximately 70° south.

Southern limb beds form an isolated group of low linear outcrops located about 1.5 kilometre south of the main open pit and 1 kilometre from the outcropping of the pyrite marker bed (Fig. 3.3A). Minor weathered outcrop and patches of scree and float occur between the southern limb beds and the pyrite marker bed outcrop. The southern beds consist of medium- to coarse-grained micaceous sandstone with minor siltstone, shale and gossanous beds. Bedding strikes approximately east-west and dips at ~60°.
north. In the region of 101300mE, 49335mN a prominent and linear outcrop of medium sandstone overlies a one metre thick gossanous bed.

3.1.3 Footwall Beds in the Open Pit
In the open pit footwall beds are seen on the northern wall above the main access road to the pit floor. These beds occur as laminated, light grey, shale with thin (<1cm thick) limonitic and goethitic beds. Footwall beds are also observed in the eastern end of the open pit where faulting has displaced the Nifty carbonate member.

In the eastern end of the open pit faulting has obscured marker horizons. The dominant lithology in this area is a finely laminated, grey shale with purple and red-orange laminae of hematite and goethite. At depth below this area the stratigraphy seen in diamond drill holes conforms to the generalised stratigraphy suggesting that footwall beds have been thrust to the south.

3.1.4 Footwall description by WMC
Norris (1987) mapped four footwall units in outcrop that he designated A, B (B1, B2, B3, B4), C and D and he suggested that these units were conformable through >900m of stratigraphy. The following descriptions are from Norris (1987a). Unit A consists of a 55m succession of brown-grey, medium-grained, quartz arenite with thin-medium planar bedding and locally developed low-angle cross-stratification. This unit also has a prominent, 2m thick brown-black, massive, silicious, gossanous bed. Unit B has be subdivided into 4 sub-units (B1-B4). Norris records the presence of Unit B on both limbs of the syncline but does not sub-divide the northern limb. Unit B1 consists of a 60m thick interval of poorly outcropping, interbedded red-brown hematitic siltstone and brown-grey quartz sandstone with minor quartz sandstone and calcareous shale. Unit B2 consists of a 50m thick interval of interbedded silty shale and bedded calcrite. In the middle of this sub-unit occurs a prominent 2-3m thick, massive, planar, medium-grained, quartz sandstone bed. Unit B3 typically consists of siltstone and sandstone and Unit B4 of siltstone to fine-grained sandstone exhibiting wavy cross-stratification. Unit C consists of a 250m thick interval of fine-grained quartz sandstone, siltstone and minor shale. Norris (1987a) noted only one outcrop of Unit C on the northern limb. Unit D consists of a 300m thick interval of interbedded shale, siltstone, minor sandstone and minor crystalline laminated limestone.

Norris (1987a) interpreted that footwall outcrops to the north and south of Nifty (Fig. 3.3A) belonged to his B unit. The relationships between the footwall beds exposed in the northern and southern outcrops and that exposed in the open pit and diamond drill holes may not be part of the same or a continuous stratigraphic succession as Norris (1987a) suggested. The true thickness of unexposed footwall between the outcropping pyrite marker bed and the southern footwall beds is approximately 540m and to the north the true thickness is approximately 860m between the pyrite marker bed in the open pit and outcropping northern footwall beds. The longest diamond drill hole (THRD780) was drilled to 814m, which was approximately 454m below the pyrite marker bed. The intervening stratigraphy between the outcropping
footwall beds and the exposed Nifty member is covered and therefore only represented by THRD780. The magnetic/TEM signatures of the northern and southern limbs of the syncline indicate that the footwall rocks on the limbs may be different. Carmichael (1992) noted a geophysical boundary in the region of the northern limb of the Nifty syncline and suggested that an "imbricate ramp through Broadhurst Formation in the Nifty area occurred where a discrete shear zone runs along the northern upright to overturned south verging limb of the Nifty syncline". The southern beds consist of medium- to coarse-grained micaceous sandstone with minor siltstone, shale and gneissic beds whereas the northern limb is dominated by fine- to medium-grained micaceous sandstone with considerably higher proportions of interbedded laminated shale. TND3 is a vertical diamond drill hole collared approximately 150m north of the north wall of the open pit and this hole provides important clues to the nature of the northern limb and its relationship to the open-pit and outcrops to the south. The evidence can be summarised as 1) the stratigraphic succession of evaporite beds observed in TND3 is not observed elsewhere in outcrop or diamond drill holes, and 2) on the northern wall bedding dips at high angles or is overturned and in TND3 bedding is right angles, or at high angles to the core axis. The high angle bedding to core axis is in contrast to the steep to overturned bedding 150m to the south. The evidence above suggests that the outcropping footwall beds are not part of a continuous stratigraphic succession as described by Norris (1987a). It is likely that the northern outcrops have been faulted into their current position. No information is available on the stratigraphic level within the Broadhurst Formation that the northern limb rocks belong to.

3.2 The Deposit Succession

The section describes the interval between the footwall beds and the top of upper shale (Fig. 3.4). The stratigraphy constructed by WMC Resources Ltd. geologists (Norris, 1985, 1987a, 1987b; Carmichael, 1990, 1992, 1993; Dare, 1994) is first presented followed by a discussion on that stratigraphy and a reinterpretation based on this study.

3.2.2 Current Deposit Stratigraphy

Mineralisation at Nifty is confined to a single unit named the Nifty carbonate member by WMC Resources Ltd. geologists. The Nifty carbonate member is divided into two stratigraphic units, the principal carbonate bed and overlying pyrite marker bed (Norris, 1985). The principal carbonate bed is sub-divided into the footwall interbedded zone, lower massive carbonate, intermediate shale, upper massive carbonate, hangingwall interbedded zone, and upper shale (Carmichael, 1990, 1992, 1993; Haynes et al., 1993; Dare, 1994).

footwall interbedded zone

A gradational lower contact occurs between the footwall beds and the overlying footwall interbedded zone. Pyritic and chloritic shale of the footwall beds grade into 14-32 metres (Figs. 3.1 and 3.4) of interbedded bluish-black chloritic shale with interbedded silicified carbonates (Carmichael, 1990). Interbeds are approximately 1m thick but as the upper contact with the lower massive carbonate is
Figure 3.4: Photo-collage of the western wall of the Nifty open pit (1997) showing the full deposit mine sequence looking west with the younging direction to the south. 280RL and 260RL (left of photograph) refers to the reduced level of the open pit benches. Ground surface is at ~300RL. Above the photograph are the stratigraphic successions defined by WMC Resources Ltd, exploration geologists and a redefined version developed as part of this study. The stratigraphic succession has been redefined on the basis of new open pit exposures, relogging of unaltered diamond drill cores, and mapping of alteration textures in the open pit and diamond drill core.
approached there is a steady and gradational increase in the thickness of silicified dolomitic shale and silicified cryptalgal carbonates beds. Darce (1994) noted that, within the open pit, the footwall interbedded zone occurs as interbedded sequence of yellow-brown, siliceous, ferruginous carbonate/chert with purple and yellow/brown shale.

lower massive carbonate
The lower massive carbonate (Figs. 3.1 and 3.4) is a 6-37m thick unit of pale grey, fine grained, massive silicified algal carbonate, and chert (Darce, 1994). Within the open pit this unit is a massive siliceous vuggy, ferruginous carbonate/chert and contains gossanous boxworks after sulphide (Darce, 1994).

intermediate shale
The intermediate shale (Figs. 3.1 and 3.4) is a 1-4m thick unit of chloritic and carbonaceous shale. Within the open pit the intermediate shale consists of yellow-brown to weakly purple-stained, clayey shale (Darce, 1994).

upper massive carbonate
The upper massive carbonate (Fig. 3.4) is a 10-43m thick unit of pale grey, fine-grained silicified dolomitic shale, with minor carbonaceous shale interbeds (Carmichael, 1990; 1993; Darce, 1994). The lithology of the upper massive carbonate is similar to the lower massive carbonate but with a higher concentration of unsilicified, or partially silicified shale bands. Within the open pit this unit is an interbedded sequence of siliceous carbonates/chert and sheared siltsone dominated by vuggy siliceous carbonates with a similar appearance to lithologies in the hangingwall interbedded zone (Darce, 1994).

Carmichael (1990) combined the upper massive carbonate, lower shale band and lower massive carbonate into a single unit he called the massive silicified algal carbonates. Carmichael (1990) described the lithologies as consisting of a relatively monotonous sequence of very fine to fine-grained, pale grey, light pink, light green, planar and irregularly laminated, intensely silicified and strongly stylitised rocks that contain relict algal, evaporitic, and colitic textures.

hangingwall interbedded zone
The hangingwall interbedded zone (Figs. 3.1 and 3.4) consists of 15-20m of interbedded, irregularly laminated, silicified algal carbonate and chert. Within the open pit this zone consists of an interbedded sequence of purple to grey translucent, thickly laminated vuggy (1-20mm) siliceous carbonate/chert and pallid thinly laminated clayey shales (Darce, 1994). A gradational sequence of interbedded and irregularly laminated (cryptalgal) silicified carbonates and carbonaceous shale (as in the shale band) with the silicified carbonate content increasing toward the base of the unit (Carmichael, 1990).

upper shale
The upper shale (Figs. 3.1 and 3.4) consists of a 50-40m thick interval of dark grey carbonaceous shale, thin framboidal pyrite seams, minor silicified algal carbonate, and evaporites (Darce, 1994). Within the
open pit it is a very thinly laminated pallid green-grey to yellow-brown, limonitic, clayey siltstone. The upper shale band contains black goethitic stringers and oval shaped limonitic and hematitic spots after pyrite (Dare, 1994). Carmichael (1990) described the upper shale as a 20-26 m thick unit consisting of dark grey, fine-grained, partly micaceous and siliceous, strongly carbonaceous shale and occasional 1-2 mm thick frambooidal pyrite seams.

3.2.3 Comments on the Existing Stratigraphy

New exposures in the open pit, additional diamond drilling and detailed logging of alteration have suggested the need for a review of the existing stratigraphy. This review will first examine the history of the conceptual model responsible for the discovery of Nifty and the impact that this model has had on the development of the deposit stratigraphy. This will be followed by a discussion of the crystalgical laminate texture defined by Norris (1987a,b) and others (Carmichael, 1990; Haynes, 1993). The final part of this section compares the stratigraphy in distal diamond drill holes to that of the generalised stratigraphic column currently used.

Historical Development of the Current Stratigraphy

Initial exploration in the Paterson Orogen applied a conceptual model for stratiform copper deposits developed by WMC Resources Ltd. geologist Douglas Haynes (internal WMC Ltd company reports by Haynes, 1979, 1990; Haynes et al., 1993). The model and the subsequent discovery of Nifty by applying that model have had an important influence on the development of a stratigraphy at Nifty. Haynes et al. (1993) suggested that the source rocks were likely to be red coarse-grained basal clastic sediments deposited during the rift phase of basin development and in the Paterson Orogen the Coolbro Sandstone would be the source of copper in sediment-hosted stratiform copper deposits. The ore body was likely to be sheet-like, stratiform and stratabound with ore boundaries gently transgressing lithological layering (Haynes, 1979). Anticipated ore fabrics were described (Haynes, 1979, 1990) as sulphides disseminated as fine grains in the sediment matrix and along bedding planes, as lenticular aggregates along bedding planes, and as discordant and concordant veinslets within host sediment containing disseminated sulphides. Haynes (1990) defined as a search priority crystalgical laminated sediments within 300m of the basin margin and in basal sediment pinchouts and pinch downs.

The model defined by Haynes (internal WMC Ltd company reports, 1979, 1990; Haynes et al., 1993) envisaged a diagenetic infiltration of ore brines into reduced sediments above a red-bed clastic copper source. The key term in the previous sentence is diagenetic. The model driven exploration programme suggested an early timing of mineralisation and the presence of crystalgical laminated carbonates and this encouraged WMC Resources Ltd. geologists to use mineralisation as criteria for defining stratigraphic horizons and groupings as shown in WMC Resources Ltd drill logs.

Crystalgical Laminated Carbonates

Previous workers (Norris, 1987, p58A; Carmichael, 1990; Haynes, 1993, Dare, 1994) have used the term crystalgical laminated carbonates to describe "very finely wavy-laminated, grey-brown, dolomitic,
sideritic, phosphatic and locally silicified rocks. Norris (1987a) provides a second description of cryptagal laminate facies as "relatively uniform intervals of wavy-, thirty-to-thickly laminated, grey-black, brown, carbonaceous carbonates" (Norris, 1987a, p94). Norris (1987) also noted the presence of stylolites and stylolamine developed throughout his cryptagal laminate facies and further noted that wavy parallel laminated shales locally resembled carbonaceous, micro-cryptagal laminated sedimentary rocks (Norris, 1987, p77).

The presence of cryptagal laminates has an important implication when considering the palaeoenvironment of deposition and furthermore their distribution has been used as part of the definitions for stratigraphic units at Nifty. Atkinson (1967) defined cryptagal laminate as discontinuous, more or less planar laminations believed to have resulted from the activities upon and within the sediments of successive mats or films of blue-green or green algae. Pratt (1982) described cryptagal laminates as organo-sedimentary structures that were by implication constructed by passive sediment binding and/or calcium carbonate-precipitating activities of micro-organisms, mainly blue-green algae.

Norris (1987a) examined samples of his the cryptagal laminate facies for fossil content and observed two forms of microfossil, filamentous and spheroidal forms. The filamentous microfossils occurred in what Norris (1987a) described as cryptagal laminated siderites and cherts of his Cryptagal Laminated Facies and Cryptagal laminite-Shale Facies and in clasts of cryptagal laminated limestone from the Polymeric Breccia Facies. Small filaments comprising intertwined aggregates with rare branch-ling 4 to 20 µm thick were the most common form observed and two textural varieties were recorded: 1) filaments with poorly defined outlines in microporphy siderite and 2) equivalent filaments with a thin rim of silica. Both textural varieties occur locally as clusters of disorganised tightly entwined aggregates. The second form of microfossil observed was a well preserved, black, spheroidal microfossil 16 to 34µm in diameter, typically solitary and rarely clustering in groups of two or three. Norris (1987a) tentatively identified this form to be Cyanophyta. Norris (1987a) concluded that the presence of these fossils indicated that that carbonates at Nifty formed from calcium carbonate-precipitating activities of micro-organisms, mainly blue-green algae.

The cryptagal laminated carbonate interpretation is not supported in the present study because:

1) The wavy laminated texture is formed by progressive sym-D2 quartz replacement alteration that has occurred along bedding planes (see Chapter Five) and has resulted in the replacement of the precursor lithology and concentrated carbonaceous material into thin wavy bands. In the majority of areas within the mineralised zone no calcareous or dolomitic material remains and complete replacement of the protolith has occurred.

2) Microfossils are recorded (Norris, 1987a) as occurring in only a few of the Nifty diamond drill holes (TND4, TND8, TND9, and TND26, see Fig. 5-2 for locations). While it is clear that limited forms of microfossils are present in Nifty dolomitic mudstones, the extent and distribution of the microfossils is questionable. The microfossil evidence present by Norris (1987a) has not been supported by subsequent palynological tests (Grey, 1995). Palynological investigation of samples from diamond drill hole
THRD633 at 274.4m and 518m (Orey, 1995) suggests that no identifiable palynomorphs were recovered but that the samples contained abundant particles that were unidentifiable due to the high thermal maturity of the samples. Recent diamond drilling (since Norris, 1987a) has resulted in no addition occurrences of microfossils being reported.

3)Cryptagal laminated carbonate or stromatolitic units are not reported elsewhere in the Broadhurst Formation or even the Throssel Group.

In summary, it is the interpretation of this study that the texture described by Norris (1987a) as cryptagal laminated carbonates is an alteration texture (Chapter Five) and not a biologically derived sediment.

Examination of Stratigraphy in Distal Diamond Drill Holes

It has been suggested that the cryptagal texture is the result of a progressive and zoned alteration system (described and discussed in Chapter Five), however this reinterpretation leaves open the character of the original host lithology. An examination of distal diamond drill core provides information on the pre-alteration lithologies and three diamond drill holes (TND8, TND14, and TND26, see Fig. 3.2 for locations) with complete, unaltered or slightly altered, lithological sequences were examined to establish the stratigraphic successions away from mineralisation. Figure 3.5 presents stratigraphic columns for TND8, TND14, TND26 and a generalised ore deposit column.

TND8 is one of the few diamond drill holes drilled on the southern limb of the syncline. TND8 was collared at 50100mN, 102100mE (Fig. 3.2) and drilled to the south with an inclination of 65° and to a depth of 323.4m (Fig. 3.5). Interbedded carbonaceous shale and dolomitic mudstone units dominate the lower part of TND8 from the end of hole at 322.4 to 265.5m. Between 254.2-265.5m a poorly developed zone of quartz-dolomite alteration occurs. Quartz-dolomite alteration is associated with cross-cutting quartz-dolomite veins. Above the alteration zone is a 78m thick package of interbedded pyritic shale and pyrite-rich carbonaceous shale marks the pyrite marker bed position. Above the pyrite marker bed are carbonaceous shale and dolomitic mudstones of the hangingwall beds. TND14 was drilled to 536.6m at 50200mN, 102650mE (Fig. 3.2), about 400m east of the main primary ore concentration (Fig. 3.5). Pyritic and carbonaceous shale dominates the basal portion of TND14. The lower shale sequence grades into alternating beds of silicified dolomitic mudstone and carbonaceous shale beds. A poorly developed 2.5m thick bed of shale with high concentrations of frambooidal pyrite occurs between 413-415m and this is interpreted to be the pyrite marker bed. Above the pyritic beds are shales and dolomitic mudstones of the hangingwall beds and the upper part of this unit is impinged by a 17m thick dolerite sill. The third diamond drill hole used in this comparison is TND26 (Fig. 3.5). TND26 was collared at 50100mN, 103000mE (Fig. 3.2) and drilled to 615.7m. The lowestmost interval from 615-580m consists of black, carbonaceous shale with minor interbedded dolomitic mudstone. Above 580m the sulphide concentration increases to approximately 1-3% pyrite and pyrrhotite in a shale host. The first major dolomitic shale bed occurs between 542-527m and this interval consists of interbedded shale and light-grey, fine-grained dolomitic mudstone with minor pyrite in the shale dominated beds. Above 527m a thick interval of fine-
Figure 3.5: A comparison between the stratigraphic sequence observed in mineralised and unmineralised diamond drill holes of TND8, TND14, and TND26 (see Fig. A.3 for collar locations). TND14 and TND26 are collared east of, and TND8 south of, the main Nifty mineralisation and contain only minor quartz-dolomite alteration.
grained, black to blue-black, carbonaceous shale with minor dolomitic shale beds. A thin (2.5m) pyrite marker bed occurs at approximately 492m as very finely laminated, grey beds separated by thin black laminae.

The successions described in the generalised stratigraphic column (Haynes, 1993) are not observed in distal-diamond drill holes such as TND8, TND14, and TND26. A common feature with the three distal diamond drill holes is that the stratigraphic packages are dominated by thick interbedded sequences of carbonaceous shale and dolomitic mudstone below a prominent pyritic shale bed. The stratigraphic units defined by WMC Resources Ltd. geologists were based on lithological characteristics, alteration textures and occasionally geochemical trends (WMC Resource Ltd. diamond drill hole logs). As a result the spatial continuity of some units is limited not by sedimentological or facies controls but through proximity to the silicous alteration halo that surrounds the ore body and therefore, a reinterpretation of the stratigraphic succession is proposed.

3.2.4 Reinterpreted Nifty Member Stratigraphy

The Nifty carbonate member consists of interbedded carbonaceous shale and dolomitic mudstone and therefore the term “carbonate member” is misleading therefore it is proposed that the term Nifty member replaces the term Nifty carbonate member. The term principal carbonate bed is no longer used by company geologists at the mine or in exploration and is also therefore abandoned. The mine sequence stratigraphy is simplified to consist of the footwall beds, Nifty member, pyrite marker bed, and hangingwall beds (Fig. 3.6). The Nifty member consists of the lower unit, intermediate shale, upper unit and upper shale (Figs. 3.4 and 3.6). The WMC Resources Ltd. descriptions for the footwall beds, hangingwall beds and upper shale remain unchanged (Fig 3.1). Changes to the definition of the pyrite marker bed are presented in a following section.

lower unit

The lower unit (Figs. 3.4 and 3.6) consists of 40-70m thickness of interbedded fine-grained, pale grey, dolomitic mudstone and blue-black, carbonaceous shale, variably overprinted by a quartz-dolomitic alteration associated with chalcopyrite mineralisation (Fig. 3.7A-F). Individual beds are generally ~1-2m thick and alternate between shale dominant and dolomitic mudstone dominant with the other as the minor lithology. Shale beds consist of dark-grey to blue-black, parallel planar laminated, graded, poorly sorted, quartz-mica silt and shale with abundant very fine-grained carbonaceous material disseminated throughout the bed. Dolomitic mudstone beds are light to mid-grey, parallel planar laminated, much finer grained and better sorted than the shale beds. Grain size of each lithology does not vary significantly. Within dolomitic shale intervals thin lenses of very fine-grained carbonaceous material occur and occasional beds containing fine-grained (~10µm) dolomite rhombs. Pyrite occurs predominantly in the shale beds as fine grained disseminated framboids, coarse-grained clots, and bedding parallel blebs and trains. The concentration of pyrite decreases up stratigraphy away from the footwall beds. The upper contact with the intermediate shale is sharp.
Revised Stratigraphic Column (this study)

(5-60m) upper carbonate bed, finely laminated dolomitic and calcareous silty beds.

(20-60m) hangingwall beds, carbonaceous pyritic shale.

(1.5-22m) pyrite marker bed, frambooidal pyrite in carbonaceous shale.

(20-40m) upper shale, carbonaceous pyritic shale and minor interbedded siltslime, generally unaltered. Evaporite pseudomorphs (after gypsum).

(25-60m) upper unit, interbedded carbonaceous shale and dolomitic mudstone overprinted by a zoned quartz-dolomite alteration system associated with chalcopryite mineralisation.

(1-8m) intermediate shale, pale grey, soft and soapy, chloritic shale with distinctive quartz pseudomorphs of iron or gypsum evaporite rossettes.

(40-70m) lower unit, interbedded carbonaceous shale and dolomitic mudstone overprinted by a zoned quartz-dolomite alteration system associated with chalcopryite mineralisation.

(35-40m) footwall beds, chloritic shale, some frambooidal pyrite lamellae overprinted by alteration.

Figure 3.6: New exposures in the open pit and diamond drill holes have suggested the requirement for a revision of the stratigraphy of the Nifty deposit. The stratigraphic succession shown above has been overprinted by a zoned quartz-dolomite alteration system and the alteration textures associated with this system are described in Chapter Five.
intermediate shale

Separating the lower and upper units is a prominent 1.4 metre thick bed of dark-grey to black, very fine-grained, soft andropy, chloritic shale (Figs. 3.4 and 3.6). The intermediate shale is distinctive because of 1) the presence of light grey quartz-dolomite spots that displace bedding and appear to have nucleated or, evaporite pseudomorphs, and 2) distinctive pseudomorph of evaporitic rosettes (Fig. 3.8E). Evaporite rosettes occur in a range of sizes up to approximately a maximum of approximately 2x1cm, with the long axis parallel to bedding. Rosettes appear to have nucleated on a small cubic central crystal and have up to eight "petals" fanning outward and these rosette "petals" cross-cut laminations and have been pseudomorphed by quartz-dolomite and pyrite. Rhomboedral to sub-hedral pyrite occurs within the evaporite pseudomorphs and as subhedral grains that cross-cut the pseudomorph margin. The pseudomorphs may have formed after trona or gypsum (Eugster and Hardie, 1972; Cody and Cody, 1988; Southgate et al., 1989) and the implications of deposition of these evaporites is discussed in a later section. Within the open pit the intermediate shale occurs as a prominent pale grey bed (Fig. 3.4).

upper unit

The upper unit (25-60m) has a similar composition to that of the lower unit and consists of alternating beds of laminated carbonaceous shale and dolomitic mudstone (Figs. 3.4 and 3.6). Bed thickness is approximately 1-2m and towards the top of this unit the frequency and thickness of shale beds increases. Irregularly spaced laminae, <1-10mm thick, are separated by thin (<1mm) seams of black carbonaceous material. Shale beds are generally coarser-grained than the dolomitic mudstone beds and have a higher concentration of carbonaceous matter in the former lithology. Within individual shale laminae minor grain-size grading can be observed. As discussed above, the concentration and thickness of shale beds increase toward the upper shale and the contact can be defined as the upper surface of the last major (1m) dolomitic shale bed.

In the open pit (Fig. 3.4) the upper unit consists of light grey to orange-brown, resistant beds approximately 2m thick with each bed consisting of laminations of fine-grained, blue-grey shale with blebs and lenses of red and orange iron oxides and pale-grey, dolomitic shale laminae. The dolomitic shale is typically finer-grained than the shale lamina.

upper shale

The upper shale (20-40m) consists of dark-grey to black, laminated, carbonaceous shale with thin to massive framboidal pyrite seams and blebs, disseminated very fine-grained framboidal pyrite, minor dolomitic mudstone, and evaporite beds. One to five metres below the contact with overlying the pyrite marker bed is the first appearance of fine evaporite blades (after gypsum) pseudomorphed by quartz, dolomite and rarely chalcopyrite (Fig. 3.8A, C-D). Quartz pseudomorphs of evaporitic minerals occur as fine ~2mm (and rarely to 2cm) long prismatic blades with offset terminations (Fig. 3.8C-D) with angles consistent with that of gypsum (Cody and Cody, 1988). The upper contact with the overlying pyrite marker bed is gradational over approximately two metres. In this transitional zone the concentration of
Figure 3.7A-E: A. Outcropping Nifty member (101500mE, 50250mN) occurs as a series of low rubble, scrub-covered mounds on the southern limb of the Nifty syncline. Northern limb outcrops of the Nifty member have been removed during open pit excavation. B. Graded beds in a quartz-rich shale from the upper shale (THIRD65, 315.1m), note the high concentration of carbonaceous material and prominent S cleavage. C. Plane-polarised photomicrographs showing fine-grained, poorly sorted silt-mudstone with abundant carbonaceous material (TN98, 289.6m). D. Photomicrograph in cross-polars of interbedded carbonaceous shale and dolomitic mudstone laminae (TN98, 240.5m). E. As in (D), dolomitic mudstone beds in carbonaceous shale (THRS780, 305.1m). Note the flame structures in the carbonaceous shale of the central lamina and the thin planar veins.
pyrite increases gradually over several metres until the last 5-10cm where a rapid increase in pyrite is observed. In the open pit the upper shale occurs as laminated, light grey shale and siltstone beds between 20-50mm thick with occasional beds up to 5cm thick. The concentration of geothitic and limnic beds increases up stratigraphy towards the contact with the overlying pyrite marker bed.

3.3 Pyrite Marker Bed (PMB)

3.3.1 Pyrite Marker Bed in Diamond Drill Holes

The lower contact of the pyrite marker bed is defined as the first major bed (~5cm thick) consisting of high concentrations (>15%) of frambooidal pyrite (Figs. 3.9A-D and 3.10). The frambooidal pyrite is hosted in finely laminated, blue-black carbonaceous shale (Fig. 3.9C-D). Initially, shale is the dominant lithotype and pyrite occurs within the shale as thin beds of frambooids, isolated clots and concentrations, and disseminated frambooids. Higher in the unit the concentration of frambooidal pyrite beds increases and the clots and concentrations decrease. The upper contact of the pyrite marker bed is gradational over several centimetres with a rapid decrease in frambooidal pyrite. Coarser grained euhedral pyrite + chalcopyrite + galena + sphalerite and a silicicaceous alteration overprints the shale and sedimentary pyrite and as the concentration of this late, syn-mineralisation, pyrite and silicicaceous alteration increases the interval takes on a green tinge.

![Diagram of pyrite marker bed in Diamond Drill Holes](image)

Figure 3.10: Detail of the pyrite marker bed as observed in TND13 (50300mN, 102250, Fig. 3.2). %Py is a visual estimate of the concentration of pyrite.

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Figure 3.8A-E: A. Gypsum evaporites pseudomorphed by quartz and dolomite are common in the upper shale immediately below the contact with the pyrite marker bed. B. Beds of evaporite pseudomorphs occur in TND3 located 150m north of the open pit. High concentrations of evaporite beds are not observed elsewhere in the deposit. C and D. A closeup of the evaporite blade highlighted in (A) showing pseudomorph crystal terminations. E. The intermediate shale is characterized by the presence of evaporite rosettes pseudomorphed by quartz and dolomite. The original mineralogy of these evaporite rosettes is interpreted to be either gypsum or trona.
Figure 2.9A-D: A. Outcropping gossanous pyrite marker bed at 109620mE, 50510mN (refer to Fig. 2.3). B. The pyrite marker bed as exposed in the open pit (1996). This photograph shows the pyrite marker bed as a brown-orange gossanic unit on the left (southern) side of the pit wall. This view looks west and the younging direction and hangingwall beds are to the left. Note the sharp lower contact of the pyrite marker bed and underlying upper shale and the gradational top contact with the overlying hangingwall beds. C. The hand specimen from the pyrite marker bed showing laminated beds of fine-grained framboidal pyrite in a carbonaceous shale matrix (THIR635, 451.2m). D. Reflected light photomicrograph showing pyrite framboids (THIR645, 265.7m).
3.3.2 Outcropping pyrite marker bed

The pyrite marker bed outcrops on the southern limb of the Nifty syncline (to the south of the open pit, Fig. 3.2) as a series of gossanous beds (Fig. 3.9A). Figure 3.9A shows outcropping siliceous and geothitic pyrite marker bed (100820mE, 50510mN) from the southern limb of the Nifty syncline.

3.3.3 Pyrite marker bed in the open pit

In the open pit, the pyrite marker bed occurs as a prominent, steeply dipping, 1-10m thick unit of laminated purple-black hematitic and yellow brown limonitic shale (Fig. 3.9B) with laminae ranging in thickness between 1mm and 10mm. Figure 3.9B shows the pyrite marker bed as a brown-orange geothitic unit on the left (southern) side of the western wall of the open pit. The lower contact with the upper shale is sharp and the upper contact with overlying hangingwall beds is gradational over approximately two metres. The pyrite marker bed is not seen in the eastern end of the Nifty open pit however it is recorded in the diamond drill holes at depth below that area.

3.3.4 Pyrite marker bed description by WMC

Norris (1987) defined the pyrite marker bed as a 2-20m thick unit consisting of four lithologies, (i) pyritic crystalgal laminated limestone, (ii) pyritic carbonaceous shale, (iii) calcareous mudstone, and (iv) massive pyrite beds. Norris (1987) also noted that the pyrite marker bed was host to stratiform Pb and Zn mineralisation. Carmichael (1990) described the pyrite marker bed as an interbedded pyrite marker consisting of fine framoidal pyrite with coarse concretions and fine euhedral interbedded with black carbonaceous shale as above. These bands are interbedded with silicified carbonate beds that show algal laminae and contain weakly disseminated coarse-grained chalcopyrite. Bands of coarse-grained euhedral pseudomorphs occur. Dolomite and quartz veins are common and contain minor coarse-grained sphalerite and galena plus medium green chlorite aggregates (WMC Resources Ltd. diamond drill hole log, THR6438A). In a more recent company memorandum Carmichael (1993) defined the upper boundary of the pyrite marker bed in the open pit as the first 5-10cm wide massive ironstone/limonitic band beneath the hangingwall shale.

As discussed in earlier sections, the initial exploration model (Haynes, 1979, 1990; Haynes et al., 1993) suggested the presence of beds containing disseminated diagenetic galena and sphalerite coeval to stratigraphy. In common usage by WMC Resources Ltd is that the occurrence of Pb and Zn mineralisation defines the pyrite marker bed and in some situations the upper and lower contacts of the pyrite marker bed are defined on the concentration of Pb and Zn in drill hole assays (WMC Resources Ltd. diamond drill logs). Figure 3.10 shows detail of the pyrite marker bed in TND13 and Pb and Zn assay data from this drill hole shows high concentrations at 292m and 303-307m suggesting that Pb and Zn mineralisation is discordant to the pyrite marker bed. Chapters Five and Seven suggest a later timing of Pb and Zn mineralisation and Chapter Eight shows that the distribution of Pb and Zn is discordant to stratigraphy and limited in extent and concentration.
3.3.5 Summary of pyrite marker bed

New work adds to, and refines, the existing descriptions of the pyrite marker bed rather than discarding them. An important difference is the relationships between Pb and Zn mineralisation and frambooidal pyrite. Pb and Zn mineralisation occurred after the formation of frambooidal pyrite and during bedding parallel alteration associated with quartz + chalcopyrite + euhedral pyrite. Pb and Zn mineralisation also occurs in the lowermost hangingwall beds and uppermost footwall beds. Therefore unlike previous WMC Resources Ltd. descriptions of the pyrite marker bed the refined definition does not rely on the presence of Pb-Zn.

3.4 Hangingwall beds

The hangingwall beds consist of units confined between the outcropping pyrite marker bed on the southern limb of the Nifty syncline and pyrite marker bed exposed in open pit mining (Fig. 3.2). The most complete stratigraphic section of hangingwall beds occurs in TND26 where approximately 475m are observed.

3.4.1 Hangingwall beds in diamond drill holes

The contact between the pyrite marker bed and hangingwall beds is gradational over approximately 0.5m with a decrease in frambooidal pyrite within the hangingwall beds away from the contact. The hangingwall beds are dominated by thinly laminated, dark grey to black pyritic, carbonaceous silt and silty shales. Rare interbeds of light grey laminated dolomitic shale and micaceous silt shale are distributed throughout the hangingwall beds. Pyrite occurs as cleats and some beds of frambooids. Gradational contacts are observed between laminae. A prominent, 20-40m, finely laminated, calcareous dolomite interval occurs above the pyrite marker bed and this interval has been informally named the upper carbonate bed.

3.4.2 Outcropping hangingwall beds

Surface outcrops of the hangingwall beds consist of small, isolated occurrences of rock and scree located near the outcropping southern limb of the Nifty syncline. The limited extent and advance state of weathering of these hangingwall beds prevents meaningful information being gained from these outcrops.

3.4.3 Hangingwall beds in the open pit

Exposures of the contact between the hangingwall beds and underlying pyrite marker bed in the open pit (Fig 3.11) show as two prominent bands of light grey Fe-Mg rich, Ca-poor carbonate (EI-Mg Fe-Carbonate, see Chapter Five) several metres above the pyrite marker bed. The lower carbonate band is 0.3m wide and is composed of an alteration texture defined in Chapter Five as EI. The second band, also consists of EI, occurs one metre lower, and is characterised by an increase of fracture veins at a high angle to bedding (described in Chapter Six). Above the EI bands hangingwall beds consist of fine-
Very fine-grained, laminated, carbonaceous shale of the hanging wall beds.

0.25m thick bed of cryptocrystalline, brown-grey Mg-Fe rich carbonate with numerous high angle fracture veins.

0.30m thick interval of laminated, carbonaceous shale

0.30m thick bed of cryptocrystalline, pre-mineralisation alteration texture S1 with numerous high angle fracture veins (Vein stage IC)

A gradualon contact with the underlying pyrite marker bed starts slightly above the 6 metre mark. Between the 6 and 5 metre marks the concentration of pyrite increases rapidly.

Figure 3.11: Photograph of the contact between the pyrite marker bed and the overlying hanging wall beds. The photograph was taken at the bottom of the open pit looking east in 1997. The younging direction and hanging wall beds are to the left (south) and bedding dips 60-65 degrees to the south.
grained, light grey shale laminae (<1mm thick) in 40cm beds. Clay, carbonaceous and limonitic laminae are also observed.

The best exposures of the hangingwall beds are in a northeast facing wall in the open pit in an area named by mine geologists as stage 2. The stage 2 pit wall cross-cuts the S1 synclinal fold axis and shows intensely folded, orange-brown geothite shales. Bed and lamination thickness are consistent throughout the stage 2 area with the exception of a single massive, 40cm thick bed of coarse-grained quartz sand to grit in a clay matrix located at 101810mE, 505130mN. The 40cm bed has been cross-cut by a weakly developed cleavage. In this section the sand and grit consists of angular to sub-angular, quartz and lithic fragments with minor metamorphic biotite and the matrix consists of fine-grained quartz-sericite and biotite. Lithic fragments include tuff to isoclinally folded, fine-grained quartz sandstone.

3.4.4 Hangingwall beds description by WMC

Norris (1987a) recognised two lithologies in the hangingwall beds and described these lithologies as dark-grey to black, planar to wavy, very finely laminated carbonaceous shale and interbedded, partly calcareous siltstones, argillaceous limestones and carbonaceous shales.

3.5 Discussion and Interpretation of Nifty Stratigraphy

3.5.1 Early Stratigraphic Interpretations

Norris (1987a, 1987b) interpreted thickness variations in the principal carbonate bed to reflect local topographic highs and lows. Three intraformational debris flow breccia units were identified by Norris (1987a, 1987b) and used to correlate the principal carbonate bed stratigraphy across the deposit. Norris (1987a, 1987b) also noted that these breccia units were not laterally extensive and were spatially related to areas of dramatic thickness change. Norris (1987a) extrapolated the breccia horizons into his shale and cryptogal laminate units. Retracing of diamond drill holes showed that the majority of brecciated intervals are alteration-related pseudo-breccias of green quartz clasts in a black quartz pseudo-matrix.

An important distinction between the current stratigraphic succession (Norris, 1985; 1987a,b; Carmichael, 1990, 1992, 1993; Haynes et al., 1993, and Dure, 1994) and that proposed by the current study is the absence of cryptogal laminated carbonate and the reinterpretation that this texture is not of algal origin but is part of a zoned quartz-dolomite alteration of interbedded shales and dolomitic mudstone. Figure 3.12 compares the WMC Resources Ltd. stratigraphy and a new version developed during this study. The succession defined in the WMC Resources Ltd. stratigraphy reflects discordant to discordant, localised quartz-dolomite alteration that has overprint the original succession whereas the proposed stratigraphy uses the pre-alteration lithologic sequence as observed in unaltered core from diamond drill holes. The main changes proposed are that the new stratigraphy consists of the footwall beds, Nifty member, pyritic marker bed and the hangingwall beds. The Nifty member can be further divided into the lower unit, intermediate shale, upper unit and the upper shale.
Figure 3.12: A comparison between the stratigraphy established by WMC Resources exploration geologists and that interpreted from this study. The stratigraphy developed by WMC Resources geologists used a combination of lithology, alteration, and geochemistry to define individual units. This study has revisited the stratigraphy using successions observed in diamond drill holes unaffected by syn-mineralisation quartz-dolomite alteration and relating these to new exposures in the open pit. The alteration zones are discussed in Chapter Five.
3.5.2 Stratigraphic Position of the Nifty Member in the Broadhurst Formation

The stratigraphic position of the deposit within the Broadhurst Formation is uncertain because of the poor exposure of the formation, however an estimate of the stratigraphic position is given by geophysical characteristics (Carmichael, 1992). Carmichael (1992) divided the Broadhurst Formation into three magnetic domains (Fig. 3.13) and to these domains ascribed lithologies. Figure 3.13 shows a magnetic-conductive stratigraphy of the Throustell Group developed by Carmichael (1992). Carmichael (1992) suggested that an informally named “upper unit” of the Broadhurst Formation is host to the Nifty Cu deposit. Warrabarty, Maroochydore and Nifty were interpreted to be located in stratigraphically equivalent rocks (Carmichael, 1992).

![Magnetic-conductive stratigraphy](image)

Figure 3.13: Magnetic-conductive stratigraphy of the Yeneena Supergroup (after Carmichael, 1992). This stratigraphy was developed from an interpretation of the geology and geophysics of the Yeneena Group. Note the location of the Nifty Cu deposit in the upper unit of Carmichael (1992).

### 3.5.3 Depositional Setting

Norris (1987a, 1987b) interpreted the depositional setting of the Nifty carbonate member as a low energy, low gradient shelf under subtidal conditions, with possibly very local emergence. Basinal carbonaceous muds pass up-slope to algal mats and calcarenites. Shale deposition gradually encroached upon the carbonates. The pyrite marker bed marks a local return to algal mat formation and calcarenite deposition. Syn-sedimentary tectonic activity is reflected in local debris flow breccias and is probably responsible for the local topographical relief and locally extreme thickness changes. The pyritic and chloritic, laminated shale of the footwall beds were deposited in low energy, sub-storm wave base conditions that frequently became reduced (Norris, 1987a,b).
The accurate identification of evaporite minerals is significant in the interpretation of the depositional environment. Pseudomorphs after gypsum are common in the upper portion of the upper shale and pseudomorphed rosettes are found in the intermediate shale (Fig 3.8). The pseudomorphed rosettes may be after either gypsum or trona.

**Gypsum depositional environment**

Cody and Cody (1988) examined the nucleation and crystal morphology of gypsum grown under experimental conditions. The aim of their experiments was to determine the effects of water salinity, temperature, pressure, and amount of dissolved organic compounds, and pH on the nucleation of gypsum in evaporites. In addition to forming prismatic and bi-pyramidal forms similar to those observed in Figure 3.8A-C-D, Cody and Cody (1988) grew gypsum rosettes similar in appearance to those observed in the intermediate shale. The type V rosettes (Cody and Cody, 1988) were described as individual “petals” formed of lenticular crystals that fan out from a parent lenticular crystal. Gypsum rosettes formed in conditions of high concentrations of dissolved organic compounds and moderate salinity and are most widespread at temperatures of 23-50°C. Cody and Cody (1988) suggest that these evaporites are indicative of very warm, saline, continental sediments that contain very high concentrations of organic compounds. They go on to propose an environment where such conditions may occur is in a shallow water evaporite-lake sediments in arid regions fed by streams draining vegetated highlights and that the streams would be enriched in dissolved organic compounds that might be concentrated through evaporation of the lake waters. No vegetated highlands existed in the Proterozoic and therefore, in the Nifty depositional environment the dissolved organic compounds are likely to be provided by locally produced organic material, possibly algae.

**Trona depositional environment**

Southgate et al. (1989) showed photographs of radiating trona rosettes from a Cambrian playa from the Officer Basin, South Australia. Single crystals, random clusters and rosettes of trona and shortite are found in saline mudflat dolostones (Southgate et al., 1989) and are associated with stromatolite crusts. Southgate et al. (1989) interpreted the conditions of trona formation to be brine-charged mudflats where vadose conditions and a relative lowering of the brine below the sediment surface promoted the slow growth of alkaline evaporites. Egli and Hardie (1975) also discussed the depositional environment of trona evaporites in the Wilkins Peak Member of the Green River Formation of Wyoming, USA and compared their formation to currently forming trona in Lake Magadi, Kenya. During dry periods, trona and halite precipitated in the central area of impounded playa-lake complex.

The original composition of evaporitic minerals pseudomorphed by quartz and dolomite cannot be determined however similarities between the interpreted conditions of gypsum and trona formation suggest an isolated, saline, organic-rich (algae?), water body in continental sediments. A possible implication for the presence of either gypsum or trona evaporitic minerals is that the Nifty basin became isolated from water recharge and the intermediate shale may represent the period of maximum isolation. The lack of water recharge and high evaporation resulted in conditions conducive to the formation of
trona and/or gypsum evaporitic minerals. This period of isolation would be followed by a return to the conditions experienced during the deposition of the lower unit. The upper shale signifies a change to minimal carbonate deposition and increasingly reduced conditions.

3.6 * The Nifty Dolerite*

Dolerite has been intersected in shallow drill core and is exposed in the eastern end of the Nifty open pit. Thin section examination of fresh samples from drill core shows fine-grained cumulusic labradorite in a matrix of clinopyroxene, and fine plagioclase laths (WMC Resources Ltd. written comm., 1992). Plagioclase and clinopyroxene make up approximately 50% of the dolerite with traces of chlorite as an alteration product. Dykes have well defined chilled margins with a contact aureole between 1-3 cm thick. No cleavage is evident however the dolerite dyke exposed in the open pit has been crosscut at high angles by normal faults. A post-mineralisation timing is interpreted for the emplacement of the Nifty dolerite because 1) a mineralised xenolith in the dolerite (TND15, 431.65m) and 2) S<sub>0</sub> cleavage is absent in the dolerite.

3.7 * Deposit Metamorphism*

The metamorphic grade of Nifty host rocks has not previously been determined, however an estimate of the is provided by equilibrium mineral assemblage. At Nifty dolomite and quartz are stable and talc and calcite absent suggests sub-greenschist conditions in the metamorphic equilibrium in the system CaO-MgO-SiO<sub>2</sub>-H<sub>2</sub>O-CO<sub>2</sub>-NaCl (Bowers and Helgesen, 1988a,b). A typically example is the reaction of dolomite and quartz to talc and calcite is:

\[ 3\text{Dol} + 4\text{Qtz} + H_2O \rightarrow \text{Talc} + 3\text{Cal} + 3\text{CO}_2 \]  

(1)

In order to better constrain the metamorphic grade the illite crystallinity method was applied to a series of shales.

3.7.1 * Illite Crystallinity*

In other areas of very low to low metamorphism illite crystallinity has been used to define the metamorphic grade (e.g. Offit et al., 1987). The illite crystallinity technique relates the width at half-height of the 10-Å diffraction peak of (001) illite minerals to metamorphic grade (Robinson et al., 1990). This section presents results of an illite crystallinity study conducted on five Nifty shale samples. The objectives of using this technique are to constraining the background temperature and pressure caused by metamorphism and this would enable; 1) differences between metamorphism and mineralising system to be estimated, and 2) assist in constraining the pressure correction that will be used in the calculation of fluid inclusion homogenisation temperature.
3.7.2 Method

The illite crystallinity technique is a XRD technique that measures the half peak width of the 10-Å illite peak on oriented clay preparations of the <2-µm fraction (Kubler, 1967, 1968). The result is expressed in °Δθ. The illite crystallinity technique defines three zones: the diagenetic zone, anchizone, and epizone (Kubler, 1967). A standardised scale, the crystallinity index scale, sets the anchizonal boundary limits of 0.25° Δθ to 0.42° Δθ.

The exact factors that control the shape of the 10-Å peak are largely unknown but we are being in control to be temperature although it is acknowledged that many other factors may exist. An influence (Frey, 1987). These other factors include fluid pressure, stress, lithology, crystal chemistry, mineralogy, and time (Frey, 1987).

As analytical and sample preparation methods greatly affect illite crystallinity results (Warr and Rice, 1994) the full analytical details are presented (Table 3.1). Samples were analysed by R.N. Woolley of the Tasmanian Development and Resources Department on an automated Philips X-ray diffractometer system: PW 1729 generator, PW 1050 generator, PW 1710 printing recorder and microprocessor, with nickel filtered copper radiation at 40kV/30mA, a graphite monochromator (PW1752), sample spinner and proportional detector (sealed gas filled PW 1711). Data plotting was on a Philips thermal chart recorder (speed 40 mm/min, time constant 5 seconds) with manual measurement of peak widths (Woolley, pers. comm.).

The analytical procedure is based on the Warr and Rice (1994) method. A sedimented mount is prepared for each sample. The (001) illite peak is scanned four times (speed 0.01°/second). An average width at half peak height is calculated.

3.7.3 Results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lithology</th>
<th>Raw width (°)</th>
<th>Corrected width</th>
<th>CPS</th>
<th>Load (mg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN112, 280.1m</td>
<td>HW Shale</td>
<td>0.31</td>
<td>0.36</td>
<td>1600</td>
<td>1.5</td>
</tr>
<tr>
<td>TN113, 281.6m</td>
<td>HW Shale</td>
<td>0.30</td>
<td>0.34</td>
<td>1400</td>
<td>1.6</td>
</tr>
<tr>
<td>TN114, 351.08m</td>
<td>Nifty member</td>
<td>0.30</td>
<td>0.33</td>
<td>450</td>
<td>0.3</td>
</tr>
<tr>
<td>THRD647, 288.1m</td>
<td>HW Shale</td>
<td>0.44</td>
<td>0.47</td>
<td>700</td>
<td>2.2</td>
</tr>
<tr>
<td>THRD747W1, 378.2m</td>
<td>Nifty member</td>
<td>0.27</td>
<td>0.30</td>
<td>700</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Table 3.1: Illite crystallinity results from Nifty shale samples. Width measured in °Δθ at half peak height. All samples were air dried. CPS = peak height measured in counts per second. Width corrections made by calibration against Warr and Rice (1994) Standards.

Most of the data from Nifty samples fall within the upper anchizone. The exception is THRD647, 288.1m that plots in the diagenetic zone. A comparison of illite crystallinity values and accepted metamorphic facies suggests that the illite crystallinity values approximately 0.30 to 0.34 °Δθ quies to prehnite-pumpellyite facies (Araki, 1991).
The limited number of analyses and the restricted distribution of those samples suggest that interpretations based on these results should be treated with caution. Another issue that may have influenced illite crystallinity results is the proximity of samples to mineralisation, especially samples from the Nifty member, and the effect that may have on results. Assuming that the results are indicative of the metamorphic conditions at Nifty then this illite crystallinity study of the Nifty Cu deposit suggests that the metamorphic grade is within the prehnite-pumpellyte assemblage of green schist metamorphic facies. Therefore, the maximum temperature experienced due to metamorphism was 200-300°C. Assuming an average Proterozoic geothermal gradient of ~30-50°C/km, 200-300°C this temperature range equates to a burial depth of between 5 to 10 km.

3.7.4 Metamorphic Grade

It is interpreted that the peak metamorphic grade experienced at Nifty is sub-green schist to prehnite-pumpellyte facies.

3.8 Deposit Structure

The deposit structure is described and discussed in the next chapter.

3.9 Summary and Conclusions

The deposit stratigraphic succession at Nifty has been reinterpreted and now consists of the footwall beds, Nifty member, pyrite marker bed, and the hangingwall beds. The footwall beds to the Nifty mine sequence are grey to bluish-black, thinly laminated, carbonaceous, framboidal pyritic shale with micaceous and chloritic siltstone and minor light grey dolomitic mudstone. Some beds of contain evaporitic minerals pseudomorphed by quartz and dolomite occur within the footwall.

The mine sequence consists of the Nifty member and this is sub-divided into the lower unit, intermediate shale, upper unit and upper shale. The lower unit is 40-70m thick interbedded fine-grained, pale grey, dolomitic mudstone and blue-black, carbonaceous shale. Separating the lower and upper units is a prominent 1-4 metres thick bed of dark-grey to black, very fine-grained, soft and soapy, chloritic shale. The intermediate shale is distinctive because of the presence of rosette pseudomorphs. The upper unit (25-60m) has a similar composition to that of the lower unit and consists of alternating beds of laminated carbonaceous shale and dolomitic mudstone. The upper shale (20-40m) consists of dark-grey to black, laminated, carbonaceous shale with thin to massive framboidal pyrite seams and blebs, disseminated very fine-grained framboidal pyrite, minor dolomitic mudstone, and evaporite beds.

Conformably overlying the Nifty member with a gradational contact is the pyrite marker bed and this consists of fine-grained siltified black shale and grey-green very fine-grained siltified dolostone with laminations of fine-grained framboidal pyrite. The concentration of framboidal pyrite commonly exceeds 70% of an interval. Conformably overlying the pyrite marker bed with a gradational contact is the
hangingwall beds. The hangingwall beds are dominated by thinly laminated, dark grey to black pyritic, carbonaceous silt and silty shale. Rare interbeds of light grey laminated dolomitic shale and micaceous silt shale are distributed throughout the hanging-wall beds.