Chapter 1

INTRODUCTION

1.1 INTRODUCTION

This study focuses on a deformed and metamorphosed Palaeoproterozoic succession in northwestern Australia: the Koongie Park Formation. The Koongie Park Formation (KPF) hosts massive sulfide occurrences collectively known as the Koongie Park Prospects (KPP).

The KPP are among a handful of sub-economic Palaeoproterozoic, possibly volcanic-hosted massive sulfide deposits (VHMS) found in Australia (Plumb 1990, Large 1992, Solomon & Groves 1994). Others examples occur in granulite metamorphic rocks of the Arunta Block, Northern Territory (Mackie 1984, Warren & Shaw 1985) and in the Einsleigh Metamorphics of the Georgetown Block of Queensland (Bain et al. 1990, Solomon & Groves 1994). Elsewhere in the world significant VHMS deposits were formed between 2.0 and 1.8 Ga. Deposits occur in the Sveco-Finnian Orogen of Scandinavia (e.g., Skellefte and Bergslagen-Orajaavi and Outokoumpu districts of Sweden and Finland), the Trans-Hudson Orogen of Canada (e.g., Snow Lake-Flin Flon area, Rusty Lake), and the Ladysmith-Rhinelander district of Wisconsin and the Yavapi district of Arizona, USA. In contrast, there are no economic deposits in the Australian Palaeoproterozoic. Abundant economic deposits are present in Australia from all other major global VHMS producing periods, including Archaean deposits in the shield areas of Western Australia and in the Palaeozoic fold belts of eastern Australia (Veizer et al. 1989, Gale 1983, Large 1992).

Early VHMS interpretations of the KPP, discovered by Kennecott in the 1970s, were never tested, due to the sub-economic nature of the KPP. The Palaeoproterozoic age and uniqueness of these prospects in the Australian context, drew the attention of VHMS researchers at the Centre for Ore Deposit and Exploration Studies at the University of Tasmania (CODES). Questions about the volcanic setting of these deposits and interest in further exploration in the area prompted the establishment of this research project in conjunction with then leaseholders Anglo Australian Resources and joint venture partners Billiton Australia.

1.2 AIMS

This research was undertaken to determine the context and the nature of the KPP. Are they truly VHMS deposits, and if so, do they conform to conventional VHMS models. In order to answer these questions the following aims were pursued:

• identify effects of regional deformation and metamorphism on the KPF in order to determine the extent to which primary relationships have been modified;
• describe and interpret the lithofacies of the KPF with special emphasis on emplacement and depositional processes and depositional environment. This information can be used to assess
Figure 1.1 Location diagram of the study area in northwestern Australia. The map shows the main access roads, tracks and prospects. It also depicts the extent of outcrop (uncoloured areas north of the Angelo Fault) and widespread distribution of the Cainozoic cover sequences, including colluvium, alluvium and laterite. Some scattered outcrops are also present within patches of the cover sequence (see 1:25 000 map, backpocket). The study area straddles two 1:100 000 map areas with ANGELO west of longitude 127°30'E and HALLS CREEK east. All Australian Map Grid (AMG) intervals, provided along the edges of the map, are within Zone 52. Full grid values are only shown in the northeast corner of the map. All locations cited in this thesis use grid referencing based on the AMG. The northeast corner, for example, would be quoted as GR: 5000 8000.
whether or not setting is consistent with the interpretation of the KPP as VHMS deposits. The lithofacies data also provide a framework for a model for alteration and sulfide mineralisation;
• establish the geochemical composition of mafic and felsic lavas to further constrain the appropriateness of the KPF as host to VHMS deposits;
• describe the sulfide and alteration mineral assemblages at Onedin prospect. Sulfide and alteration minerals are intimately associated and probably related to a single hydrothermal system;
• describe the carbonate at Onedin. Carbonate demonstrates a complex paragenesis and interesting relationship with massive sulfide. Although common to many VHMS deposits, carbonate is not included in the classic VHMS models (e.g., Lydon 1988); and
• explore the possible origins for the carbonate, comparing and contrasting the Onedin prospect with modern and ancient VHMS deposits which contain carbonate.

Results of this research advance the understanding of subaqueous volcanic successions that host ore deposits. These successions are submerged in the modern and difficult to study. Although black smokers have been discovered in many tectonic settings (e.g., spreading ridges, sedimented spreading ridges, continental and oceanic backarc basins) (Scott 1992), as recently as 1998 a new setting for VHMS deposits was discovered during the research of the Izu-Bonin (Iizasa et al. 1999) and Tonga-Kermadec forearc settings. This research also broadens the knowledge base of the variety in VHMS deposits and their context. Carbonate alteration associated with many VHMS deposits has been briefly described, but has only recently become the focus of detailed research (Dixon 1990, Galley et al. 1993, 1995, Allen 1997, Halley & Roberts 1997, Herrmann & Hill 2001). Its presence was overlooked in the classic VHMS models (e.g., Lydon 1988). Furthermore, study of ancient sulfide deposits, such as Onedin, provides a view of the sub-surface parts of hydrothermal systems, which are only just beginning to be explored in the modern, by drilling of seafloor massive sulfide deposits (Davis et al. 1992, Humphris et al. 1995, Goodfellow & Zierenberg 1997, Zierenberg et al. 1998, Petersen et al. 2000, Binns et al. 2001).

1.3 LOCATION AND ACCESS

The study area lies within the area bounded by longitudes 127°25'E and 127°35'E and latitudes 18°17'S and 18°30'S in northwestern Australia (Fig. 1.1). It covers 240 km² of Koongie Park Station, on both sides of the Great Northern Highway, 15–30 km SSW of Halls Creek. The main KPP in this area are Sandiego and Onedin. The smaller prospects are Gosford, Atlantis, Puseye, Rockhole and Hanging Tree (Fig. 1.1). Access is via the highway, a sealed bitumen road, and unmade station tracks extend into the surrounding areas. Koongie Park Station was extensively fenced during the 1993–94 field period, causing some pre-existing roads to become inaccessible by vehicle. Outcrop in the area is poor and nowhere continuous in the KPF (Fig. 1.1). The best exposures occur in the Onedin-Rockhole-Gosford area, on the watershed between the Fitzroy River system to the west and the Ord River system to the east. Parts are capped by laterite and large areas are covered by colluvium and alluvium.
1.4 METHODS AND THESIS OUTLINE

Research was undertaken by field mapping between 1992 and 1994 at 1:25,000 scale, with detailed facies and structural mapping onto aerial photographs at 1:5000 or 1:2500 scale in areas of good outcrop. Well preserved and new (pre-1995) drillcores were logged from some prospects. Examination of geophysical data was undertaken to augment mapping into areas of poor outcrop. Maps are presented in the backpocket, logged drillcore records presented in Appendix 3 and a section on the geophysics presented in Appendix 1. Field work was supplemented by petrographic studies, including thin-section examination, cathodoluminescence and point counting, short wave infra-red analysis, as well as conventional whole-rock, mineral, rare earth and isotope geochemistry. Rocks collected and processed are listed in Appendix 2 and the analytical results are presented in Appendices 4 and 6–9.

The main body of the thesis is divided into ten chapters including this introduction. Chapter 2 presents background on the KPF, including a review of previous work, a review of the regional geology and tectonic context of the KPF, the local geology based on mapping during this study, a review of the regional metallogeny, and the exploration and discovery history of the KPP. Deformation effects, including the main structures and foliations, and metamorphism are documented in Chapter 3.

Chapters 4, 5 and 6 pursue information on the setting of the KPF in the Koongie Park area. Chapter 4 focuses on palaeovolcanology and palaeogeography of the volcanic and non-volcanic facies found in the study area. This is done by analysing facies and their associations. Detailed facies descriptions are presented in Appendix 5. Chapter 4 also presents the geochemistry of the ironstones, which have important implications for exploration models. Internal textures of a rhyolitic sill are documented in Chapter 5. The implications of these textures for the emplacement of this sill and the architecture of the succession are also examined. The geochemistry of felsic and mafic volcanic rocks of the KPF at Koongie Park are presented in Chapter 6. These data are a useful tool to help constrain the possible tectonic setting of the KPF.

The next three chapters focus on alteration and mineralisation. Chapter 7 describes in detail the minerals assemblages which resulted from these processes at Onedin prospect. Chlorite+white mica+quartz form the footwall assemblage, chlorite+quartz+dolomite+talc+sphene is common in association with sphalerite-dominated ore zones and albite+quartz+chlorite+white mica zones occur in the hanging wall. Paragenesis and timing of alteration and mineralisation are discussed, including the evidence for pre-deformational alteration. Arguments that discount a skarn or structural origin for mineralisation are given. Comparison with other Palaeoproterozoic and more modern VHMS deposits is presented. The intricate textures of carbonate alteration are documented in Chapter 8, along with carbon-oxygen isotope modelling for the Onedin prospect. Modern hydrothermal seafloor carbonate and ancient carbonate-bearing VHMS systems are compared to Onedin in Chapter 9. The role of sub-seafloor processes which led to carbonate development, and the role of carbonate as a trap for mineralising fluids are discussed in Chapter 9.

Finally, a synthesis and conclusions are presented in Chapter 10. This chapter concludes that the Onedin is a VHMS deposit which formed beneath the seafloor. Recommendations for further work are made at the end of this chapter.
Chapter 2

REGIONAL SETTING OF THE KOONGIE PARK FORMATION
IN THE HALLS CREEK OROGEN

2.1 INTRODUCTION

This chapter aims to provide background information for the later chapters of the thesis which deal in detail with the Koongie Park Formation (KPF) and the sulfide zones and carbonate at the Onedin prospect. It is divided into three main sections: a summary of previous investigations; a review of the regional and local geology of the area; and the regional and local metallogeny. The geology section provides information on the Palaeoproterozoic context, the regional geology, and the local geology of Koongie Park. The latter is new information based on mapping completed during this project. In the metallogeny section the regional distribution of copper, lead and zinc in the Halls Creek Orogen is reviewed, the exploration history of the KPP is summarised and each of the main prospects is described.

2.2 PREVIOUS INVESTIGATIONS OF THE HALLS CREEK AREA

The presence of gold, platinum, nickel, zinc, copper and rare earth element (REE) occurrences in the Halls Creek Orogen has guaranteed exploration since the discovery of gold near Halls Creek by Hardman (1885). Reports on the goldfield were made by Woodward (1891) and Smith (1898). A small mining boom ensued, but was short lived due to dry conditions, remoteness and discovery of the richer gold deposits of Kalgoorlie and Coolgardie further south in the 1890s.

Early research focussed on hydrology (Jack 1906), petroleum (Maitland 1920, Blatchford 1922, Wade 1924) and mining (Blatchford 1928, Finucane 1938, 1939a, b, c, Finucane & Sullivan 1939, Jones 1938). Systematic mapping of the area commenced in the late 1940s when the Bureau of Mineral Resources (BMR) began projects in the Fitzroy Basin, Halls Creek, Mt Bannerman and Noonkanbah areas (Matheson & Guppy 1949, Guppy et al. 1958, Thomas 1958, Wells 1962). The Commonwealth Science, Industry and Research Organisation (CSIRO) Land Research and Regional Survey team also worked in the East Kimberley (Traves 1955). A series of 1:250 000 maps with accompanying reports was completed in the 1960s (Gemuts & Smith 1968, Gellatly & Derrick 1968, Roberts et al. 1968) and a compilation of the geology of the East Kimberley was produced by Dow & Gemuts (1969).

Serious mineral exploration during the 1960-70s defined many of the major zinc, copper and lead prospects including Little Mt Isa, Ilmars, Sandiego, Onedin and Gosford, some of which are

1 BMR was renamed to the Australian Geological Survey Organisation (AGSO) in 1993 and renamed again recently as Geoscience Australia.
still being explored today (see also discussion on exploration history of the KPP below).
Compilations of exploration results appeared in memoirs and reports of the Geological Survey of Western Australia (Blockley 1971, Marston 1979, Davies & Blockley 1990, Fergusson 1999). Discovery of diamonds at Argyle by CRA in the 1970s attracted other diamond explorers, including Stockdale and Ashton.


Most recently a joint Geological Survey of Western Australia (GSWA) and AGSO project generated a series of 1:100 000 and 1:250 000 geological maps of the East Kimberley region (Griffin & Tyler 1992, Tyler et al. 1998, Blake et al. 1999). Radiometric dating was part of the reappraisal of the area (Page & Sun 1994, Page et al. 1994). Numerous publications on a range of topics that ensued from this work are listed in Hoatson & Blake (2000) and many are cited in this study.

2.3 GEOLOGICAL CONTEXT OF THE PALAEOPROTEROZOIC KPF

2.3.1 THE PALAEOPROTEROZOIC EARTH

During the Palaeoproterozoic Archaean shields formed the cores of all continents and were shedding detritus into surrounding basins (Fig. 2.1). Early life forms, such as stromatolites and free living cyanobacteria and Archaea, grew in shallow water. The embryonic Earth had oceans and an atmosphere. The chemistry of these is debated. Kempe & Degens (1985) suggested that the Palaeoproterozoic oceans contained higher levels of bicarbonate, but Grotzinger & Kasting (1993) disagreed and concluded that the ancient oceans had a pH around 8, similar to the value of modern oceans. Fluctuating oceanic isotope values were reported by Veizer & Hoefs (1976), Veizer et al. (1992), Strauss et al. (1992) and Kahru & Holland (1996). Other authors debate these variations and maintain that little has changed in either ocean chemistry or oceanic isotope values since the late Archaean (Gregory 1991, Solomon & Sun 1997). Oxygen had become a free component of the atmosphere by 2000 Ma, although at lower levels than found in the modern atmosphere. This is marked by the transition from extensive ironstone deposits to red bed formation at the end of the Archaean, and the end of uranium deposition on continents (Holland 1984). Although free oxygen was present in the atmosphere, development of aerobic oceanic bottom waters is debated. Walker et al. (1983) suggested that the fewer widespread ironstone formations at the end of the Palaeoproterozoic pointed to aerated bottom waters, but recent work on sulfur isotopes (Canfield & Raiswell 1998, Canfield 1999) indicated that aerated bottom waters did not form until the Neoproterozoic.
Figure 2.1 Worldwide distribution of Archaean and Palaeoproterozoic regions (after Windley 1984 and Hoffman 1988). KPF is arrowed.

Figure 2.2 Distribution of Australian Archaean and Proterozoic basins and orogens (after Myers et al. 1996). Halls Creek orogen is highlighted. The Pine Creek Inlier, Arnhem Inlier, Tennant Creek Inlier, Mt Isa Inlier and Granites Tanami Blocks as well as the northern portion of the Arunta Block in north and central Australia are considered to have amalgamated into the North Australian Craton between 1300 and 1000 Ma.
Early Palaeoproterozoic sediment-dominated rifting (2.4 - 2.2 Ga) of the Archaean cratons was followed by extensive volcanism in both the oceanfloor and arc environments (1.9 - 1.74 Ga), accompanied by prolific VHMS development (Franklin 1986). A hiatus in the development and/or preservation of VHMS deposits occurred between the end of the Palaeoproterozoic and the onset of the Palaeozoic (Gale 1983, Veizer et al. 1989). Currently there are no explanations for this hiatus, although Hoffman (1989), Barley & Groves (1992) and Barrie & Hannington (1999) suggested a correlation with limited arc magmatism and the dawn of stable cratons, such as the supercontinent Rodinia at this time in Earth history.

2.3.2 AUSTRALIAN PALAEOPROTEROZOIC PROVINCES
Preserved in Australia today are several basins and fold belts which were the locus of deposition and volcanism in the Palaeoproterozoic (Fig. 2.2), including the Halls Creek Orogen. in the northwest, host to the KPF. Myers (1993) and Myers et al. (1994) interpreted rocks of the Capricorn Orogen, between Archaean cratonic blocks in Western Australia (Fig. 2.2), to be products of conventional plate tectonic processes operating during the Palaeoproterozoic. Myers et al. (1994, 1996) suggested that the numerous Archaean and Proterozoic cratons were amalgamated into the Australian Continent, as part of Rodinia, between 1300 and 1000 Ma. Tectonism was concentrated repeatedly along zones between the cratons, such as at the southern edge of the North Australian Craton, and in the Strangways of central Australia (1880-1870 Ma) (Myers et al. 1996). Most recently Scott et al. (2000) suggested that the North Australian Craton moved south during the Palaeoproterozoic and that the Halls Creek Orogen was a marginal area where early repeated strike-slip movements were focussed. This is consistent with the interpretation of the Halls Creek Orogen as a suture zone where several crustal elements collided (Hancock & Rutland 1984, Tyler et al. 1995, Shaw et al. 2000) and the large strike-slip faults which were active over a long period (White & Muir 1989, Shaw et al. 1992b, Tyler et al. 1995, 1999). The exact nature of this boundary is debated. Sheppard et al. (1999) and Tyler et al. (1995) suggested the presence of an early subduction zone in the area, whereas other authors advocated a transpressional boundary (Shaw et al. 2000).

2.3.3 HALLS CREEK OROGEN
The Halls Creek Orogen is one of two Palaeoproterozoic orogens in the Kimberley area of northwestern Australia. It trends northeast, nearly orthogonal to the WNW-trending King Leopold Orogen (Fig. 2.3). The Halls Creek Orogen is 300 km long and 50 to 60 km wide. It is composed of folded sedimentary and volcanic rocks intruded by large ultramafic, mafic and felsic complexes, aged between 1912 Ma and 1805 Ma (Blake et al. 1999), which are grouped into the Lamboo Complex2 (Dow & Gemuts 1969, Gemuts 1971). These rocks are considered to be the basement in this area.

Sedimentary and volcanic rocks of younger Proterozoic and Palaeozoic basins overlie the Lamboo Complex and although some occurrences are scattered amongst basement rocks, most are on the margins of the orogen (Fig. 2.3). Palaeoproterozoic basin remnants include strike-slip basin

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2 Although this term is still used by publications of the GSWA it has not been used in the most recent literature on the area by Geoscience Australia (Hoatson & Blake 2000).
Figure 2.3  Simplified geology of northwestern Australia displaying the Palaeoproterozoic Halls Creek and King Leopold Orogens with overlying and abutting Proterozoic and Palaeozoic basins.

(Blake et al. 1999, Sheppard et al. 1999) and the extensive Kimberley Basin to the north and west. Mesoproterozoic and Neoproterozoic deposits are scattered to the north and throughout the area (Fig. 2.3, see also Fig. 2.9). The Cambrian to Cainozoic Bonaparte Basin lies to the north, the Cambrian to late Devonian and Cainozoic Ord Basin as well as the Cambrian to Cainozoic Birrindudu Basin are in the east, and the Ordovician to Cainozoic Canning Basin is in the south (Fig. 2.3).

Zones of the Halls Creek Orogen

Hancock & Rutland (1984) recognised four basement zones within the Halls Creek Orogen. Recent 1:100 000 scale mapping and geochronology reduced these to three zones and modified their boundaries (Griffin & Tyler 1992, Tyler et al. 1994, 1995) (Fig. 2.4). They parallel the orogen and are bounded by NNE strike-slip faults. The zones are from east to west are the Eastern, Central and Western zones. The KPF lies in the southern portion of the Central zone. Tyler et al. (1995) argued that each of these zones is a distinct tectonostratigraphic terrane and that the boundary faults may be the reactivated Palaeoproterozoic terrane boundaries.
Kimberley Basin Group (1835 - 1790 Ma) in the west; Undifferentiated Meso- to Neo- Proterozoic & Phaner-ozoic rocks elsewhere

Basic intrusions (MacIntosh Gabbro, Panton Sill, Toby Sill etc.) 1855-1830 Ma

Granitoid suites (Paperbark supersuite, 1860 Ma & Sally Downs supersuite 1820 Ma)

Moola Bulla Formation

Milba Formation

Koongie Park Formation 1843 Ma

Tickalara Metamorphics (1865 Ma, metamorphosed 1850 Ma)

Whitewater Volcanics (1855 Ma)

Halls Creek Group (metasedimentary rocks, mafic and felsic volcanics; 1880 -1847 Ma)

Marboo Formation 1872-1861 Ma

Ding Dong Downs Volcanics 1910 Ma

Figure 2.4 Regional geology of the East Kimberley. The Koongie Park Formation occurs both south and north of Halls Creek. Three zones and their boundaries are depicted (after Tyler et al. 1995). Note the study area in the south of the Central zone. Map based on data from Kimberley Mapping Accord (GSWA, AGSO).
Figure 2.5 Simplified time-space plot for the Palaeoproterozoic rocks of the Halls Creek Orogen divided into the three zones recognised by Tyler et al. 1995 (after Hassan 2000).
**Eastern zone**
The Eastern zone is composed of the Halls Creek Group (Figs 2.4, 2.5). Shallow marine sedimentary units of the Saunders Creek Formation unconformably overlie the oldest rocks in the Halls Creek Orogen: the Sophie Downs Granite (1912 ± 3 Ma) felsic Ding Dong Downs Volcanics (1907 ± 6 Ma) (Blake et al. 1999). Biscay Formation basalts and fine-grained sedimentary rocks are overlain by the Olympic Formation (Figs 2.4, 2.5). The Milba Formation is faulted against the Biscay Formation near the western edge of the zone. The younger Moola Bulla Formation overlies the Olympic Formation east of Halls Creek and an inlier of the Kimberley Basin is faulted against the Olympic Formation south of Halls Creek (Blake et al. 1999). These older sequences are covered in the east by the Neoproterozoic Wolfe Basin and the Palaeozoic Ord Basin, and faulted against the Central zone by the Angelo-Halls Creek Fault system.

**Central zone**
The Tickalara Metamorphics, which were deformed and metamorphosed between 1865 and 1856 Ma and 1850–1845 Ma (Page & Sun 1994, Tyler & Page 1996, Bodorkos et al. 1999), are surrounded by granite and mafic intrusions in the northern portion of the Central zone. In the south lies the KPF which was dated at 1840 ± 4 Ma (Page & Sun 1994, Page et al. 1994) (Figs 2.4, 2.5). The KPF is overlain by the Moola Bulla Formation in the east. The Springvale-Ramsay Range Fault system bounds the zone to the west and the Angelo-Halls Creek Fault system forms the eastern boundary.

**Western zone**
In the western zone granite and mafic bodies intrude the older metamorphosed flysch sequences of the Marboo Formation and ignimbrites of the Whitewater Volcanics (1855 Ma, Figs 2.4, 2.5) (Page et al. 1994). The older rocks are overlain by sedimentary sequences of the Kimberley Basin in the west and abut the Central zone along the Springvale-Ramsay Range Fault system.

**2.3.4 MAJOR DEFORMATION EVENTS AND THEIR IMPACT ON THE HALLS CREEK OROGEN**
Major tectonism took place along the orogenic belt during the Palaeoproterozoic, Mesoproterozoic, Neoproterozoic and Palaeozoic. Five main orogenies are recognised (Tyler et al. 1995, Tyler et al. 1998). The oldest is the Hooper Orogeny which caused at least two deformation events recorded in the Tickalara Metamorphics of the Central zone (Fig. 2.5, D1/M1 and D2/M2). The Hooper Orogeny occurred before the deposition of the KPF, but the other four orogenies affected the KPF. The first of these was the Halls Creek Orogeny which caused widespread extension and later regional metamorphism and deformation in the Eastern and Central zones (Griffin & Tyler 1992, Tyler & Page 1996, Sheppard et al. 1997b) (Fig. 2.5 D1/M1 and D2/M2). During the Mesoproterozoic, the Yampi Orogeny caused ductile strike-slip movements along the NNE-striking Springvale, Ramsay Range, Angelo and Halls Creek faults, as well as some associated folding in the Central and Eastern zones (Tyler et al. 1995). The Neoproterozoic King Leopold Orogeny (Shaw et al. 1992b) produced sinistral strike-slip faults and open WNW-plunging folds (Blake et al. 1999). Limited refolding of earlier folds and late reactivation along faults was caused by the Palaeozoic Alice Springs Orogeny (Shaw et al. 1992b, Blake et al. 1999).
The KPF at Koongie Park has been overprinted by the Halls Creek Orogeny and subsequent orogenic events which have affected the Central zone. In the study area, the metamorphic grade of the KPF varies from amphibolite facies near granite contacts to middle greenschist facies near Onedin. This is discussed in detail in Chapter 3. The prefix 'meta' is omitted in most of the thesis for simplicity. Rocks are folded and display penetrative cleavages.

2.3.5 STRATIGRAPHY AT KOONGIE PARK

Three main stratigraphic units form the geology at Koongie Park. The oldest rocks belong to the KPF. These are unconformably overlain by the Moola Bulla Formation in the south. The sequence is intruded by granitoids of the Sally Downs supersuite: in the north and northwest, by the Loadstone Monzogranite; and in the east, by undifferentiated leucogranite (Fig. 2.6). A small granophyre intrusion near Puseye is probably the same age, or slightly younger, than the KPF.

Previous stratigraphic subdivisions

Early mapping subdivided the rocks at Koongie Park into the Olympio Formation and the Bow River Granite (Gemuts & Smith 1968, Dow & Gemuts 1969) (Table 2.1). Re-mapping and isotopic dating recognised the main unit in the area as the KPF, intruded by later granite (Tyler & Griffin 1992). On ANGELO3 1:100 000 geological sheet, Griffin & Tyler (1994) assigned mafic igneous and sedimentary units north of Sandiego to the Tickalara Metamorphics. The KPF was dated at 1843 ± 2 Ma and the Moola Bulla Formation recognised further south. The intruding granite was renamed the Loadstone Monzogranite and dated 1827 ± 2 Ma. On the latest geological map of the area (HALLS CREEK 1:100 000), Blake et al. (1999) did not recognise the Tickalara Metamorphics north of Gosford but included these rocks in the KPF. The Onedin Member was mapped within the KPF and the Loadstone Monzogranite was classified as part of the Sally Downs supersuite.

All the different stratigraphic subdivisions and those used in this study are presented in Table 2.1. The stratigraphy on the most recent map, HALLS CREEK 1:100 000, is followed in this thesis. The only difference is that here the KPF is further subdivided into informal upper and lower units.

Naming the Koongie Park Formation

Griffin & Tyler (1992) recognised a ‘Koongie Park Member’ of the Tickalara Metamorphics. Many earlier mining company reports also used informal names such as Koongie Park beds for these rocks. Isotopic dating by Page et al. (1994) indicated that this unit was 1843 ± 2 Ma old, younger than the Tickalara Metamorphics (1865-1856 Ma), requiring definition as a new formation. The Koongie Park Formation (KPF) is cited in all recent publications. The older Tickalara Metamorphics are now restricted to north of the KPF (Fig. 2.4).

Although the Koongie Park succession contains numerous intrusions, rules of the Australian Guide for Stratigraphic Nomenclature (Staines 1985) allow it to be defined as a formation.

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3 All map names are given in upper case following the publication convention of geological surveys around Australia.
Figure 2.6 The geology of Koongie Park showing the distribution of the lower and upper KPF and the dolerite within the KPF. The Onedin Member of the KPF is in the north and the overlying Moola Bulla Formation in the south. These are intruded by the Loadstone Monzogranite in the north and west. The contact aureole in the KPF is shown. Undifferentiated leucogranite of the Sally Downs supersuite intrudes the succession in the east. Minor granophyre near Puseye may be related to the KPF. Main fold axes and major faults are depicted.
2.3.6 THE KOONGIE PARK FORMATION

The KPF occurs in the southern portion of the Central zone of the Halls Creek Orogen (Griffin & Tyler 1992, Tyler et al. 1994, 1995). It extends for 85 km, NNE and southwest of Halls Creek (Fig. 2.4) (Blake et al. 1999, Tyler et al. 1998). The KPF at Koongie Park is composed of mafic and felsic volcanic and associated sedimentary facies including sandstone, mudstone, carbonate, chert and ironstone intruded by rhyolitic to rhyodacitic sills, dolerite bodies and basalt dykes. Basaltic volcanic rocks are slightly more common north of the study area (Blake et al. 1999), whereas further south the succession resembles that at Koongie Park (Griffin & Tyler 1994).

In the Koongie Park area, the KPF can be divided into two informal units. The lower unit (lower KPF) is dominated by mafic volcanic units, quartz sandstone and mudstone turbidites, chert, possible ironstone and minor felsic volcaniclastic units. The upper unit (upper KPF) is more lithologically diverse, comprising felsic volcanic units, carbonate, ironstone, chert, mudstone, quartz-bearing volcaniclastic beds and lithic sandstone. Table 2.2 lists all the facies recognised in the study area and their stratigraphic position in the KPF. Figure 2.7 depicts schematic lithofacies relationships for the KPF at Sandiego and in the Onedin-Rockhole area.

Base metal prospects are concentrated in the upper KPF at Koongie Park. Company geologists identified footwall, hanging wall and host units at the prospects which are informally named the

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**Table 2.1 Stratigraphic nomenclature in the Central zone of the Halls Creek Orogen**

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<td>part of the Sally Downs supersuite (1835-1805 Ma).</td>
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<td>Intrudes Koongie Park Formation and provides a minimum age for deformation of the Koongie Park Formation.</td>
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<td>Undivided gabbro/dolerite.</td>
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<td>Koongie Park Formation (1843±2 Ma).</td>
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<td>Tickalara Metamorphics (1865-1856 Ma).</td>
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<td>Lower Koongie Park Formation.</td>
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Table 2.2  Principal facies and stratigraphic units of the KPF at Koongie Park.

<table>
<thead>
<tr>
<th>STRATIGRAPHIC UNIT.</th>
<th>SEDIMENTARY FACIES.</th>
<th>VOLCANIC FACIES.</th>
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| Upper Koongie Park Formation. | • Poorly-sorted, lithic-rich pebbly sandstone.  
• Granule conglomerate.  
• Interbedded graded sandstone and mudstone.  
• Siliceous sandstone-mudstone.  
• Thinly bedded to cross-bedded, fine sandstone and mudstone.  
• Mudstone.  
• Thinly bedded to laminated grey mudstone and fine-sandstone.  
• Black mudstone with cherty nodules.  
• Calcareous mudstone.  
• Chert.  
• Ironstone. | • Aphyric rhyolite;  
• Quartz-phyric rhyolite;  
• Feldspar-phyric rhyolite;  
• Quartz-feldspar porphyry.  
Sub-facies include: amygdaloidal, spherulitic, lithophysae-rich, perlitic, peperitic, granular and massive.  |
| Lower Koongie Park Formation. | • Interbedded graded sandstone and mudstone.  
• Poorly-sorted, lithic-rich pebbly sandstone.  
• Mudstone, ferruginous mudstone.  
• Chert.  
• Sub-surface ironstone(?). | • Basalt.  
• Dolerite.  |


‘Coolibah tuff’, the ‘Weldons lava’ and the ‘Camp shale’ respectively (Sewell 1999). The ‘Camp shale’ contains a carbonate+mudstone+ ironstone-dominated member known informally as the ‘Mimosa member’. Elsewhere, this subdivision is not valid and has led to some confusion. For example, units typical of ‘Weldons lava’ occur within the ‘Coolibah tuff’ beneath the Onedin prospect. These informal names have also been used in areas north of the KPF, at Little Mt Isa and Ilmars, where the host succession is now known to be a lower unit of the Biscay Formation (Blake et al. 1999, Sewell 1999, Hassan 2000) (Fig. 2.5). For these reasons the informal nomenclature is not followed in this thesis. The former ‘Mimosa member’, is in fact a mappable unit and present in drillholes at Onedin, Rockhole and probably Gosford prospects, and has been renamed as the Onedin Member of the KPF (Orth 1997, Blake et al. 1999). Renaming was necessary as no geographical features with the name ‘Mimosa’ occur in the area.
Lower Koongie Park Formation (lower KPF)

The lower KPF consists of basalt, dolerite, interbedded graded sandstone and mudstone, mudstone, chert, ironstone and poorly sorted, lithic-rich pebbly sandstone facies. The interbedded graded sandstone and mudstone facies and mudstone facies dominate with isolated outcrops of chert. Large areas of basalt and dolerite occur in the north and west (Fig. 2.6, 1:50 000, 25 000 map, backpocket). In the north, tabular basalt is intercalated with rare beds of poorly sorted, lithic-rich pebbly sandstone. Contacts between the basalt and dolerite and the sedimentary facies are not exposed. In the southwest small units of basalt are intercalated with interbedded graded sandstone and mudstone facies which are conformably overlain by interbedded graded sandstone and mudstone and ironstone facies of the overlying upper KPF.

On ANGELO, the succession in the west, dominated by basalt and turbidites, are mapped as Tickalara Metamorphics. The Tickalara Metamorphics north of the KPF comprise turbidites and mafic volcanic facies, dated at 1865–1854 Ma (Page & Sun 1994, Page et al. 1994). These older rocks display the effects of two metamorphic and deformational events that occurred during the Hooper Orogeny, prior to the deposition of the KPF (Tyler & Page 1996, Tyler et al. 1998). If the basalt and turbidite succession in the west belonged to the Tickalara Metamorphics as envisaged by Griffin & Tyler (1992), an angular unconformity should separate it from the KPF. In most of the area, the contact between this unit and that mapped as KPF on ANGELO is covered. Where it is well exposed, at Hanging Tree, basaltic volcanic facies and sandstone are directly overlain by ironstone, chert and felsic volcanic facies, typical of the upper KPF, with no obvious structural or metamorphic break between the two units (see map 1:25 000, back pocket). Furthermore, similar basaltic volcanic and sedimentary successions comprise the KPF further north on HALLS CREEK (Blake et al. 1999). For these reasons, classification of the mafic volcanic and sedimentary facies in the study area as Tickalara Metamorphics is abandoned and they are referred to in this thesis as lower KPF.

Dolerite float is common in areas of black soil plains. Outcrop is hard to find and relationships between the dolerite and the lower KPF cannot be established. However, at Gosford, dolerite intrudes the upper KPF, implying that dolerite also intrudes the lower KPF. North of Gosford, dolerite is closely associated with basalt facies and may form the interior parts of basalt units within the lower KPF.

The lower KPF is intruded in the north and west by granitoids. These belong to the Loadstone Monzogranite, part of the 1835–1805 Ma Sally Down supersuite recognised by Tyler et al. (1994) in the central area of the Halls Creek Orogen. The metamorphic grade of the lower KPF increases towards the granite with andalusite and cordierite (?) schist near the contacts. Andalusite typically appears within 50 m of the granite contact (Fig. 2.6). The random orientation of andalusite crystals on cleavage planes indicates that the granite intruded at the end of the main regional deformation in the area.

True thickness of the lower KPF is difficult to estimate because the unit is complexly folded and the base is intruded by granitoids. However, an estimated minimum thickness, based on cross-sections (backpocket) is about 1500 m.
**Upper Koongie Park Formation (upper KPF)**

The upper KPF is lithologically diverse (Chapter 4). It contains abundant felsic volcanic facies and carbonate both of which are uncommon in the lower KPF. Sandstone turbidites and mudstone, which make up most of the lower KPF are less abundant in the upper KPF. Other important facies in the upper KPF are ironstone, black mudstone, granule conglomerate, volcanic-clast bearing mudstone and breccia deposits.

The upper KPF was previously mapped as Olympio Formation (Dow & Gemuts 1969, Gemuts & Smith 1967) or as KPF (Griffin et al. 1994). The Olympio Formation is now known to be restricted to east of the Halls Creek and Angelo Faults (Figs 2.4, 2.5) (Tyler et al. 1998). The lack of structural differences between this unit and the underlying mafic volcanic and turbidite sequence of the lower KPF, along with abundant mafic and felsic volcanic units within the KPF further north (Blake et al. 1999), indicates that these are all part of the same formation.

The upper KPF is overlain in the south by the Moola Bulla Formation. Erosional contacts occur between these units. The base of the Moola Bulla Formation locally cuts down into upper KPF chert, mudstone and sandstone, fragments of which are abundant in the lower portions of the Moola Bulla Formation. At one location where the two units are exposed (GR 359 615), folded ironstone is overlain by coarse basal Moola Bulla Formation sandstone. This suggests that an angular unconformity separates these units.

The upper KPF is estimated to be 1000–1500 m thick, based on cross-sections (backpocket). [The total thickness estimate for the KPF is 2500–3000 m, which is slightly thicker than the 2000 m estimated for the KPF by Tyler et al. (1998).]

**Onedin Member**

The Onedin Member is the only formally defined member within KPF (Orth 1997). It is important as it is the host to sulfide zones at Onedin, Rockhole and Gosford. It encompasses the informal ‘Mimosa member’, ‘Camp shale’ and ‘host horizon’ used in company reports (Asarco 1983 to 1989, Sewell 1999, Saunders 1999).

The thickness of this unit varies from at least 150 m at Onedin to only 50 m some 500 m northeast. The Onedin Member is continuous for at least 3.5 km northeast of Onedin. It is folded and also present at Gosford (Fig. 2.6).

Between Onedin and Rockhole and east of Gosford, the Onedin Member is faulted against and appears to overlie the quartz-bearing mudstone facies. At Gosford, it is associated with blue-quartz-phyric, flow-banded rhyolite and amygdaloidal rhyolite. Relationships between these units have not been constrained. It is intruded and overlain by spherulitic rhyolite at and east of Onedin. East of Gosford, it is overlain by sandstone turbidite and mudstone with mudstone and ironstone more common upsequence.

Outcrops of the Onedin Member are composed of ironstone interbedded with red mudstone, chert, nodular chert, minor carbonate and gossanous layers. In drillcore at Onedin, lithologies include dark green chloritic and talc-rich schist and black mudstone, lenses of carbonate and calc-silicates, including tremolite+talc-bearing schist and iron-rich dolomite.
2.3.7 MOOLA BULLA FORMATION

The Moola Bulla Formation outcrops in a refolded synform on the southeastern side of the Highway Fault and as a narrow fault sliver further north on the northwestern side of this fault (Fig. 2.6, 1:50 000 and 1:25 000 maps, backpocket). The maximum thickness of the unit, measured in the synformal hinge is 1350 m thick.

The Moola Bulla Formation in this area consists of a basal sandstone unit overlain by mudstone. These are overlain by an upper coarse-grained sandstone unit. A similar stratigraphy is recognised in the Moola Bulla Formation further north near Halls Creek (Dow & Gemuts 1969, Blake et al. 1999).

Description

In the synformal hinge area, the basal unit is up to 1000 m thick and composed of sandstone and granule conglomerate which contain abundant fragments of mudstone, sandstone and chert derived up from the KPF. Heavy-mineral bands and trough cross-bedding as well as normally graded sandstone beds feature near the base. Amalgamated coarse-grained sandstone beds are up to 1 m thick. The overlying mudstone-dominated unit is composed of red to pink fine sandstone and mudstone with minor iron-rich red mudstone. It is 320 m thick. Overlying the mudstone-dominated sequence are several beds of coarse-grained sandstone. Each bed is up to 30 m thick and the unit may reach up to 700 m thick in the synformal core, 2 km north of its southernmost exposure.

Along-strike facies changes are interpreted from aerial photographs. The lowermost unit identified in the southern area of the fold thins northward on both sides of the synform. The middle unit changes character around the fold: mudstone and fine- to medium-grained sandstone are dominant on the northern side of the fold, but are not apparent in the hinge or at the southern nose of the fold, where more abundant medium- to coarse-grained sandstone lenses occur. The upper, coarse-grained sandstone unit is prominent in the northern portion of the refolded fold, where it comprises large outcrop-scale cross-bedded sandstone and abundant parallel-bedded coarse-grained sandstone.

Petrography

The sandstone is moderately well sorted to poorly sorted with fragments displaying low sphericity and ranging from angular to subrounded. Very few well rounded fragments occur, which together with a high lithic fragment component, indicates that the sandstones are submature to immature (Folk 1974).

Lithic fragments are abundant in the lower two units (20-50%), but are less common in the upper sandstone (<20%) which contains a higher proportion of quartz (near 80%, Fig. 2.8). The provenance of these components included granite, hydrothermal veins, pegmatites and metamorphic rocks, as well as volcanic rocks (possibly some KPF) in the source region.

Palaeocurrent indicators

Cross-bedding in the lowermost unit, indicate transport from the west/southwest towards the east/ northeast. This is consistent with the transport direction found in the Moola Bulla Formation in the Halls Creek area (Blake et al. 1999).
2.3.8 SALLY DOWNS SUPERSUITE

The Sally Downs supersuite is extensive in the Central zone of the Halls Creek Orogen (Tyler et al. 1995, Blake et al. 1999) (Figs 2.4, 2.5). SHRIMP U-Pb dates on zircon indicate a range in age from 1835 to 1805 Ma for these granites (Sheppard et al. 1995, 1997a, b, Page et al. 2001). They intrude most of the other units in the Central zone.

**Loadstone Monzogranite**

The Loadstone Monzogranite occurs in the north and west of the study area (Fig. 2.6, 1:50 000 map and 1:25 000 map, backpocket). It forms scattered outcrops, commonly covered in laterite. It has a SHRIMP U-Pb zircon age of 1827 ± 2 Ma (Blake et al. 1999).

North of Gosford, the Loadstone Monzogranite is composed of coarse quartz, feldspar (microcline and plagioclase) and biotite. It intrudes dolerite and muscovite schist and contains large elongate blocks (10 m x 50 m) of these lithologies. Granitic veins (up to 1 m wide) also occur along the bedding of some of the schist blocks. Biotite in the veins is aligned, but elsewhere no foliation is present in the Loadstone Monzogranite in the study area.

Further west, the Loadstone Monzogranite consists of medium to coarse porphyritic and leucocratic monzogranite composed of large feldspar crystals in a groundmass of quartz, feldspar and biotite. It contains xenoliths of high-grade biotite-rich metamorphic rocks. Cross-cutting the granite are later microgranite veins, pegmatite veins and faults, marked by massive quartz or mylonite up to 5 m wide (Chapter 3).
The granite contacts are sharp in the west where the granite intrudes and cross-cuts the KPF. A contact aureole, marked by andalusite, is noticeable up to 50 m from the boundary in the host KPF and further north, fine-grained biotite hornfels outcrop near the contact.

Undifferentiated Sally Downs supersuite
An unnamed Sally Downs supersuite leucogranite occurs south and east of Puseye. Although contacts between the granitoid and the surrounding KPF are not exposed, the metamorphic grade of the latter increases towards the granite. Near the junction of the Tanami Road and the Great Northern Highway (GR 4750 7380), a northeast trending quartz ridge marks a fault, which appears to separate leucogranite in the south from the KPF in the north (Fig. 2.6, maps, backpocket).

The leucogranite is fine-grained with quartz, feldspar and biotite as the main components. A foliation in the leucogranite is thought to relate to the Yampi Orogeny (Blake et al. 1999).

2.4 METALLOGENY

2.4.1 BASE METALS IN THE EAST KIMBERLEY
Abundant small base metal deposits of various origins occur within the Halls Creek Orogen. These are summarised by Saunders (1999) and Hassan (2000) with earlier reviews by Marston (1979) and Fergusson (1999). Most base metal occurrences are concentrated in the Central and Eastern zones. In the Central zone, most are stratabound volcanic- and sediment-hosted deposits within the KPF (Fig. 2.9). A porphyry copper prospect occurs in the Angelo Microgranite (Sewell 1999, Saunders 1999). Nickel-copper occurrences are associated with layered mafic intrusions. In the Eastern zone, most base metal occurrences are in the Biscay Formation. Undifferentiated vein and hydrothermal base metal occurrences (Hassan 2000) are scattered widely across all three zones. The amphibolite-granulite grade Tickalara Metamorphics in the northern portion of the Central zone host these as well as skarn base metal occurrences.

Base metals occur in some of the overlying units of the Kimberley and younger basins. These include copper in sedimentary rocks associated with basalt of the Carson Creek Volcanics and basalt of the Cambrian Antrim Volcanics (Saunders 1999, Hassan 2000). Base metals are mined from Mississippi Valley-type deposits in the carbonate sequence of the Ordovician Lennard Shelf, on the edge of the Canning Basin, to the south.

2.4.2 EXPLORATION HISTORY AND DISCOVERY OF THE KPP
KPP applies to several sub-economic Zn-Cu-Pb occurrences within the KPF in the vicinity of Halls Creek. Most are at Koongie Park, but several significant base metal occurrences lie outside the study area and were not investigated. These are the large deposit at Angelo North, which is in a fault sliver of the KPF, within the Angelo Fault zone (Griffin et al. 1998, Saunders 1999), Golf Course at Halls Creek (Blake et al. 1999, Saunders 1999) and two base metal occurrences on Lamboo Station at Dusty Bore and Emull (Griffin et al. 1998, Saunders 1999).
Figure 2.9  Map of base metal occurrences in the East Kimberley (after Hassan 2000). The white area in the middle of the map represents the Palaeoproterozoic Halls Creek Orogen, which are overlain by younger sedimentary sequences.
The KPP were first discovered by Picklands Mather and Company International and Peko Mines NL in the 1960s. Follow up work by Kennecott Explorations (Australia) Ltd. in the 1970s led to significant intersections of copper, zinc and lead at Sandiego prospect (originally referred to as Gordon Downs Two), Onedin prospect (originally referred to as Gordon Downs One), Hanging Tree prospect (originally referred to as Gordon Downs Three) and Gosford prospect (originally referred to as Gordon Downs Four). Between 1978 and 1979, Newmont Pty. Ltd. drilled known occurrences and magnetic anomalies coincident with electromagnetic potential (EMP) conductors between the main prospects. North Broken Hill Pty. Ltd. and Asarco Australia Ltd. tested the supergene-enriched zone of Sandiego prospect during 1980 and from 1983 to 1988, and established a resource estimate at Sandiego (Table 2.3). Rotary air blast (RAB) and percussion drilling of areas anomalously high in rock base metal geochemistry failed to locate any significant base metal occurrences. Between 1989 and 1994, a joint venture of Billiton Australia (Metal Division of Shell Co. of Australia Ltd.) and Anglo Australian NL continued exploration in the area, discovering the Puseye prospect, coincident with a significant magnetic anomaly, and upgrading the resource at Onedin (Table 2.3). Lachlan Resources NL, in joint venture with Anglo Australian NL, tested magnetic anomalies at Rockhole and continued to re-assess Onedin and Sandiego during the mid 1990s. Limited work has been carried out on the area recently by Homestake Mining Company Australia.

Prominent gossans that define the largest prospects, Mt Angelo North and Sandiego, and the subdued gossan above Onedin, allowed these prospects to be delineated and tested early in the exploration history of the area. Although numerous chemical anomalies have been found, none have proven associations with base metals (Woodhouse 1989, Sewell 1999). The most significant recent discovery at Puseye prospect is coincident with a strong magnetic signature (Sewell 1999).

### 2.4.3 IMPORTANT KOONGIE PARK PROSPECTS

Following is a review of all the main mineral occurrences in the study area including Sandiego, Onedin, Onedin South, Gosford, Rockhole, Puseye and Hanging Tree. Other small prospects, delineated by geochemistry, ground magnetic anomalies and/or limited RAB drilling (Sewell 1999), have not been included in this study. The limited data on each of these prospects precluded them from this discussion.

<table>
<thead>
<tr>
<th>Prospect</th>
<th>Tonnes</th>
<th>Zn %</th>
<th>Cu %</th>
<th>Pb %</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandiego.*</td>
<td>supergene primary</td>
<td>0.33Mt</td>
<td>6.7</td>
<td>0.5</td>
<td>Ag 288g/t.</td>
</tr>
<tr>
<td></td>
<td>primary</td>
<td>4.3Mt</td>
<td>7.9</td>
<td>0.5</td>
<td>Ag 31g/t.</td>
</tr>
<tr>
<td>Onedin.**</td>
<td>1Mt</td>
<td>11</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Puseye.**</td>
<td>0.1Mt</td>
<td>14</td>
<td>0.2</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

*estimate from North Broken Hill Pty. Ltd. and Asarco Australia Ltd. 1983-88
**estimates from Billiton Australia (Metal Division of the Shell Co. Australia Ltd.) (1992-4), in Sewell (1999)
This review of the sulfide zones, alteration assemblages and structure of each prospect, is based on this study, drilling data completed by different companies and published reviews (Marston 1979, Sewell 1999, Saunders 1999, Hassan 2000). The prospects are described in order of decreasing discovered tonnage. Sulfide zones at all of the prospects are stratabound and dominated by sphalerite with galena, chalcopyrite, pyrite, pyrrhotite and magnetite. Sulfide deposits can be massive or form veins and breccias. Gold, copper (chalcocite) and silver are enriched in the upper supergene zones of some of the deposits.

**Sandiego**

Sandiego is the largest prospect in the study area and hosted by the upper KPF. It is marked by a prominent gossan which forms a ridge in the area. Outcrop around the ridge is poor. Although sulfide minerals are scattered throughout the host rocks, drilling indicates three high grade lenses (Doeppel 1990). From west to east, these are the supergene copper-silver-rich lens, west and east zinc lenses (Fig. 2.10). Oxidation and leaching extend to 100–110 m. The zinc lenses plunge steeply to the south to at least 580 m below the surface (Fig. 2.10). The full depth of the east lens has not been tested. The ore lenses may be confined to the cores of isoclinal fold axes and are cut by a series of northwest- and east-striking shear zones (Sewell 1999, Saunders 2000).

Surrounding the sulfide are alteration zones composed of chlorite, actinolite/tremolite, talc, quartz and carbonate.

The footwall to the southernmost sulfide lens is a quartz-bearing volcaniclastic unit. The hanging wall is composed of fine sandstone interbedded with mudstone, minor chert and a quartz-phyric rhyolite. These rocks are intruded by quartz-phyric and feldspar-phyric, syn-volcanic sills.

Further sulfide lenses may occur to the southeast of the main bodies where carbonate outcrops.

**Onedin**

A brief review follows as a detailed study of the altered sequence and base metal sulfide at Onedin is presented in Chapter 7.

Onedin is the second main prospect in the study area. It is found 2 km northeast of Koongie Park Homestead (Fig. 2.6). It is hosted in the Onedin Member with a quartz-bearing mudstone at the base and is overlain and intruded by aphyric spherulitic rhyolite. Late basalt dykes cut the sequence. The prospect is marked by a subdued gossan. Nine drillholes over 500 m intersected sulfide-rich zones up to 300 m below the surface. These are concentrated in a southwest-plunging refolded antiform-synform system southwest of the access track (Fig. 2.11). This cross-section is slightly different from that of Sewell (1999); the differences are discussed in detail in Chapter 7.

Massive sulfide bodies are stratabound, with most hosted by elongate carbonate lenses which appear to thicken in the fold hinges (Fig. 2.11). Sphalerite with lesser chalcopyrite, pyrite, pyrrhotite and galena replace carbonate. Magnetite is present in parts of the massive sulfide. Pyrrhotite, sphalerite and chalcopyrite are also present in the chlorite schist and within sandstone and mudstone. Some sulfide minerals occur in cross-cutting veins associated with quartz and
Figure 2.10 Sandiego: geology, drillhole locations and cross-section. Note that SG, W and E in the geology map refer to supergene, west and east zinc lenses respectively. These have been projected to the surface. Legend applies to Figures 2.10-2.14
carbonate and others are drawn into folds, sulfide remobilisation textures (see section 7.3.3), shears and foliations. Faults striking northeast cut the sulfide zones (Fig. 2.11).

**Onedin South**

Onedin South is 750 m southwest of Onedin. It is hosted by a similar sequence within the Onedin Member, with quartz-bearing mudstone units at the base and spherulitic rhyolite at the top. The sequence is intruded by amygdaloidal rhyolite and basalt dykes. Small pods of gossan mark the prospect at the surface in association with chert, breccia and silicified carbonate. DDH 9 is the only drillhole testing this prospect (Fig. 2.12).

Pyrrhotite and chalcopyrite are the main sulfide minerals intersected by DDH 9. Pyrite, sphalerite and galena are less abundant. These minerals are associated with quartz, carbonate, tremolite and chlorite. Pyrrhotite is abundant in sections dominated by ironstone. Two carbonate lenses were intersected at depth in DDH 9. Scattered sulfide minerals replace carbonate in the lower western carbonate lens, but the overlying eastern lens is barren. Most sulfide minerals occur along bedding planes, in fractures and parallel to foliation in chloritic sandstone and mudstone.

**Gosford**

Gosford lies 2.5 km north of Onedin (Figs 2.6, 2.13). It is hosted by deformed ironstone and mudstone which may be correlative of the Onedin Member. Massive sulfide was intersected in four drillholes. The main sulfide minerals in order of decreasing abundance are pyrrhotite, pyrite, sphalerite, chalcopyrite and minor galena. The footwall is amygdaloidal rhyolite and the hanging wall consists of sandstone, mudstone, chert, minor quartz-bearing mudstone and carbonate intruded by spheroidal rhyodacite. The host unit comprises sandstone, mudstone, ironstone, chert and carbonate. Dolerite and a basalt dyke intrude the succession.

Pyrite and pyrrhotite are disseminated in the chloritic sedimentary host sequence, with pyrrhotite in ironstone. Stringers of pyrrhotite and pyrite are associated with talc and tremolite in chert and carbonate+chlorite units. Cross-cutting quartz+carbonate veins contain trace pyrrhotite and galena. In DDH 12, sulfide minerals are associated with chert breccia.

**Rockhole**

Rockhole is the easternmost prospect in the study area. It is located 3.5 km northeast of Onedin and is hosted by the Onedin Member (Figs 2.6, 2.14). Although no gossan has been found, the prospect is marked by numerous pods of silicified carbonate and is coincident with a prominent bulls-eye-like magnetic anomaly (Appendix 1) and anomalous base metal surface geochemistry. Two drillholes intersected this prospect: RKD 1 and KPD 33.

Below the Onedin Member is a footwall of altered quartz-bearing mudstone units (Fig. 2.14). Overlying the Onedin Member is a sequence of sandstone, mudstone and minor carbonate, intruded by syn-sedimentary quartz-phryic and aphyric rhyolite. These wrap around a northeast-plunging anticline with faulting and shearing on the northern limb. The Onedin Member is composed of thick carbonate and carbonate breccia units, sandstone, and mudstone with thin
Figure 2.11  Map and cross-section of the Onedin Prospect. Legend same as figure 2.10. See chapter 7 for further discussion.
Figure 2.12 Onedin South. Legend as per Figure 2.10. No vertical exaggeration.
Figure 2.13 Gosford map and cross-section. No vertical exaggeration in the section. Legend as per Figure 2.10.
Figure 2.14  Rockhole map and cross-section. For legend see Figure 2.10. No vertical exaggeration in cross-section.
quartz-bearing mudstone units. Pyrite and magnetite replace carbonate and are associated with
talc, chlorite and tremolite. Veins containing pyrite and magnetite are also abundant.

**Puseye**
Puseye was discovered by its prominent bulls-eye-like magnetic anomaly (Appendix 1) caused by a
quartz+magnetite unit at the surface (Sewell & Hungerford 1993). It is 3 km south of Koongie
Park Homestead (Fig 2.6). Percussion holes, drilled in 1992-3, defined zinc with minor copper and
lead lenses beneath the quartz+magnetite unit. The footwall is composed of chlorite-tremolite
schist and the hanging wall is an albitic, aphyric rhyolite (Sewell 1999). The sulfide minerals are in
a quartz+magnetite host. From RAB drilling results, Sewell (1999) suggested that these lithologies
form a south plunging anticline. This structure forms the basis for her resource estimate (Table
2.3).

**Hanging Tree**
Hanging Tree prospect lies in the southwest of the study area (Fig 2.6). It is near the nose of a
north-plunging fold (F_{KP3}). It is marked by a quartz+magnetite unit at the surface, similar to
Puseye. This prospect has been tested by four percussion holes, KPP 56–59, drilled in 1992 by
Billiton (Sewell & Hungerford 1993, Sewell 1999). Disseminated pyrite and pyrrhotite are hosted
in chloritic schists at a depth of 60-80 m below the surface. The footwall is chloritised basalt with a
hanging wall of chlorite schist. Scattered outcrop of albitic aphyric rhyolite occur in the hanging
wall.