CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The Neoproterozoic Zambian Copperbelt (ZCB) and the contiguous Congolese Copperbelt (CCB) form one of the world’s most significantly endowed sediment-hosted metal provinces, the Central African Copperbelt (Fig. 1.1). Hitzman et al. (2005) estimated a global resource of in excess of 120 million metric tons of copper and 10 million metric tons of cobalt. The deposits of the ZCB have been subject to large-scale mining of copper and cobalt for the past 70 years, however evidence of exploitation by indigenous cultures dates back to the Iron Age. To date, in excess of one billion tonnes of ore at ~2.7% Cu has been extracted (McGregor, 1991).

This study deals specifically with the Nkana-Mindola Cu-Co deposit (NKM). The deposit is situated in the south-western part of the ZCB (Figs 1.1b and 1.2) and has an estimated global resource of in excess of ~670 mT @ 2.2% Cu and 0.1% Co (McGregor, 1991), making it one of the larger Cu deposits in the ZCB (Digital Appendix 1). It has a strike length of ~16 km and consists of one main stratabound orebody, which is confined to a common stratigraphic interval. The ores are deformed and occupy the nose and eastern limb of a major northwest-plunging synform, known as the Nkana Syncline (Fig. 1.2). Contiguous, yet uneconomic Cu mineralisation (< 1% Cu) occurs on the south-western limb of the Nkana Syncline.

The intensity of deformation affecting the rocks of the NKM increases progressively from the limbs of the Nkana Syncline towards its core. Due to the moderate (~30°) north-westerly plunge of the Nkana Syncline, the apparent deformation gradient within mining operations (ranging 200 m to 1000 m vertically from surface) increases from north to south (Fig. 1.2). Paralleling this deformation gradient are systematic and interrelated variations in host lithotype, stratal thicknesses (principally in the footwall to ore), metal tenor, sulphide assemblages, and ore texture. Many of these relationships are common to other ZCB deposits and appear, in part at least, to have been inherited from, or linked to, embryonic basin architecture (Selley et al., 2005). Unique to the NKM however, are the significant variations in the intensity of deformation, and resultant structural styles, which occur throughout the deposit. Whereas the northern ores, although rotated about the axis of the Nkana Syncline to dips of ~70°, preserve pre-deformation mesoscale ore textures, the southern ores are largely partitioned into structural sites at both the meso- and macro-scales. The NKM provides an excellent setting within which to examine the relationships between ore formation and extensional basin architecture as seen in other deposits, but also the role of deformation in ore genesis and/or modification of existing mineralisation.
Figure 1.1a. The Zambian Copperbelt region to the north of Lusaka, the capital of Zambia. The Nkana Mindola deposit is located on the outskirts of the city of Kitwe.

Figure 1.1b. The Zambian Copperbelt showing the major towns, mines and roads infrastructure.
1.2 OVERVIEW SEDIMENT-HOSTED COPPER DEPOSITS

Sediment-hosted stratiform copper deposits account for ~20% of world-wide copper production and reserves (Kirkham, 1989; Hitzman et al., 2005). In addition, sediment-hosted copper deposits are one of the largest sources of cobalt in world as well as a major source of silver and minor quantities of gold, platinum group elements and lead. Although common, both globally and throughout geologic history, the vast bulk of the Earth’s resources are shared between two provinces: the Permian Kupferschiefer of Poland, and the Neoproterozoic

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Figure 1.2. The Nkana-Mindola Deposit is situated on the western edge of the City of Kitwe. All economic resources are confined to the north-eastern limb of the Nkana Syncline. The mine has four operating mine shafts which are used to extract ore from depths of 200 m to 1000 m.
### Dominant Host

<table>
<thead>
<tr>
<th>Location</th>
<th>Copper Belt</th>
<th>Southern Zambian Copperbelt</th>
<th>Kenya Copper Belt</th>
<th>Central African Copperbelt</th>
<th>Mount Isa, Australia</th>
</tr>
</thead>
</table>

### Tectonic Setting

- IB: Intracratonic Basin
- G: Geosyncline

### Metamorphism

- ▲: High-grade metamorphism
- △: Lower-grade metamorphism
- □: None

### Average % Cu

<table>
<thead>
<tr>
<th>Location</th>
<th>Copper Belt</th>
<th>Southern Zambian Copperbelt</th>
<th>Kenya Copper Belt</th>
<th>Central African Copperbelt</th>
<th>Mount Isa, Australia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.5</td>
<td>2.8</td>
<td>4.8</td>
<td>4.5</td>
<td>~2.7</td>
</tr>
</tbody>
</table>

### Ore Structure

- D: Disseminated
- P: Panned

### Red Bed Association

- 3: Strong association
- ?: Weak association

### Evaporite Association

- 3: Strong association
- X: Weak association

### δ34S Pattern

- P: Panned
- S: Spread

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Figure 1.3. Location of large tonnage sediment-hosted copper deposits and basic characteristics of sediment-hosted copper deposits (modified from McGowan, 2003). Appendix 1 documents the key characteristics and tonnages of the copper deposits on the Zambian Copperbelt.
Central African Copperbelt (Fig. 1.3).

Sediment-hosted copper deposits are predominantly:

- Restricted to host rocks of Palaeoproterozoic, Neoproterozoic or Permo-Carboniferous age;
- Hosted by sedimentary sequences formed within rift basins which lack evidence of coeval igneous activity however were conducive to the formation of evaporites and redbed clastic rocks;
- Hosted by black shales which are immediately adjacent to clastic sedimentary rocks and the sedimentary rocks contain abundant sulphur in the form of sulphate or biogenically reduced sulphate; and
- Exhibit disseminated copper sulphide zonation, both vertically and laterally throughout the host rock, particularly those argillite hosted deposits (sulphide mineralogy away from basin margins includes – barren - chalcocite – bornite – chalcopyrite – sphalerite, galena – pyrite (Mendelsohn, 1961).

Despite the concentration of ore, several geologic features appear common to some sediment-hosted stratabound copper deposits (Table 1.1). In terms of basin setting, ores typically occur in intracontinental rift, or rifted continental margin environments (Gustafson and Williams, 1981; Lefebvre and Tshiauka, 1986; Jowett, 1989; Lefebvre, 1989). There is a diversity of host lithotypes, however a spatial association of mineralisation with reduction-oxidation (REDOX) boundaries appears ubiquitous (Kirkham, 1989; Hitzman et al., 2005) (Appendix 1). REDOX boundaries generally correspond to lithostratigraphic contacts, host organic-rich black shale or siltstone overlying oxidized redbed (± evaporitic) sandstone being a particularly common litho-/chemo-stratigraphic arrangement (Maiden et al., 1984; Kirkham, 1989; Oszczepalski, 1989; Binda, 1994; Lefebvre and Alldrick, 1996). In some cases, the REDOX boundary corresponds to the fringes of trapped mobile reductant bodies, such as hydrocarbon or sour gas reservoirs (Kirkham, 1989; Hitzman et al., 2005; Selley et al., 2005). Hypogene ore assemblages typically consist of chalcopyrite, chalcocite, bornite and pyrite, with a broader pyritic hangingwall (Hitzman et al., 2005). Metal associations can be varied and include cobalt, zinc, silver, vanadium, nickel and to a lesser extent zinc, gold, the platinum group elements (PGEs), lead and iron (Gustafson and Williams, 1981; Kirkham, 1989; Hitzman et al., 2005).

Although sediment-hosted stratabound copper deposits are one of the world’s largest sources of copper, lead, zinc, and cobalt, they remain poorly understood, and models for their formation are controversial (Table 1.2). Syngeneticists would argue that the copper was derived during sedimentation, and transported directly from hinterland regions as either detritus, organic complexes, or weakly bonded to clay minerals. However, there are problems in both leaching and transporting sufficient metals to form a large deposit under the low temperature and predominantly low salinity conditions in the sub-areal and marine environments.

Alternatively, diageneticists argue that copper mineralisation occurred after sedimentation, during lithification of the sediment to a sedimentary rock. Importantly, it is proposed that mineralisation during diagenesis preceded a significant reduction in host rock permeability through recrystallisation and compaction. In a diagenetic model, both hypersaline ore-fluids and metals are considered to have been derived from basinal sediments, and driven upward and outward through sediment pile and along basin structures. The high salinity and moderate temperatures of the are fluids allow for the transport of enough copper as chloride complexes, under oxidising conditions, to account for known mineralisation in districts such as the Central African Copperbelt and Kupferschiefer.

However, there are problems in applying a diagenetic model to sediment-hosted deposits which lack the oxidising redbed environment required to maintain the metals in solution as chloride complexes at low temperatures. Neither does a diagenetic model account adequately for fluid inclusion temperatures higher than those expected for diagenesis. Similarly, a diagenetic model cannot explain the common presence of copper mineralisation in structures formed during compressional deformation and metamorphism. Epigeneticists have proposed both magmatic and metamorphic origins for the ore-fluids, with mineralisation resulting from the...
Table 1.1. Characteristics and comparison between the different stratabound copper deposits in Zambia, Australia and Poland (modified from Reed, 1996). Zonation refers to away-from-basement highs and up stratigraphy.

<table>
<thead>
<tr>
<th></th>
<th>Zambian Copperbelt</th>
<th>Nifty</th>
<th>Mt Isa</th>
<th>Kupferschiefer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grade and Tonnes</strong></td>
<td>~3000Mt @ 3.5% Cu and 0.1% Co</td>
<td>~90mt@ 3.2% Cu</td>
<td>~150mt@ 5.2% Pb, 6.4% Zn and 128 g/t Ag, 225mt @ 3.3% Cu</td>
<td>~2800m@ 2.5% Cu</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td>Neoproterozoic</td>
<td>Neoproterozoic</td>
<td>Mesoproterozoic</td>
<td>Permian</td>
</tr>
<tr>
<td><strong>Host Rock</strong></td>
<td>Kitwe Formation. Dolomitic and carbonaceous shales. Mindola Formation Quartzites and quartz arenites</td>
<td>Bradhurst Formation – dolomitic and carbonaceous shale</td>
<td>Urquhart Shale Pyritic, dolomitic siltstones and shales</td>
<td>Zechstein Grey Beds Carbonaceous shale, carbonate, sandstone</td>
</tr>
<tr>
<td><strong>Trace metals</strong></td>
<td>Co, Pb, Zn</td>
<td>Co, Ag, Pb, Zn.</td>
<td>Co, Ag</td>
<td>Ag</td>
</tr>
<tr>
<td><strong>Alteration</strong></td>
<td>Ore Shale: alkali feldspar, muscovite, quartz, phlogopite</td>
<td>Silica-dolomite</td>
<td>Silica-dolomite</td>
<td>Hematite</td>
</tr>
<tr>
<td><strong>Association with redbeds</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Basement highs</strong></td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Metamorphism and deformation</strong></td>
<td>Greenschist to amphibolite facies. Strongly folded and faulted.</td>
<td>Greenschist facies. Moderately folded and faulted</td>
<td>Greenschist facies. Strongly folded</td>
<td>Unmetamorphosed, Minor faulting.</td>
</tr>
<tr>
<td><strong>Igneous Associations</strong></td>
<td>Gabbroic intrusions – pre or syn ore?</td>
<td>Post-ore mafic dykes</td>
<td>Sybella Granite, Fiery Creek Volcanics, Carter Bore Rhyolite</td>
<td>Lower Rotliegendes volcanics</td>
</tr>
<tr>
<td><strong>Relative Timing</strong></td>
<td>Controversial. Syngenetic, diagenetic, and later epigenetic remobilization</td>
<td>Controversial. Diagenetic to epigenetic.</td>
<td>Controversial. Copper magmatic. Lead and zinc diagenetic to epigenetic</td>
<td>Diagenetic</td>
</tr>
</tbody>
</table>

cc=chalcocite; bn =bornite; cr=carrollite; py=pyrite; az=azurite; ma=malachite; gn=galena; sl=sphalerite; Cd=cadmium; Pb=lead; Zn=zinc; Ag=silver; Co=cobalt; Cu=copper.

The interaction of copper bearing hypersaline fluids, with sulphidic shales at elevated temperature (Tables 1.2, 1.3). Despite the affinities between many sediment-hosted stratiform deposits, there has been much debate regarding ore genesis, particularly in provinces such as the ZCB, which have a complex inversion history. Both strain and metamorphism in such provinces creates textural and mineralogical relationships which in turn obscure temporal relationships between Cu introduction, alteration history, and various stages of basin evolution (Table 1.2). In addition, the source of metal, the origin and migration of ore fluid and the source of sulphur remain contentious issues in the genesis of ZCB ores. Accordingly, models for ZCB are diverse and have included:

- syngenetic theories involving precipitation of sulphides from Cu-laden river waters (e.g. Garlick, 1961; Mendelsohn, 1961),
- diagenetic theories that involve various mechanisms of passing metalliferous brine through uncompacted
Table 1.2. Summary of the key characteristics of different models for the genesis of sediment-hosted stratabound copper deposits. The three basic models are syngenetic, diagenetic and epigenetic.

<table>
<thead>
<tr>
<th>Syngenetic Model</th>
<th>Diagenetic Model</th>
<th>Syn-Orogenic (epigenetic) Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Input of sediment and dissolved metals, derived from the hinterland and transported in both rivers and ground waters, into marginal marine environments.</td>
<td>• Changes after lithification, but under the same conditions of pressure and temperature. Allows for the disseminated flow of ore fluids through an as-yet unconsolidated sedimentary pile.</td>
<td>• The introduction of saline cupriferous fluids, derived from either the metamorphism of sedimentary and volcanic rocks of basinal origin, or from an igneous intrusion.</td>
</tr>
<tr>
<td>• Precipitation of copper and related sulphides in accordance with the laws of metal solubility. This results in a zoning parallel to palaeo shorelines, with haematite, uranium, tungsten and molybdenum precipitated inshore, within the oxygenated environment, whereas copper, cobalt, lead, zinc, and iron sulphides are deposited with increasing water depth and distance from the shoreline, under reducing conditions.</td>
<td>• The introduction of saline cupriferous fluids, derived from deeper in the sedimentary basin, after sedimentation but prior to lithification of the sedimentary pile.</td>
<td>• The expulsion of these fluids along unconformities, faults, and reactivated extensional structures, away from either the intrusive source or metamorphic front.</td>
</tr>
<tr>
<td>• A zonation to the copper-bearing sulphide mineralogy that reflects the decreasing copper solubility, with an away from shore chalcopyrite-borneite-chalcocite zonation becoming fixed during diagenesis.</td>
<td>• The expulsion of fluids by compaction, both upward and outward, toward the basin margins.</td>
<td>• An increase in salinity to the connate fluids through interaction with evaporitic material within the sedimentary pile.</td>
</tr>
<tr>
<td>• An upwardly grading sulphide zonation within the host horizon, from copper-rich to iron-rich, resulting from the increasing availability of sulphur within an evolving sedimentary environment.</td>
<td>• An increase in salinity to the connate fluids through interaction with evaporitic material within the sedimentary pile.</td>
<td>• Derivation of the metals either from detrital material, or from an igneous melt.</td>
</tr>
<tr>
<td>Evidence:</td>
<td>Evidence:</td>
<td>Evidence:</td>
</tr>
<tr>
<td>• The extreme lateral continuity and finely disseminated nature of the copper mineralisation, and the apparent conformity of the copper mineralisation with bedding.</td>
<td>• A common regional discordance to copper mineralisation relative to the stratigraphy.</td>
<td>• Much of the textural evidence applicable to the diagenetic model is equally applicable to an epigenetic model for copper mineralisation: ego the regional discordance of copper mineralisation to bedding and the post-depositional alteration associated with mineralisation.</td>
</tr>
<tr>
<td>• A copper zonation, demonstrable in both the Kupferschiefer and the Central African Copperbelt, the boundaries of which closely approximates that of the palaeoshoreline.</td>
<td>• The replacement and pseudomorphing of early diagenetic pyrite by copper sulphides</td>
<td>• The introduction of saline cupriferous fluids, derived from either the metamorphism of sedimentary and volcanic rocks of basinal origin, or from an igneous intrusion.</td>
</tr>
<tr>
<td>• The apparent impermeability of the sedimentary rocks to mineralising fluid movement soon after their deposition.</td>
<td>• Haematitic alteration along the fringes of copper mineralised zones, in rocks originally deposited in a reducing environment</td>
<td>• The expulsion of these fluids along unconformities, faults, and reactivated extensional structures, away from either the intrusive source or metamorphic front.</td>
</tr>
<tr>
<td>• Mineralised sedimentary features, including cross-beding planes and mud-cracks.</td>
<td>• An upward zonation within mineralised horizons of copper to pyrite.</td>
<td>• An increase in salinity to the connate fluids through interaction with evaporitic material within the sedimentary pile.</td>
</tr>
<tr>
<td>• Sulphur isotope values that are suggestive of a sulphur source derived from the biogenic reduction of seawater sulphate.</td>
<td>• The common association of mineralisation in a reduced host-rock, above an oxidising terrestrial sedimentary rock sequence, suggesting a process of reduction as the mechanism for ore precipitation.</td>
<td>• Derivation of the metals either from detrital material, or from an igneous melt.</td>
</tr>
<tr>
<td>• A lack of alteration associated with copper mineralisation.</td>
<td>• Multiple stages of minor element concentration are required to produce large enrichments of metals within a consolidating and compacting sedimentary rock sequence.</td>
<td>• Utilisation of a sulphur source, either evaporitic or sulphidic, at the site of deposition.</td>
</tr>
</tbody>
</table>

References - Gray, 1929; Davidson, 1931; Mendelsohn, 1961; Brown, 1971; Gustafson & Williams, 1981; Garlick et al., 1972; Bartholome et al., 1973; Gustafson & Williams, 1981; Haynes, 1986a & b; Reed, 1996; Anderson et al., 2001; Selley et al., 2005; Hitzman et al., 2005.
8

Table 1.3. Copper mineralising systems and their relationship to sediment-hosted stratabound copper deposits

<table>
<thead>
<tr>
<th>Deposit type</th>
<th>Mafic and ultramafic complexes</th>
<th>Porphyry copper</th>
<th>VHMS</th>
<th>Mississippi Valley-type</th>
<th>Stratabound sandstone-hosted</th>
<th>Stratabound shale-hosted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form</td>
<td>Layered igneous intrusion</td>
<td>Alteration halos around hypabyssal epizonal I-type granite plutons.</td>
<td>Massive sulphide, disseminated, and stockwork mineralisation forming lenticular-shaped orebodies.</td>
<td>Stratabound in clean platformal carbonate host-rocks.</td>
<td>Stratabound in terrigenous clastic sedimentary rocks.</td>
<td>Stratabound, sheet-like bodies</td>
</tr>
</tbody>
</table>

| Geologic setting | Rift basins. | Compressive plate margin. | Margin to intracratonic extensional basin. | Margin to intracratonic extensional basin. |

| Formation process | Partial melting and devolatisation of country rocks with derivation of sulphur and carbon resulting in localisation of sulphide melts. | Interaction of meteoric and magmatic fluids with flow and source patterns about a felsic pluton. | Syn-sedimentary exhalative processes involving hot seawater and associated with felsic and mafic volcanism. | Outward and upward expulsion of basal brines during compaction of basal sedimentary sequences. | Controversial Hot saline fluids are driven either by compaction during diagenesis or compression during regional metamorphism. Metal deposition on interaction of the ore fluids with hydrocarbons contained in the sedimentary rocks. | Controversial Hot saline fluids are driven either by compaction during diagenesis or compression during regional metamorphism. Metal deposition occurs on interaction of ore fluids with a reducing, and sulphur-rich, shale host. |


sediiments (e.g. Renfro, 1974; Sweeny and Binda, 1989), and

- a variety of epigenetic models that invoke either late diagenetic basin wide fluid flow (e.g. Annels, 1989; Unrug, 1989; Selley et al., 2005), syn-orogenesis (e.g. Molak, 1995; McGowan et al., 2003), and even magmatic origins (e.g. Bateman et al., 1920; Darnley, 1960).

The NKM deposits provides an opportunity to document of the roles played by the sedimentary environment, diagenesis, and deformation, in the process of copper mineralisation in a sediment-hosted stratabound copper deposit.

1.3 OBJECTIVES

The broad aim of this thesis is to determine the geological controls on Cu-Co mineralisation at the NKM, and to use these relationships to further constrain sediment-hosted Cu ore genesis in the ZCB. Specific objectives include to:

- analyse basin evolution during accumulation of the NKM host succession, at the scale of the deposit and its immediate environment;
- determine whether the present structural configuration of the NKM, including variation in strain intensity, is influenced by, or inherited from, structural geometries and stratigraphic architecture developed at early stages of basin growth; and
- examine the relative roles of lithofacies variation, depositional environment, and structural history (during both basin growth and inversion phases), in determining ore distribution and style.
Figure 1.4. Examples of proposed genetic models for sediment-hosted stratiform copper deposits on the Zambian Copperbelt. a). Zonation patterns of sulphides for a syngenetic copper model as explained by the reflux model from Renfro (1974). b). Interpretative diagram of the 'diagenetic' mineralising process as proposed by Annels (1984). c). Diagram from McGowan et al. (2006) suggesting that the mineralisation at the Nchanga deposit resulted from the generation of hot saline fluids from within the Zambian sedimentary basins. These fluids migrated towards the basin margins during compression and the precipitation of the sulphides resulted from ore fluid interaction with methane. The orebodies were then deformed by ongoing progressive deformation during the Lufilian orogeny.
1.4 METHODS

A range of field based and analytical methods were used in this investigation of the NKM. A total of nine months field work was completed over a three-year period. This work included components of drill core logging and underground mapping. As is the case with many mining operations, a relatively comprehensive drill core dataset is preserved at the level of ore. This dataset provides an excellent basis for examining aspects of sedimentology, structure, and sulphide assemblage at ore levels. By contrast, drill core data from the footwall and hangingwall rocks to the orebodies are much more limited. An extensive review of archived drill cores held both at the Mopani Copper Mines and Zambian Chamber of Mines (Kalulushi) drill core repositories failed to uncover any intact surface drill cores. To partially overcome this problem, considerable effort was directed towards extracting information from the high quality, yet patchy, historical cartographic and drill core log datasets.

Access to all underground areas at the NKM was via four operating shafts, positioned at approximately 3km intervals along the NE limb of the Nkana Syncline (Fig. 1.2). Underground investigations were undertaken at all shafts. The products of this work include profile or plan maps, constructed at scales of 1:100 or 1:250 using survey referenced mine plans or gridded paper as base sheets. Geological units, contacts, ore boundaries, and faults were extrapolated between key cross cuts with varying degrees of confidence. The most informative exposures occur in active mining areas, where walls and backs washing facilities are available. However, time spent in these areas was restricted due to daily mining operations. No surface mapping was undertaken as part of this study as all old pits and costeans are now overgrown and/or within caving areas of the current operations. Sections of the now disused Mindola Pit (Fig. 1.2) were logged as part of facies and structural analyses.

Laboratory-based samples preparation and analysis included:

- polished thin sections for optical mineralogy and microscale structural analysis;
- electron microprobe based mineral chemistry analysis;
- XRF and ICP-MS whole rock geochemical analysis; and
- C- and O-isotope analysis of carbonate phases and S-isotope analysis of anhydrite.

A complete description of each analytical technique is presented in relevant chapters and appendices referenced therein.

Clemmey (1976) summarises aspects of working underground at the Nkana-Mindola deposit:

“Special problems are inherent in any underground study, especially one of a sedimentological nature. The advantages of three dimensional exposure are offset by the selective nature of mine development and drilling; the logistics of gaining access and even moving a few metres underground when this involves changing levels, the ephemeral nature of most exposure, … a hostile working environment caused by a combination of heat, light, and excessive noise; the restrictive access period (blasting) and finally the compulsive tendency that mining engineers have for whitewashing any bare rock!”

All of the local maps and sections in this thesis are referenced to the longitude and latitude (WGS84). For the purpose of this thesis, all orientations are discussed with reference to magnetic north as at June 2005.

1.5 OVERVIEW OF THE STUDY AREA

1.5.1 Location

The NKM deposit is situated on the western fringe of the City of Kitwe (population ~360 000), central-eastern
Zambia, approximately 300 km due north of the capital, Lusaka (Fig. 1.1). The Nkana Mining Area (ML 3/2) is approximately 11 200 hectares and is presently operated by Mopani Copper Mines. The deposit is one of several currently operating Cu-Co mines on the ZCB with other significant mines including the Chambishi, Konkola and Nchanga mines (Fig. 1.2; Digital Appendix 1).

1.5.2 Geography

There are three climatic seasons in central and eastern Zambia. From May to August it is dry, sunny and cool with a hazy atmosphere. Temperatures increase throughout the dry months of September to November, with wet, monsoonal conditions persisting from December to April. On average 1300 mm of rain inundates the region each wet season. The average temperature is about 23°C and maximum daily temperatures rarely exceed 32°C. The climate of this tropical region is tempered by the 1200 to 1600 m altitude associated with the great plateau of east and southern Africa.

The south-eastern portion of the ZCB is characterised by a monotonous featureless landscape, punctuated by the Muva and Mpata Hills located southeast of Kitwe. The originally densely vegetated environment, now virtually destroyed as a result of charcoal burning and slash and burn agricultural practices, is known as Miombo Woodland. River drainages occupy broad gently sloping valleys in which sparse outcrop is located, whereas poorly drained areas form dambos (swampy lowlands). The Kafue River is the major drainage system in the southeast portion of the ZCB. There are also substantial groundwater resources, with particularly rich subterranean aquifers occurring close to the principal ore-bearing horizon. Saprock commonly extends between 2 and 20 m depth, however, the significant groundwater flow around the level of ore has led to depths of sulphide oxidation in excess of 1 km.

From the earliest days of European copper exploration, and even prior to European settlement, geobotanical anomalies, referred to as “copper clearings”, were recognised. These clearings are naturally occurring treeless areas, comprising short grasses and distinctive floral assemblages, which are confined to soils with increased copper concentrations. Approximately 30 species of copper flowers have been identified in the area (Holmes, 2006).

1.5.3 Central African Copperbelt Industrial Development

Copper in this region of central Africa had been mined for centuries prior to the modern exploitation of the resource from the early 20th century. In ancient times copper was used as currency and in the making of ornaments, the latter practice persisting today. Ancient miners exploited only the oxidised upper parts of the sulphide deposits.

The following summary of the modern mineral exploitation in the Central African Copperbelt is sourced from Holmes (2006).

The geographic exploration exploits of David Livingstone between 1852 and 1873 are considered to have heralded European colonisation of central Africa. Soon after, mineral exploration activities were initiated by both British and Belgian consortiums. Starting in 1889, British South African Company (BSAC) concession seekers encouraged Cecil Rhodes to win minerals rights in the Katanga region. However, with the death of Chief Misidi of Katanga at the hand of Belgian colonisers, the majority of the highly prospective region fell under Belgian control. Today this region is known as the Katanga Province of the Democratic Republic of Congo. In 1924 after years of objectionable rule by the BSAC, the British government through the Colonial Office claimed the area as a protectorate where African interests were paramount.

During the time of BSAC control, the first copper occurrences in modern Zambia were brought into
modern production: principally Kansanshi (1906) situated ~100 km west of the classical ZCB, but also other small supergene-enriched deposits located west of Lusaka, and at Bwana Mkubwa, near Ndola. With the aim of fully exploring the region, the Rhodesian Selection Trust and the Rhodesian Anglo American Corporation began activities in the 1920's. This work led to the discovery of the Chambishi, Luanshya, NKM (formerly Rokana), and Chingola deposits within the newly formed Rhodesia Congo Border Concession. Continued development of the ZCB occurred until the next significant political change in 1970, when the mines where nationalised, following dissolution of the Rhodesian Federation in 1963. All Anglo American mines, including NKM, were reorganised into Nchanga Consolidated Copper Mines (NCCM) Limited, whereas the mines owned by the Roan Selection Trust formed the Roan Consolidated Mines (RCM) Limited. In 1982 these two companies were consolidated to form Zambia Consolidated Copper Mines Limited (ZCCM). However during this period and up until 2000 the copper mines suffered from a lack of investment in maintenance, infrastructure and exploration. The most recent and major change to the Zambian copper industry has been the privatisation of the ZCCM operations in 2000. In more recent times exploration success has occurred in the southeast region of the ZCB, with the discovery of the Frontier and the Lonshi deposits (Fig. 1.2), while major mining activities commenced at Kansanshi.

1.5.4 History of NKM

Two accounts exist for the ‘European’ discovery of the NKM. The following section is a summary of (Vitter, 1970 and 1972). An unsubstantiated account reports that Orlando Baragwanath and Frank Lewis were led to the Wusikili discovery outcrop by an African in 1898. However, the most widely accepted version credits the discovery to J.M. Thomas, a north-western Rhodesia government official, who in 1910 was led to a mineralised black shale outcrop near the Wusikili stream. In 1923, the Nkana exploration area was the first locality on the ZCB at which fresh copper sulphides were intersected in drill core. The near full extent of the NKM orebodies was delineated by J.A Bancroft for the Anglo American Corporation using a regional pattern diamond drilling program and extensive pitting. Mining operations have been continuous since 1929, surviving the depression of 1931 and 1932, unlike many other operations.

The only significant extension to Bancroft’s originally defined group of orebodies resulted from underground exploration activities between 2000 and 2002, deep within the core of the Nkana Syncline. The orebody, known as the Nkana Synclinorium Area and intended to be exploited via SOB Shaft (Fig. 1.2), contains inferred reserves of ~95 Mt @ 2.3%Cu and 0.15% Co. A further ~90 Mt at 2.2% Cu and 0.14% Co of undeveloped reserves and resources occurs across the whole deposit. The currently uneconomic west limb of the Nkana Syncline has a resource estimated at 91 Mt @ 1.8% Cu with an average true thickness of 2.3 m (Macfarlane and de Vente, 1990). At present, the total remaining resource is approximately 185 million tons at 2.28% Cu and 0.13% Co. The longevity of the mining operations at the NKM has prevented an accurate determination of the total Cu and Co resource due to the variations in the way records have been archived. The deposit is estimated to have originally contained ~670 Mt @ 2.2% Cu and ~550 Mt @ 0.1% Co (Digital Appendix 1).

Mining operations extend from the original near surface operations to a present depth of approximately 1500 m. All supergene Cu-Co mineralisation was exploited prior to the mid 1980s via two open pits. The operation was privatised during 2000 and 2001 and is presently operated by Mopani Copper Mines, a joint venture between Glencore, First Quantum Minerals and ZCCM (Zambian Government).
1.6 PREVIOUS GEOLOGICAL WORK AT NKM

Considering the size and the longevity of the NKM mining operations, there have been relatively few publications that deal specifically with the deposit (Jordaan, 1961; Richards, 1965; Clemmey, 1974, 1976). The NKM has, however, provided an important source of data for several research programs that have studied the ZCB more regionally (Darnley, 1960; Mendelsohn, 1961; Dechow and Jensen, 1965; Garlick et al., 1972; Annels, 1989; McGowan et al., 2003; Barra et al., 2004; Greyling et al., 2005; Selley et al., 2005). The foci of these studies are diverse and include structural analysis, sedimentology, petrography, geochronology, S isotopes, fluid inclusions and ore genesis in general.

In 1961, a comprehensive geological account was compiled by F. Mendelsohn in 'The Geology of the Northern Rhodesian Copperbelt'. Chapter 10 from this book, “Chambishi-Nkana Basin” by Jordaan (1961), documents the basic sedimentology, structure, ore textures, and sulphide/gangue mineralogy of the Chambishi, Nkana (i.e. NKM) and Chibuluma deposits. Numerous internal company reports, dealing with geological, petrology and metallurgical aspects of NKM, were written by employees of ZCCM between 1970 and the early 1990s, and are today archived at the central office of Mopani Copper Mines in Kitwe, and at the Zambian Chamber of Mines Kalulushi library and core facility. These reports focus on issues arising from mining operations and as such provide vital information on mining areas which are now inaccessible.

Richards (1965) undertook a research project on the South Orebody (i.e. SOB Shaft) as part of a Diploma of Science at Imperial College of Science and Technology. A complete copy of this research was never obtained during the course of this study, however several pieces of the work's geological sections and plans are held by Mopani Copper Mines. The work by Richards (1965) focused on the copper orebody geometry and deformation of the host sequence in the southern area of the NKM deposit. As part of this research project, documentation of the deformation history and relationships to pre-existing basin geometry and effects on orebody geometry is examined.

Clemmey (1974, 1976) completed a detailed stratigraphy and sedimentological study focusing mainly on the northern section of the mining area based around the Mindola Shaft and Mindola Pit. This work included a rigorous study of stratigraphy hosting the Cu mineralisation and devised a regional stratigraphic subdivision which is used in this study. This research project expands on the work by Clemmey (1976) and the extensive work undertaken by Annels (1989) elsewhere in the Chambishi Basin describing the basin evolution of the Katangan Supergroup.

More recently (Greyling et al., 2005) have described fluid inclusions from syn- and post-tectonic veins from the NKM deposit. Barra et al. (2004) presents new geochronological data on the sulphides samples from NKM. Brems et al. (2009) provided a detailed examination of the South Orebody. These recent studies will be discussed and cited when discussing vein and sulphide paragenesis documented as part of this study.

This study formed part of a broader multi-researcher project (AMIRA-ARC Project P544: Proterozoic Sediment-hosted Copper Deposits) that was based largely on the ZCB. The results of the project, which include data and interpretations presented in this thesis, are summarised in Selley et al. (2005). Aspects of the research that involved data collected outside the scope of the NKM study will be introduced in appropriate chapters in the thesis. The reader is also directed to a series of 2001 to 2003 progress reports on the NKM (Digital Appendix 2).
1.7 STRUCTURE AND CONVENTIONS

The thesis has been divided into six remaining chapters:

• Chapter 2 – Regional and District Geology commences with a review of the regional setting of the ZCB. It summaries the stratigraphy and structural history of the belt, and compares these geological aspects with those of other major Neoproterozoic belts of southern Africa. The chapter concludes by introducing the host stratigraphy and deposit scale structure at NKM.

• Chapter 3 – Sedimentology of the Lower Group documents and interprets the sedimentology of the main ore hosting stratigraphic units at NKM. It concludes by discussing basin development, drawing upon studies based elsewhere on the ZCB, and published accounts of modern and ancient analogues world-wide.

• Chapter 4 – Structural evolution of NKM describes the structural history and setting of the NKM deposit. In doing so, it considers inheritance of extensional structural geometries and its control on strain variations developed during basin inversion.

• Chapter 5 – Orebody geometry and sulphide assemblage uses the structural framework introduced in Chapter 4 to examine the macroscopic to mesoscopic distribution of Cu and Co throughout the deposit.

• Chapter 6 – Geochemical and isotopic characterisation of the Copperbelt Orebody Member presents whole rock geochemistry and stable isotope data from the ores and host strata. Whole rock geochemical data is analysed in an attempt to understand geochemical differences between mineralised and unmineralised portions of the stratigraphy. This chapter concludes by investigating the stable isotope results of host carbonates, gangue, vein stages and mineralisation and discusses the context of these results in the context of placing additional constraints on the type of mineralised fluids.

• Chapter 7 – Synthesis concludes the thesis by presenting a genetic model for the formation of the NKM and discusses this deposit model within the broader context of sediment-hosted Cu deposits on the Zambian Copperbelt. Aspects of the genetic model that may be relevant to future exploration are also discussed and recommendations for future research are suggested.

Figure 1.5. Underground at Mindola Shaft and photograph of the headframe at SOB Shaft.