Chapter 7

Discussion

7.1 Introduction

Debate regarding the genesis of sediment-hosted Cu deposits typically involves diagenetic versus syn-tectonic timing for the Cu mineralisation. Most research favours post-depositional and diagenetic origins for the ore fluids and metals (e.g. Gustafson and Williams, 1981; Annels, 1989; Kirkham, 1989; Sweeney et al., 1991; Hitzman et al., 2005; Selley et al., 2005; El Desouky et al., 2009). This study develops the understanding of the copper mineralising events at the NKM deposit. Documenting the relationship between sedimentology, basin architecture sulphide distribution and associated gangue mineralogy is critical to this understanding. These observations are supported by the geochemical and isotopic characteristics of the host sequence and provide information on the basinal and orogenic fluid evolution phases. Furthermore deposit based research must consider the wider basin scale processes. At NKM, the majority of primary host rock textures are extensively modified by a considerable fluid flux during the mineralising and metamorphic events. Consequently the attempt to relate the timing of copper mineralising events to specific periods of basin development and subsequent basin inversion are equivocal.

The documenting of sedimentology, basin inversion features, orebody geometry, sulphide textures and geochemistry highlights the complexity of the NKM deposit and suggest a long-lived mineralising processes. The discussion of copper mineralising events at the NKM includes sources and migration paths for sulphur and metals, mechanisms for the precipitation of sulphides, the influence of basin architecture on fluid flow and the early-diagenetic to late-diagenetic to syn-tectonic timing of the multi-stage mineralising system. These findings improve the broader understanding of sediment-hosted copper systems and potentially aid exploration targeting of Zambian style sediment hosted copper systems.

Given the prolonged and basin-wide scale of the mineralising processes which are required for the accumulation of large amounts of metal-bearing fluid for sediment-hosted copper systems, an attempt has been made to place the NKM system within the presently understood model for diagenetic sediment-hosted copper deposits (as reviewed by Jowett et al., 1987; Kirkham, 1989; Cailteux et al., 2005; Hitzman et al., 2005; and Selley et al., 2005; Dewaele et al., 2006; Summary in Section 1.2). The mineralising processes at play in such a system vary between, and even within basins, however they grossly envisage that the deposits are the products of large basin-scale fluid-flow systems with metal precipitation occurring at key redox boundaries within the basin. The deposits are commonly formed in chemically reduced rocks, adjacent to a more oxidizing sedimentary sequence and the rocks hosting the copper mineralisation contain abundant sulphur in the form of sulphate and/or sulphide (Gustafson and Williams, 1981; Kirkham, 1989). These characteristics are a direct result of a depositional environment which was conducive for the formation of evaporites and redbeds.
This chapter is divided into two sections. The first section discusses the basin architecture, structural setting, orebody geometry, mineral paragenesis constraints and concludes with a geological model for the NKM deposit. The subsections and figures summarise the key aspects of the evolution of the NKM deposit within the context of large scale basinal processes. The second section discusses the significance of this research to exploration for Zambian style sediment hosted Cu deposits and suggests directions for future research at the NKM deposit and the ZCB.

7.2 BASIN TO DEPOSIT SCALE GENETIC MODEL

7.2.2 Sedimentology and Basin Framework Controls on Sulphide Precipitation

Sedimentary Environment and Early Diagenesis processes
Chapter 3 presents a new interpretation for the depositional environment of the Mindola Clastic and Kitwe Formations at NKM. New facies associations, depositional systems and basin evolution models for the Lower Roan Group at NKM are presented. Significantly five key depositional stages are recognised within the Lower Roan Group at NKM. These are:

- MCF - Basal Sandstone Member (BSM) - sub-aerial, alluvial fan and braided fluvial assemblage;
- MCF - Kafue Arenite Member (KAM) - sub-aerial to subaqueous alluvial fan-fan delta to braided deltaic assemblage;
- KF - Copperbelt Orebody Member (COM) and Rokana Evaporite Members (REM) - shale-argillite-sandstone, deltaic-peritidal depositional environment with local evaporitic conditions;
- KF - Nchanga Quartzite Member (NQM) - sandstone-siltstone assemblage; braided deltaic environment; and
- KF - Chambishi Dolomite Member (CDM) and Roan Clastic Member (RCM) - peritidal carbonate-evaporite assemblage with a transition to shallow marine conditions.

Diagenetic and upper greenschist facies metamorphism overprint many of the primary textures in the Lower Roan Group sediments. The formation of sedimentary rocks included processes of compaction, organic transfer and transformation, cementation, pressure solution, fluid expulsion, authigenesis, replacement and recrystallisation. Carbon isotopes from Chambishi Dolomite Member and massive carbonate facies of COM support a marine origin for the massive carbonate facies (Section 6.10).

Early diagenesis resulted in significant fluid expulsion, as evidenced by soft sediment deformation structures within the middle to upper portions of the Kitwe Formation. The precipitation of fine-grained, disseminated framboidal pyrite (recrystallised during metamorphism at NKM) occurred in portions of the basin hosting organic rich sediments, such as those associated with facies association COM 2 and upper portions of the COM. The formation of the pyrite occurred in the 1 to 3m window below the sediment-water interface and was likely to have been facilitated through biogenic anoxygenic photosynthesis, utilising organic matter as a reductant in the conversion of sulphate to sulphide (Bauld, 1981; O’Brien and Slatt, 1999). Synchronous with pyrite precipitation by bacterial sulphate reduction at low temperatures (< 50°C) was the precipitation of evaporite nodules, now pseudomorphed by dolomite/albite, pyrite and chalcopyrite. Sulphur isotope results from anhydrite nodules and cements provide further evidence for the diagenetic precipitation of evaporite minerals (Section 6.11). Similar nodules documented by Annels (1984) and Muchez et al. (2008) were used as evidence to propose that the sulphur was obtained by bacterial sulphate reduction forming after an early dolomitization event.
Pyritization during early diagenesis is commonly considered an important process in early diagenetic metal enrichment in carbonaceous sediments (e.g. Leventhal and Hosterman, 1982). This process in euxinic environments is strongly controlled by the availability of dissolved sulphate, reactive organic matter and reactive iron minerals, with the limiting factor being the amount of iron minerals. V/Cr ratios exceeding ~2 for the carbonaceous argillite rocks at NKM support the sediments being deposited under anoxic/euxinic conditions. In addition Co and Mo are significantly enriched relative to ‘average shale’ abundances. Some degree of metal enrichment of the carbonaceous argillite facies in the COM likely occurred during early diagenesis considering the abundant sources of sulphate and organic matter. Early diagenetic metal enrichment mechanisms have been documented at other sediment-hosted systems such as the Kupferschiefer (Sawlowicz, 2000).

The precipitation of frambooidal pyrite during diagenesis of the Lower Roan Group sediments represents the first mineralising event at NKM. This relationship suggests the age of frambooidal pyrite precipitation should be close to the depositional age of sequence. Although the age of the Lower Roan Group is poorly constrained, it is bracketed between A-type granite intrusions into the basement rocks at 877 ± 11Ma (Armstrong et al., 1999) and an upper constraint is provided by mafic and intermediate lavas and intrusive complexes associated with a relatively short-lived magmatic event dated between ~765 and ~735 Ma (Key et al., 2001; Barron, 2003). The presence of early diagenetic mineralisation in ZCB, is supported by the six-point Re-Os isochron age of 816+62 Ma (Barra et al., 2004) on chalcopyrite and bornite from the Konkola deposit. This is the oldest age recorded for mineralisation on the ZCB.

The depositional environment of the Katangan Supergroup provided vital constraints on the mineralising processes. The deposition of organic matter, particularly for facies of the COM, facilitated the formation of a reducing environment leading to frambooidal pyrite formation. Additionally, the depositional environment potentially provided a supply of a reductant for metal precipitation, sourced from the fluids circulating through the lithified sedimentary package (see below). The precipitation of evaporites at the same stratigraphic level and higher in the Katangan Sequence resulted from a hypersaline marine environment during deposition.

**Basin Framework**

The rocks of the Lower Roan Group at NKM represent only a small percentage of a larger rift system which is preserved to the south and to the north of the NKM deposit. The sedimentology at NKM has provided a number of constraints on the sedimentary package and possible early diagenetic processes. These features have allowed for the development of a basin evolution model for the Lower Roan sequence which was critical to the migration of ore fluids and precipitation of sulphides. Before discussing basin framework and relationships to mineralising events and orebody characteristics, key features identified include:

- The identification of lateral facies, facies thickness and geometry variations of the MCF, suggesting syn-rift deposition of the sequence within small basin compartments which were controlled by a complex, predominately NNW extension fault array with interference from WNW structures at linkage zones;
- The broad scale lateral facies changes of the COM from a dolomite-argillite to carbonaceous-carbonate facies association being coincident with a shift in the geometry of the basement-MCF contact;
- The recognition that the location of laterally discontinuous facies at the base of the COM are coincident with facies variations and/or thickness changes in the MCF;
- Within the MCF, the thickness and lateral distribution of the strata is strongly controlled by compartmentalized syn-rift fault architecture, however these early syn-rift faults do not significantly control the architecture of the KF; and
The onset of sedimentation of the Kitwe Formation at the rift climax phase was accompanied by an amalgamation of smaller syn-rift basins and the deposition of mixed-carbonate platformal sediments during a tectonically stable period (during which regional subsidence generated accommodation space).

The 0.5 % Cu orebody envelope at NKM is grossly stratabound and confined to an interval from the upper portion of the MCF to the lower section of the COM. Changes in the facies at the base of COM are one controlling factor on localisation of the mineralisation, suggesting the need for suitable reductant facies. The economic portions of the orebody are separated by barren gaps. These barrens gaps (carbonate and arenaceous types) at NKM are associated with either thin MCF or strike flexures in the MCF, which have influenced the geometry of subsequent folding (Section 3.8). Importantly the distribution of Cu within the argillite-hosted orebody varies in the vicinity of these structures. Despite these facies being devoid of copper themselves, COM facies adjacent to these zones show the Cu grade broadly decreasing away from these structures and a gross lateral sulphide zonation from bornite-chalcopyrite to chalcopyrite-pyrite is identified in the northern portion of NKM away from each zone (Section 5.5). This suggests that the circulation of ore fluids was in part controlled by syn-rift basin structures and the KF formed effectively formed a seal across the MCF. With the partial partitioning of basinal fluids in Katangan sequence, this allowed for the interaction of high volumes of ore fluids with reductants in the COM. Fluid connectivity was maintained between portions of the sequence by bounding faults active throughout the Katangan depositional history and lateral fluid flow along more permeable horizons. The variable and widespread potassic and sodic alteration throughout the Katangan sequence supports larger scale basinal fluid flow beyond that confined to the MCF. This will be further discussed in the coming sections.

One of the unique aspects of NKM is the presence of a small, arenite-hosted orebody at SOB Shaft (Basal Quartzite Orebody; Section 5.5.5). The schematic reconstruction of the original basin architecture of this now folded orebody has shown it formed within a partly inverted, semi-restricted depositional trough, near the edges of a basement block and, in such a setting is typical of hydrocarbon trap sites. There is insufficient data at NKM to comment on the distribution of sulphide assemblage and geochemical changes within the orebody, however such a stratigraphic and basin trap setting has been well documented at Mwambashi B and Chibuluma deposits (Selley et al., 2003, 2005).

Elsewhere on the ZCB, the sedimentation of the Lower Roan sequence of rocks has previously been proposed within a rift basin model (i.e. Annels, 1989; Hitzman et al., 2005; Selley et al., 2005) and the new results from NKM provide further evidence, and local detail, of an evolving rift system during the deposition of the Lower Roan package of rocks which subsequently influenced the circulation of basinal fluids. Beyond the ZCB, many basins hosting sediment-hosted stratiform copper deposits formed as rifts, characterised by a classical 'steer's head' cross-sectional shape with many deposits forming along the edges of the basins (Watts et al., 1982; Hitzman et al., 2005).

The main Cu sulphide assemblage is bornite, chalcopyrite and pyrite with minor amounts of chalcocite and digenite. Despite recrystallisation and local redistribution, the vertical zonation seen across the deposit, even preserved in high strain domains, from Cu sulphides at the base of the orebody (COM), through to a pyritic hangingwall, to the Cu orebody is evidence of the importance of the REDOX boundary between the MCF and KF and also the presence of in situ reductants in the COM and/or mobile reductants at stratigraphic/structural traps in the upper portion of the MCF. Importantly the precipitation of Cu-sulphides into cleavage and syn-tectonic veins is confined within the overall folded and stratabound Cu orebody geometry. The sulphide assemblage and zonation, the broad scale copper grade distribution and relationship to basin margins at NKM is a typical feature of late diagenetic sediment-hosted copper deposits (Hitzman et al., 2005).
Alteration

As alluded to at the beginning of this chapter, significant volumes of basinal fluids are typically required to form sediment-hosted copper deposits and, as would be expected, these fluids commonly result in significant and widespread alteration of the sedimentary package. The precipitation of different alteration and sulphide phases during diagenesis and metamorphism will be directly influenced by a change of fluid composition during copper precipitation, wallrock interactions and by the redox front provided by the MCF-KF contact resulting from the change in basin architecture.

In summary, a variable potassic-sodic-magnesium-carbonate alteration assemblage has been identified for the upper MCF and lower COM at NKM (Section 3.5 and 6.3). Based on whole geochemical studies of the COM at NKM (Section 6.8), the potassic-sodic alteration event has affected the MCF and COM and Selley et al. (2005) describe the same alteration assemblage affecting the hangingwall rocks at other deposits. This style of potassic alteration is also indicative of near-neutral to slightly acidic fluid pH conditions, with a pH of approximately 5 being optimal for the co-transport of copper, sulphur and iron (Beane, 1974; Rose and Burt, 1979). The alteration assemblage varies at NKM, in part being controlled by the original facies association of the COM. However, facies association COM 4 (massive carbonate-Barren Gaps) still records the precursor Neoproterozoic marine sedimentary signature and only weak evidence of significant alteration exists, based on Sr isotopic results (interpreted to be associated with recrystallisation during metamorphism) (Section 6.11). These results support the previously discussed interpretation, based upon sulphide assemblage and grade distribution, that this particular facies association was dominantly impermeable for much of the basin fluid history. Additionally, despite significant fluid flow during metamorphism, as evidenced by the formation of the altered carbonaceous argillite (Contact Ore Shale) in high strain domains, this metamorphism was largely isochemical.

Importantly, the MCF and COM at NKM exhibit coupled and strongly depleted carbon and oxygen isotopic values compared to the sedimentary carbonates of the barren gaps. The lowest $\delta^{13}C$ value for the host lithotype is recorded in facies association COM 2 (carbonaceous-carbonate argillite) and the overall depletion of $\delta^{13}C$ for the COM is interpreted to be a combination of factors, including low temperature isotope exchange reactions, variation in the fluid source and/or fluid mixing, organic oxidation and, to a lesser degree, local decarbonation reactions during metamorphism. Further evidence supporting the interpretation of organic oxidation is in that facies association COM 2 (carbonaceous-carbonate argillite) has Total Organic Carbon (TOC) values varying between 0.01 to 3.54% and thus would have been a significant source of organic, an ideal reductant for an oxidised ore fluid. The poor relationship between TOC and metal concentration level for Cu and Co at NKM is possibly a function of further organic oxidation during metamorphism and remobilisation, subsequent to the main pre-tectonic mineralising event.

Bedding parallel carbonate veins, formed at the onset of compressional deformation ($D_2$), have depleted $\delta^{13}C$ values compared to the host carbonaceous argillite. All mineralised syn- and post-cleavage vein sets have consistent carbon and oxygen isotopic signatures, similar to the immediate host COM, suggesting that much of the peak-metamorphic fluid forming the veins in high strain domains was of a relatively local origin.

Based on observations and the distribution and variation between facies association COM 1 and COM 2, this would suggest the organic matter is not evenly distributed, however despite this, the C-O isotope values are very similar. The process leading to the development of a relatively even distributed $c_{\text{org}}$ isotopic signature is open to debate whether the process is syn-depositional or resulting from remobilisation and distribution during
The range of new and published sulphur isotopes from NKM, when interpreted within the geological framework of the system presented in this study, suggest the process of bacterial sulphate reduction (BSR) (early diagenesis prior to lithification) and, more significantly, thermochemical sulphate reduction (TSR) of in situ sulphate and possibly sulphate-enriched fluid had a significant control on sulphide precipitation (Section 6.11). For the purpose of proposing a model for the mineralising events for the NKM deposit, it must be recognized that the alteration phases recognized at NKM are part of larger, basin wide alteration events, most likely related mineralisation events (Hitzman et al., 2005; Selley et al., 2005). Richards et al. (1988a, b), Lefebvre (1989) and Selley et al. (2005) interpreted similar hydrothermal alteration assemblages as indicative of K-rich, Mg-rich and Na-rich fluid phases altering the sedimentary package of rocks.

The palaeoenvironment of the Lower Roan Group at NKM has played a significant role in controlling sulphur availability and salinity. Typically in sediment-hosted copper deposits the chemically reduced rocks and oxidized arenites hosting the Cu sulphides may contain abundant sulphur either in the form of sulphide, sulphate or H₂S and such characteristics are a direct result of the depositional environment and subsequent diagenesis.

Source of basinal fluids resulting in widespread alteration
Within a sedimentary basin, different fluid flow systems may operate at different stages during the basin history. Such fluids may include residual basinal brines, brines from evaporite dissolution, aqueous fluids produced during hydrocarbon maturation, evolved seawater brines, gypsum dehydration, smectite-illite transformation and low-grade burial metamorphic dehydration reactions along with liquid hydrocarbons and gases such as CH₄ and CO₂ (Barnes, 1979; Hanor, 1979; Hitzman et al., 2005; Kyser, 2007). Chemically bound water, together with connate water, are potential sources of water for ore fluid. The depth of burial is important as it places constraints on the flow of fluids compared to near-surface hydrothermal regimes (Fyfe et al., 1978; Hanor, 1979). Of particular importance are the high salinity brines, which are commonly thought to originate from seawater brines and/or evaporite dissolution and have the potential to carry elevated concentrations in metals. Evaporitic fluids are important sources for the generation of high salinity Mg-rich brines and oxidized sulphur (in the form of sulphate SO₄^{2-}) (Eugster, 1980).

The formation of sediment-hosted copper deposits requires an enormous amount of fluid especially as often saline brines commonly carry less than ~100 ppm Cu (Haynes, 1987; El Desouky et al., 2009). Ore formation by the process of basinal brine circulation involves the genesis of a moderate temperature saline solutions, commonly deep within the sedimentary basin, and migration throughout reservoirs type rocks, with the change in fluid composition being a result of water-rock interaction (Sverjensky, 1984; Garven and Raffensberger, 1997). The potential significance of evaporites acting as a major source for the basinal fluids on the ZCB has long been suggested (Annels, 1989; Cailteux and Kampunzu, 1995; Jackson et al., 2003; Hitzman et al., 2005; Selley et al., 2005). The presence of evaporitic units higher in the Katangan Sequence (Cailteux et al., 2005) is interpreted to indicate that brines were derived from higher in the stratigraphic section. At NKM, lines of evidence supporting these previous observations include:

- The widespread abundance of Mg- alteration phases (phlogopite);
- Sulphur isotope values of anhydrite compatible with Neoproterozoic seawater;
- Oxidised mineral assemblage (hematite in footwall rocks);
- The recognition of preserved evaporitic textures within the Lower Roan sequence;
- Oxygen isotopes suggesting ore-forming fluids were a combination of seawater, meteoric or evaporitic
sourced connate waters;

- Recognition (from historic mapping) of stratabound evaporitic breccia units within the Upper Roan at NKM; and

- The moderate to high salinity of fluid inclusions from samples taken at NKM (Greyling et al., 2002, 2005).

Another fluid source for the basin could have been from meteoric inflow along basin margins, with these fluids attaining increased salinities through the leaching of the evaporites (Hitzman et al., 2005; Selley et al., 2005). This interpretation is supported by evidence from within the Chambishi Basin, including at NKM, by the presence of breccia units within the Upper Roan and Lower Mwashia Groups. This proposed mobilization of salt, with an approximate interpreted age for the onset of evaporite dissolution of 765 to 740 Ma age (Key et al., 2001; El Desouky et al., 2009), would have significantly influenced the distribution and timing of fluid pathways and the circulation of fluids within the evolving basin. Additional, fluid forming during such an event would most likely be of moderate temperature and moderate to high salinity.

The oxidised and hypersaline nature of the proposed copper mineralizing fluid and its ability to transport metals, by effecting the oxygen fugacity conditions (Sverjensky, 1984), was directly influenced by the dissolution of the evaporite sequence. In addition, this fluid could have also provided an additional source of sulphur for sulphide precipitation along with the \textit{in situ} sulphur in the sedimentary rocks at the site of ore deposition.

Beyond the ZCB, the similarities and long held belief of the genetically similar styles of mineralization between the Kuperferschifer and ZCB supports the interpretation of the significant role of evaporites. The Kuperferschiefer is overlain by the regional extensive Zechstein salt. Warren (1996, 1997, 2000) proposed that the copper concentration in the underlying carbonaceous shale unit to the Zechstein salt resulted from the circulation of brines which allowed the large scale interaction of the fluid with rock (including basement rocks). Similar processes have been documented in the Neoproterozoic rocks of South Australia, in the Dongchuan area of Hunan Province in China (Huichi et al., 1991) and in the Carboniferous rocks of Dzhezkazgan in Kazakhstan (Gablina, 1981).

\textit{Basin Framework control on Fluid Flow}

The regional-scale migration of fluids can be invoked by at least three conceptual models. Garven and Freeze (1984) promote gravity-driven fluid flow involving the continuous supply of meteoric fluid that evolves in composition as it migrates through aquifers. Oliver (1986) documents the compactive expulsion of basal fluids associated with major prograding orogenic fronts, resulting in high temperature fluids from basin sections migrating upward and outward into lower temperature regimes (Fig. 7.1). The third mechanism, invoked by Jowett (1986) and Lydon (1986), involves the convective circulation of basal fluids in a rift environment and with the advective recharge or convective fluid recirculation to reconcile large-scale mass transfer.

At NKM, it is postulated the migration of the fluids was primarily controlled by the permeability of the underlying MCF; the vicinity to the smaller scale syn-rift structure and master fault sets active throughout the deposition of the Katangan strata. The overlying argillite rocks of the KF would have acted as a seal until the onset of deformation and, to lesser extent, during deformation, thus promoting the flow of fluids through the more permeable sandstones and increased volumes of fluids accumulating at the MCF-KF REDOX boundary. In addition, master faults, active during the syn-rift and more importantly during the post-rift phases of basin evolution, would have been key pathways allowing fluids to circulate through permeable horizons at higher levels in the stratigraphy. The presence and significance of larger-scale structures in controlling cross stratal fluid flow connectivity is evidenced by basin wide alteration in many of the basins hosting sediment-hosted copper deposits (e.g. Darnley, 1960; Selley et al., 2005; Hitzman et al., 2005).
At NKM, relay ramp sites (transfer zones) are interpreted to have controlled facies changes at some localities during the syn-rift basinal stage, and resulted in local complex fold interference patterns during basin inversion. These sites have been interpreted in this study by facies associations and/or fold interference patterns occurring to the north of the Ichimpe Barren Gap, immediately to the north and south of Mindola Shaft (arenaceous barren gaps) and at SOB Shaft (1250N-1500N-Sections 3.8 and 4.6). As previously discussed above there is also a recognition of the broad scale changes in copper grade distribution and changes in the basin geometry coincident with these sites (Sections 5.5 and 5.6) suggesting that the network of extensional faults active during the syn-rift phase and the larger master faults active during syn-rift and rift-sag phase did influence fluid flow within the basin.

Published research of modern analogues and of petroleum basins support the interpretation presented by having demonstrated that fluid within siliciclastic packages of rocks are largely confined to major aquifers, cross stratal faults and relay ramp locations, which commonly develop at the intersection of several faults (Hanor and Sassen, 1990; Gawthorpe and Hurst, 1993; Morten et al., 1995; Cathles and Adams, 2005; Hitzman et al., 2005; Kyser, 2007; Peacock and Sanderson, 1994). Fluid circulation in the basin would have also been influenced if the basin was hydrologically open or closed, which relates to the timing and chemistry of ore fluids (Hitzman et al., 2005). At NKM, the KF, and more precisely, the COM, provided a critical seal influencing fluid migration throughout the basin and during basin. Importantly, to form the Cu orebodies, basinal fluids had to be focused into a small area by volume compared to the original volume of the potential source. The formation of regional hydrological seals (carbonates, evaporites, shales) located above permeable clastic sequences of rocks and the development of long-lived periods (>10's m.y.) of basinal fluid flow during a period of tectonic stability is recognised as an important ingredient for sediment-hosted Cu deposits (Bull et al., 2009). Within the ZCB, a closed hydrological system is likely to have existed between the period of sedimentation (~877Ma;
Armstrong et al., 1999), the intrusion of gabbroic bodies (~760 Ma; Key et al., 2001) and even until the onset of the Lufillian orogenesis (~560 Ma; Hanson et al. 1993). However, this cannot be conclusively proven.

At the basin scale, the convection of basal fluids requires a source(s) of energy to drive fluid flow through a sequence of rocks with the appropriate porosity and permeability. Igneous activity and the burial of a sedimentary package may provide heat to initiate brine convection within a basin and, when combined with localized thermal anomalies or variations in the geometries of different sediment packages, this may provide an effective mechanism for fluid flow (Warren, 1998; Hitzman et al., 2005). Within the African Copperbelt, igneous activity is evidenced by the presence of gabbroic intrusions which are interpreted as coincident with continental breakup following deposition of the Roan sequence of rocks (Hitzman et al., 2005; Selley et al., 2005). Hitzman et al. (2005) suggests that the most effective means of salinity-induced enhancement of convection in rift basins results from instances where the evaporitic units have developed above the syn-rift clastic rock packages, as is the case in the Kupferschiefer and the African Copperbelt.

The convection of fluids could have been further enhanced by ice loading, rapid sea-level rises, increased seawater salinity or through changes to thermal conductivity of near-surface process during the Neoproterozoic glaciation period (Hitzman et al., 2005). In the ZCB, basal fluid flow continued through to the onset of the Lufillian orogenesis, at which point the shortening of the sequence resulted in significant fluid flow being facilitated by orogenic structures, such as the reactivation of basin faults, development of folds and the development of regional breccia zones associated with evaporitic strata. As previously discussed there is substantial evidence for syn-tectonic fluid flow at NKM, particularly in the high strain domains and associated with the contact between the MCF-KF as evidenced by the altered basal zone of the COM.

No matter at which large scale fluid migration model is invoked, permeability contrasts of units and beds directly impacted on processes and directions fluid migrate within a basin particularly due to the possible development of secondary porosities and permeabilities (Nelson and Kibler, 2000). The permeability is significantly influenced by basin and sub-basin compartment controls on sedimentary facies architecture, which at NKM is typically variable over relatively short distances (~1 to 3km), compared to regional-scale geodynamic regimes (Section 3.8). In either regime, fluid discharge, and in some cases fluid recharge, will be focused along basinal faults (Deming, 1992), while fluid movement within basin compartments is complex and highly dependent on the nature and connection between the compartments and the nature, longevity and scale of the top seal to the compartments.

Moving beyond the ZCB the influence of basin structures in controlling the distribution of Cu in sediment-hosted systems has been mapped. At the White Pine Cu orebody, syn-sedimentary faults have been documented as providing important fluid conduits for Cu-bearing brines, from the red-bed of the Copper Harbour Conglomerate to enter the reduced shales of the Nonsuch Formation (Mauk et al., 1992). In the Kupferschiefer sediment-hosted copper system, Jowett (1986, 1989) and Oszczepalski (1989) suggested that ore-forming fluids from within the oxidized Rotliegend sandstone were expelled along boundary faults due to sediment loading by the overlying Kupferschiefer shales and Zechstein marine evaporite sequences, shortly after the deposition of the host sediments. In an alternative study, the injection of hot brine from a deep-seated basement fault-fracture system into the sequence has been proposed (Blundell et al., 2003). In both these examples, the importance of basin faults in controlling fluid circulation has been shown.

**Basin inversion and structural implications**

Inversion of the Katangan rift basin occurred during the Lufillian Orogeny and the subsequent fold geometry at NKM was significantly controlled by the pre-existing basin architecture and rheological contrasts in the
sédimentaires du Groupe de Roan inférieur. La déformation a provoqué la pli- tion de la cuvette de déplacement pendant la déformation progressive à l’est de la Roan inférieur entre ~560 et ~540 Ma (Hanson et al., 1983) et importantement a pas conduit au développement d’une surface de décollement large à la base MCF ou MCF-KF.

La intensité de la déformation au NKM est étroitement liée à des variations dans la structure de bassin et le sédimentaire roche s, en particulier en relation avec des contrastes de compétence stratigraphique de niveaux adjacents et aussi dans ceux qui démontrent la contraste ductilité. La reconnaissance que les interférences pliennes sont héritées de la structure syn-rift dans le bassin, basée sur les changements de pente pliettes aux interprétations de points de croisement et de relais de faille, les changements de profils de MCF, les changements coïncident de l’attitude pliétique et les associations facies de la MCF et/ou COM, a aussi influencé le compréhension de la distribution de l’or syn-tectonique et pré-tectonique. Dans les domaines à faible déformation (i.e. Mindola Shaft area), le grade du cuivre et les assemblages de pyrites ont été montrés à diminuer/ changer latéralement éloignés de structures de margin de bassin interprétées. Toutefois dans les zones à haute déformation, l’analyse structurale au NKM a documenté la formation d’anticlinaux cœurs du sédimentaire 3e ordre avec des marges d’origine (i.e. ‘C’ anticlinal Nkana Synclinorium). Par conséquent, la formation d’anticlinaux cœurs dans les marges de bassin est interprétée dans certaines localités à être concurrent avec des zones de grade de cuivre plus élevé précipité avant la pliage progressif. Avec la pliage progressif de la séquence, les remobilisations /syn-tectonique de fluide étaient focalisées vers les zones de pli, plus typiquement anticlinaux, ce qui augmentait le concentration de Cu pyrites dans une zone haute grade existante, comme aussi proposé par Brems et al. (2009).

L’expulsion efficace des fluides d’une séquence sédimentaire en déformation variera en fonction de la perméabilité de la roche à travers laquelle les fluides sont en mouvement. Le flux de fluides pendant la déformation et le métamorphisme peuvent être causés par un certain nombre de mécanismes (Ridley, 1993) incluant :

- Modifications de gradients de température et/ou pression ;
- Expulsion des fluides de la zone poreuse (si la pression interne fluides est moins que la pression lithostatique) ;
- Augmentation du flux de l’eau comme un résultat de changement de volume de roche, favorisant le flux de fluides. Les changements de volume de roche sous la forme de développement de schistosité ou dilatation causé par le glissement de grains de déformation, qui causent une augmentation du flux de l'eau (qui peut promouvoir le flux de fluides et à la fois créer des fluides) ; et
- Augmentation de la pression de fluides résultant de l’expulsion de l’eau des noyaux de roche detriticaux.

La différence rhéologique entre le MCF et KF au NKM est largement fonction de la variabilité dans l’environnement paléoenvironnement, la structure de bassin et la résultant des changements dans le cycle de sédimentation et les facies pendant l’évolution du bassin. Ces différences résultaient dans la partition de la déformation dans les unités plus fines de la KF ou le conglomeratique unit dans le MCF. Au NKM, l’importance de la variabilité dans la composition de la séquence sédimentaire, formation de plis, veines et failles affectait la perméabilité de la roche pendant la déformation. L’évacuation syn-tectonique des fluides se produit par un processus de mouvement le long de la stratification, la schistosité, les veines, associées avec la microfissuration et par intergranulaire flux dans la lithifiée paquet de roches. Sur la taille de la déposition, les variations en pression fluides aussi être affectées par la moyenne stress dans la roche, particulière en provenance de la partition de la déformation.

Typiquement, la courbure d’une séquence de roche doit aussi être accompagnée par une réduction concomitante dans le volume de fluides, largement accompagée par la perte de fluide. Des sites distincts où il y a faible stress ou le contraire, le stress élevé, comme la stratification parallèle slip ou contraste de compétence (i.e. MCF-COM), représentent des changements dans le stress fléau vers les fluides qui vont. Importamment pour les fluides en déformation dans un bassin, une structure
or unit through which fluid is flowing is a zone of lowered fluid pressure and will form an effective channelway depending on the rate of flow (Ridley, 1993). For example, there is greater prevalence of bedding-parallel veins and altered carbonaceous argillite (Contact Ore Shale) at the boundary between the MCF and KF, in part resulting from focused fluid flow along this contact and the COM acting as a stratigraphic seal. An effective structural and/or chemical trap mechanism is still required to result in metal precipitation (i.e. fold hinge and/or REDOX boundary (MCF–KF)).

Until the onset of the Lufilian Orogeny, the KF provided a stratigraphic seal overlying the MCF resulting in the partial partitioning of circulating fluids in the Katangan rocks. Importantly, and as discussed previously, the circulating basinal fluids are likely to have interacted on a semi-continuous basis with the basal portion of the KF, at the REDOX boundary, or within the immediate vicinity of major structures. With the onset of deformation (D$_3$), basin fluids would have been further focused toward the contact between the MCF and KF. With progressive deformation (D$_3$), higher temperature fluids (syn-metamorphic) likewise would have been focused toward the same stratigraphic contact, however the effective seal character of the KF would have been disrupted and considerable fracture induced permeability would have existed. As these syn-tectonic fluids migrated along the MCF–KF contact, the fluids interacted, either via microfractures or cleavage planes, with the pre-existing sulphide assemblage of the COM precipitated prior to deformation. With the formation of D$_3$ veins and the natural buoyancy of the fluids, syn-tectonic fluids laterally migrated toward the antilclinal hinges of D$_3$ folds. High temperature sulphide textures/relationships indicates that syn-tectonic sulphide precipitation coincided with progressive deformation and prograde metamorphism. Sulphides which had precipitated during basinal fluid circulation prior to deformation, were a key source of in situ sulphur for metal precipitation (e.g. Hanor, 1979; Oliver, 1986; Garven and Raffensperger, 1997).

At NKM the facies and basin architecture controlled the type, location and relationship of the sedimentary strata hosting the copper mineralisation. The inheritance of syn-rift basin structure and competency contrast between adjacent sedimentary units significantly influenced the deformation of the orebody, and physiochemical differences between units affected the ability of basinal and syn-tectonic fluids to maintain metals in solutions prior to and during basin inversion. Although the main Cu mineralising events are subsequent to the lithification of the host-rocks, these diagenetic and syn-tectonic mineralising events were significantly influenced by the ground preparation during sedimentation.

Low angle inverted basin structures were documented at the Nehanga deposit as being crucial for the location of significant concentrations of copper and cobalt (Molak, 1995; McGowan et al. 2003). No evidence of large scale thrusting at the same level of the stratigraphy is evident in the NKM area, however, even though the fluid flow model and proposed mechanisms of sulphide precipitation of McGowan et al. (2003) is different to that proposed for NKM, the importance of underlying rift structures in controlling the basinal and syn-tectonic fluid flow is once again highlighted. The thrust and fold model involved the inversion of major granite-bounding structures with the fold geometries being influenced by the competence contrasts between the units, while low-angle structures controlled the flow of syn-tectonic fluids and resulting orebody geometry.

### 7.2.2 Timing of mineralisation

The timing of mineralising events and metal source are among the more contentious issues pertaining to the ZCB. No geochronology was undertaken as part of this study however, based upon textural and orebody geometry relationships, at least two Cu mineralising events have been established. The published age determinations at NKM Cahen et al. (1984) include reported age ranges for U–Pb between 527 Ma (206Pb/238U), 540 Ma (207Pb/235U) and 612 Ma (207Pb/206U). Darnley et al. (1961) dated uraninite from the Mindola section of
the NKM deposit and interpreted the good correlation between the first three ratios and accepted an age of 522 ± 15 Ma. Meneghel (1981) reported 468 ± 15 Ma and 235 ± 30 Ma for uranium mineralisation at Nkana, interpreting these ages as thermal events causing the redistribution of uranium mineralisation (Fig. 7.2; Digital Appendix 12).

Barra et al. (2004) (using the Re-Os method) yielded several ages for the NKM deposit. As part of their study, disseminated chalcopyrite and bornite mineralization, hosted from the dolomitic argillite at SOB Shaft, arenite at Chibuluma West deposit and disseminated carrollite from the Upper orebody at the Nehanga deposit, yielded a seven point Re-Os isochron with a slope age of 576 ± 41 Ma. They interpreted this age to coincide with the onset of basin inversion and Lufilian deformation. In addition to the disseminated ore, one sample of molybdenite from a post S3 chalcopyrite bearing vein, in the same drillhole from the Nkana Synclinorium Area, produced a 525.7 ± 3.4 Ma age. This latter age overlaps with the metamorphic peak (~530 Ma) of the Lufilian Orogeny (John et al., 2004; Rainaud et al., 2005) and is close to U-Pb ages of recrystallised uraninites from both Luiswishi (530±1 Ma; Loris et al., 1997) and Kamoto (520 ± 20 Ma; Cahen et al., 1971). U-Pb monazite ages of 531 ± 12 Ma and 512 ± 17 Ma indicate metamorphic and hydrothermal phases (Rainaud et al., 2002, 2005; John et al., 2004). Within the context of the structural evidence presented in this study, the molybdenite vein age broadly agrees with the cross-cutting relationships documented herein, suggesting post cleavage formation. The range of age dates for mineralisation at NKM and elsewhere on the ZCB is evidence for a prolonged period of semi-continuous mineralisation events from ~815 to 500 Ma.

7.2.3 Fluid Inclusions

The study of fluid inclusions provides important information for the determination of fluid characteristics, temperature, pressure and chemical composition at the time of trapping (Roedder and Bodnar, 1997). Evidence presented in the above discussion suggests the main mineralising event at NKM pre-dated peak deformation (pre-D3), with the subsequent deformation resulting in remobilisation/syn-tectonic mineralising events. A preliminary assessment of samples with fluid inclusions, trapped in quartz, inside early veins, showed extensive evidence of fluid inclusion leakage and no further work was conducted. However, previously published studies from weakly deformed copper deposits on the ZCB do provide useful (though indirect) evidence as to the possible fluid composition infiltrating through the Katangan Sequence prior to and during the Lufilian orogeny (Table 7.1). The results of Primolin (1970), Sweeney (1987), Richards et al. (1988a), Greyling et al. (2005), McGowan et al. (2006) and El Desouky et al. (2009) are relevant to the present study. These studies suggest that basinal fluids were saline with moderate homogenization temperatures and secondary higher temperature and higher salinity fluids were related to orogenesis.

Greyling et al. (2002; 2005) reported results of a diverse suite of fluid types from authigenic quartz overgrowths, pre-tectonic quartz veins and syn-tectonic quartz veins from several deposits including the NKM and Chambishi deposits (situated 10km to the north of NKM). The veins sampled at the Chambishi deposit were bedding parallel veins, the same as vein set I described in this study. Samples from the bedding parallel veins at the Chambishi deposit contained primary and secondary inclusions comprising H2O-NaCl-CO2-CH4, with salinities of approximately ~11 to 23 wt% NaCl and temperature of ~80 to 120°C. Deformation of these veins produced a second generation of inclusions (~16 to 23 wt% NaCl; ~130 to 210°C) (Fig. 7.3). Greyling et al. (2002) documented post-tectonic fluids from K-feldspar-quartz-biotite-anhydrite vein samples collected within the Nkana Synclinorium Area at SOB Shaft which are equivalent to vein sets III and IV defined in this study. These samples have higher salinity (+20 wt % NaCl equiv) and temperature (300 to 400°C) as well as aqueous inclusions containing CH4 (Fig. 7.2). The results of Greyling et al. (2005) support the field observations
Figure 7.2. Summary of geochronological data associated with Cu and U mineralization in the Lufilian Fold Belt (modified from Selley et al., 2005). The direct dating of Nkana-Mindola are circled in red. Dating of disseminated or veinlet-hosted Cu-(Co) sulfides by Re-Os and Pb-isotopic methods yields a broad range of pre-peak-metamorphic ages, from ~ 800 (diagenesis) to ~580 Ma (onset Lufilian inversion and metamorphism). The thermal events on the ZCB include:

- **T1** (765-735 Ma) extension-related magmatism (Key et al., 2001);
- **T2** (614-570 Ma) greenschist facies metamorphism in the Zambian Copperbelt (Rainaud et al., 2002);
- **T3** (577-532 Ma) felsic magmatism in the Katanga High (Hanson et al., 1993);
- **T4** (534-521 Ma) whiteschist facies metamorphism in the central part of the Domes Region (John et al., 2004); and
- **T5** (510-460 Ma) post-collisional uplift and cooling throughout the Domes Region (Cosi et al., 1992; Rainaud et al., 2002; John et al., 2004).
of this study indicating the vein sets are of metamorphic origin.

McGowan et al. (2006) analysed samples from the Nchanga deposit to compare fluid inclusions from quartz veins within inverted D\textsubscript{1} structures (rift basin faults) with those of more sulphide-rich quartz veins and thrust-related quartz veins. Their study concluded that higher temperature fluids are directly associated with fault zones and copper and cobalt were transported in a high-salinity, MgCl\textsubscript{2} - and CaCl\textsubscript{2} -rich brine between temperatures of 220° to 310°C.

Despite no fluid inclusion studies being conducted as part of this study, previously published results from the NKM deposit (as well as from elsewhere on the African Copperbelt) indicate that there are at least two Cu-Co fluid phases: a low to moderate temperature, low to moderate salinity fluid of diagenetic origin (~10 to 20 wt% NaCl equiv.; ~80 to 130°C) and a second moderate to high temperature, high salinity phase (~25 to 40 wt.% NaCl equiv.; ~220 to 330°C) (Fig. 7.3) (Greyling et al., 2005; McGowan et al., 2006; El Desouky et al., 2009). Importantly, the fluid inclusion data would suggest that over time there is an increase in the ore fluid salinity and temperature, reflecting diagenesis, early vein generation and peak metamorphic vein generation. Based on field observations, the NKM orebody geometry and textures presented in this study it is interpreted that the early fluid was directly related to fluid flow through the lithified Katangan sequence during diagenesis, until onset of progressive compressional deformation, and is associated with the main mineralising event. The second phase is interpreted to be related to significant, late evaporite dissolution during the Lufilian Orogeny and higher temperatures resulting from deep basinal circulation and syn-orogenic metamorphism (McGowan

![Figure 7.3. Fluid inclusion compiled for the Zambian Copperbelt (modified from El Desouky et al. 2009). See Table 7.1 for sources of compilation. Overall, the figure indicates the presence of two contrasting fluids, a low to moderate temperature, low salinity fluid, interpreted to be a pre-Lufilian Orogeny basinal fluid circulation through the Katangan Sequence and a second, moderate to high temperature, high salinity fluid interpreted to be associated with a syn-orogenic fluid event. Indirect evidence is used to interpret both phases of fluid being present at NKM.](image-url)
Table 7.1. Compilation of fluid inclusion data for the African Copperbelt from various sources. Table modified from Greyling et al. (2005) and data sourced from Primolin (1970), Sweeney (1987, Richards et al. (1988), Greyling et al. (2005), McGowan et al. (2006) and El Desouky et al. (2009).

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>LITHOLOGY</td>
<td>Kamoto, DRC-Copperbelt</td>
<td>Konkola, Chambishi, Z-Copperbelt</td>
<td>Musoshi, DRC-Copperbelt</td>
<td>Kabwe, Central Zambia (Pb-Zn)</td>
<td>Kansanshi, Solwezi, NW Zambia</td>
<td>Chambishi</td>
<td>Nchanga</td>
<td>Kamoto and Luiswishi</td>
</tr>
<tr>
<td>MINERALS</td>
<td>Mines Group, Roan</td>
<td>L. Roan Group</td>
<td>L. Roan Group</td>
<td>L. Kundelungu Group</td>
<td>?</td>
<td>L. Roan Group</td>
<td>L. Roan Group</td>
<td>Mines Group, Roan</td>
</tr>
<tr>
<td>SETTING</td>
<td>Cherty dolomite</td>
<td>Quartz veins</td>
<td>Quartz-hematite-uraninite veins</td>
<td>Dolomite</td>
<td>Quartz Veins</td>
<td>Quartz-dolomite veins</td>
<td>Quartz-dolomite veins</td>
<td>Quartz, dolomite, quartz veins.</td>
</tr>
<tr>
<td>COMPOSITION</td>
<td>Epigenetic stratiform Cu</td>
<td>Late diagenetic stratiform Cu</td>
<td>Epigenetic U-Pb hydrothermal</td>
<td>Epigenetic Pb-Zn</td>
<td>Epigenetic iron-oxide-Cu-Au</td>
<td>Late diagenetic epigenetic</td>
<td>Late diagenetic epigenetic</td>
<td>Diagenetic, epigenetic</td>
</tr>
<tr>
<td></td>
<td>~40 wt. % NaCl</td>
<td>H₂O, KCl, NaCl</td>
<td>H₂O, KCl-NaCl-CaCl₂(<em>{-})FeCl₃(</em>{-})CO₂(_{-})N₂³</td>
<td>11-31 wt. % NaCl</td>
<td>H₂O, NaCl-CaCl₂(<em>{-})CO₂(</em>{-}) (CH₄)</td>
<td>Phase 1 – 11.3 to 23.1 wt % NaCl</td>
<td>30 to 38 wt % NaCl</td>
<td>Phase 1 11.3 to 20.8 wt % NaCl</td>
</tr>
<tr>
<td></td>
<td>H₂O, KCl-NaCl-CaCl₂(<em>{-})FeCl₃(</em>{-})CO₂(_{-})N₂³</td>
<td>39 wt. % NaCl</td>
<td>15 wt. % KCl</td>
<td>11.3 to 20.8 wt% NaCl</td>
<td>Phase 2 – 18 to 23wt% NaCl</td>
<td>35 to 45.5 wt % NaCl</td>
<td>Phase 2 – 35 to 45.5 wt % NaCl</td>
<td></td>
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<tr>
<td></td>
<td>Phase 1 - 80 to 130</td>
<td>Phase 2 - 300-310</td>
<td>220 to 300 – ore zones; 300-310 within fault zones</td>
<td>220 to 240 – ore zones; 300-310 within fault zones</td>
<td>230-310</td>
<td></td>
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<td></td>
<td>Phase 2 - ~140 to 210</td>
<td>Phase 2 – 270 to 385</td>
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<tr>
<td>P (kbar)</td>
<td>?</td>
<td>?</td>
<td>&lt;1.2</td>
<td>0.09</td>
<td>1.2-2.5</td>
<td>.4 to .8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tn (°C)</td>
<td>?</td>
<td>120</td>
<td>~397, ~275</td>
<td>257-305</td>
<td>230-310</td>
<td>Phase 1 – 115 to 220; Phase 2 – 270 to 385</td>
<td></td>
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</tr>
</tbody>
</table>
et al., 2006; El Desouky et al., 2009). This second event resulted in a remobilisation/mineralising event.

### 7.2.4 Metal Transport and Precipitation Mechanisms

Thermo- and physiochemical characteristics of a hydrothermal fluid control the transport of base metals such as Cu. A change in these conditions is required to metal precipitation. The precipitation of a large percentage of Cu at NKM from basinal fluids in a late-diagenetic model, as is being proposed here to be the most significant mineralisation event, could have resulted from the interaction between the oxidising metalliferous fluids and the argillite rocks either containing carbonate and/or reduced organic matter and biogenically-derived sulphide. The resulting decrease in Eh and an increase in aS\(^2\)\(^-\) (H\(_2\)S) causes changes in metal solubility’s and the loss of copper from the ore solution (Rose, 1976; Gustafson and Williams, 1981; Brown, 1992). The same precipitation mechanism could apply to the higher temperature, syn-tectonic fluids which resulted in a significant remobilisation of the earlier phases of mineralisation.

The precipitation of copper from basinal and syn-tectonic ore fluids may result from a number of mechanisms (Barnes, 1979) including:

- A decrease in temperature;
- An increase in aS\(^2\)\(^-\) (H\(_2\)S) due to sulphate reduction, reaction of fluids with organic material and/or mixing with sulphides or sulphide solutions;
- An increase in pH caused by reaction with carbonate and boiling off acid gases;
- Decreased aCl\(^-\) resulting from dilution by circulating meteoric waters or caused by reactions adding strong Cl\(^-\) ion-pairing cations such as Ca\(^{2+}\); and
- A decrease in the Eh of the metal-bearing fluid.

Given the constraints on the relative timing of the main Cu mineralising events as occurring post-lithification of the sediments, however, prior to peak-deformation, the location of the main orebodies at the MCF-KF REDOX boundary, the presence of *in situ* and postulated mobile sulphur sources, distinct depletion in δ\(^{13}\)C values associated with the COM and an estimated ore fluid temperature of ~140\(^\circ\) to 200\(^\circ\)C, thermochemical sulphate reduction (TSR) is postulated as a key process for the derivation of sulphur within the NKM system (Sections 6.10 and 6.11).

As previous discussed, two *in situ* sources of sulphur within the COM were already present at the onset of moderate temperature basinal fluid flow. Sulphide textures from the low strain domain commonly show chalcopyrite has rimmed early formed pyrite within individual bedding units and is in close association with carbonate phases (Section 5.6). A similar relationship is observed in the high strain domain, however the chalcopyrite is predominately aligned to cleavage and therefore reflects remobilisation/syn-tectonic mineralisation. Such relationships as well as the earlier presented characteristics suggests that the basinal fluids (responsible for the main mineralising event) and syn-tectonic metamorphic fluids permeated through the dolomite-argillite and carbonaceous argillite rocks and, upon interacting with pyrite, *in situ* sulphate phases or pre-existing Cu sulphide phases, as in the case of syn-metamorphic fluids, resulted in an increase in aS\(^2\)- and the precipitation of Cu from solution.

The process of replacement of pyrite by chalcopyrite is a redox reaction involving the oxidation of sulphur in pyrite from S\(^2\)- to S\(^-\) in chalcopyrite (Barnes, 1979). The conversion of sulphur requires the destruction of pyrite and reduced carbon in the sedimentary rock, as is shown in the equation:

\[
4\text{CuCl}_2 + 4\text{FeS}_2 (\text{pyrite}) + \text{C} + 2\text{H}_2\text{O} \rightarrow 4\text{CuFeS}_2 (\text{chalcopyrite}) + 8\text{Cl}^- + 4\text{H}^+ + \text{CO}_2
\]
Such a reaction would involve a volume increase during the replacement process. Another product of the replacement of pyrite by chalcopyrite is the generation of acid (HCl) and excess CO$_2$, although this is likely to have been consumed to carbonate. However, interestingly, the production of carbonate would have also led to the generation of acid according to the reaction:

$$\text{CaCl}^- + \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{CaCO}_3 + 2\text{H}^+ + \text{Cl}^-$$

The above reaction, resulting in carbonate dissolution, could only have been operating on a local scale due to the reducing nature of the host-rocks and there is no evidence to suggest an overall decrease in the pH of the metal-bearing fluid throughout the sedimentary sequence.

The dissolution of evaporites from higher in the stratigraphic package, as proposed by Hitzman et al. (2005) and Selley et al. (2005), was another possible source of sulphur, with sulphur being transported as sulphate in the oxidised hydrothermal fluid. Under certain circumstances such a fluid may have a high metal carrying capacity (Large et al., 1995). Evidence for this hypothesis include the deposit and basin scale K, Mg- and Na- alteration suggesting source from the dissolution of evaporites (Sections 6.3 and 6.7).

There are a considerable variety of potential TSR reactions producing reduced sulphur for metal precipitation. These reactions may occur within any given system and the type of reaction is related to variation in composition and maturity of organic phases, relative proportions of oxygen, H$_2$S, carbonate and alkalinity, to name only a number of the variables (Machel et al. 1995). TSR is thought to be possible from ~140°C for a gas (methane) catalysed TSR and continue up to around 200°C to 300°C (Machel et al. 1995). These reactions produce simple end-member products of bicarbonate, H$_2$S, CO$_2$, heat and bitumens. At NKM, an important TSR reactions is between anhydrite +- pyrite and fluids/gas at moderate temperatures to produce H$_2$S and calcite (Section 6.11). Cooke et al. (2003) demonstrated that for ‘ore-shale’ hosted deposits, such as at NKM, mobile hydrocarbons and organic waters are chemically effective traps when sulphur is either present at the trap site or produced via sulfate reduction.

Once the TSR reactions are underway, there are a numbers of factors which can influence the system and local scale complexities. For example, the generation of methane (as evidence by presence in fluid inclusions by Greyling et al., 2005) would be favoured as temperature increases provided there is a continual supply of hydrothermal fluid and the exothermic nature of the sulphate reduction reaction (Machel et al., 1995). The methane would interact with in situ and dissolved sulphate in hydrothermal fluids, as well as dissolved metals. Importantly, as TSR reactions continue and precipitation of sulphides continue, organics in the system will be consumed. Typically methane dominated TSR occur in the upper portion of a potential reservoir as basinal flow will be focused to the structural traps sites and/or upper portions of a reservoir against a stratigraphic seal. The precipitation of both copper and cobalt within the argillite-hosted orebody at NKM could be explained if H$_2$S (from sulphate reduction) is still present following the precipitation of copper, which would then lead to the subsequent precipitation of cobalt sulphides (Rose, 1989). Such a mechanism is commonly highly variable and this variability could explain, in part, the variable distribution of cobalt in the argillite-hosted orebody at NKM.

Due to the compositional maturity of the organic phases at NKM there is no direct evidence of hydrocarbons at NKM, making it impossible establish conclusively the existence of hydrocarbon accumulations. The arenite-hosted Basal Quartzite Orebody at NKM occurs at a structural site resembling physical hydrocarbon traps for mobile reductants such as hydrocarbons and sour gas vertically escaping from reservoirs at lower
stratigraphic levels. Although detailed information about the Basal Quartzite Orebody is limited, the presence of sericite within the Basal Quartzite Orebody is potentially explained by acid generation during ore-stage oxidation of large volumes of sour gas, as has been proposed by Selley et al. (2005) for the Mwambashi B and Mufulira arenite-hosted Cu deposits.

Postulating the presence of mobile hydrocarbons during the formation of sediment-hosted copper deposits is not new. On the ZCB and DRC Cu-belt, the process involving a hydrocarbon reductant has been suggested for the Mufulira and Nchanga deposits (Annels, 1979; McGowan et al., 2003, 2006; Heijlen et al., 2008; Haest et al., 2009; Selley et al., 2005). Furthermore, beyond the ZCB, Jowett (1992) noted the presence of methane in sandstones adjacent to Cu mineralisation in some of the Kupferschiefer deposits.

Aside from the interpreted transport of metal in a highly oxidised fluid at NKM, many sediment-hosted base-metal deposits are thought to have developed from the co-transport of reduced sulphur and metals in hydrothermal fluids (Lydon, 1986; Ohmoto et al., 1990). Such models commonly result in excess H₂S being present in the environment of sulphide deposition to explain patterns of sulphur isotope fractionation between sulphur sources (Ohmoto et al., 1990). These models envisage that the reduced sulphur is produced from deeper within the basin, from evaporite sequences, and transported as H₂S or HS⁻ to the site of ore deposition. Many of these models are based on assumption of a single ore-fluid, which is thought to be unrealistic at NKM based on the extensive and variable alteration assemblages.

As well as the co-transport of reduced sulphur and metals in an ore fluid, hydrocarbon phases may

Figure 7.4. Interpreted solubility of copper at higher temperatures experienced during orogenesis at NKM. The calculated concentrations of copper in a brine containing 2.4 M NaCl at 250°C and 350°C (CuCl and FeCl⁺ respectively) as a function of pH and oxygen fugacity and circulating through rocks at depths of between about 2 and 3km (modified from Barnes, 1979). High temperature fluids associated with metamorphism have been documented at the NKM deposit (e.g. Greuling et al., 2005) however these higher temperatures are interpreted to post-date the main mineralising event. The higher temperatures did result in the remobilisation of the copper sulphides. Evidence of the aO₂ (Eh) of the higher temperature fluid is also supported by the transformation of pyrite to pyrrhotite during prograde metamorphism. This transformation only occurs at temperatures in excess of 300°C, and in the presence of a carbon reductant, at oxygen activities (log aO₂) of about -30. The pH of the higher temperature fluid is likely to have been rock buffered by the host rocks to weakly acidic at temperatures of ~350°C (Barnes, 1979). Localised temperature gradients changes may have occurred in the high strain domains in close vicinity of basement buttressing blocks. Copper solubility decreases with increasing pH or decreasing Eh and as such are two possible mechanisms for the precipitation of copper at NKM during syn-tectonic mineralising events. However changes in temperature and sulphur availability are thought to be the more significant mechanisms controlling sulphide precipitation associated with the syn-orogenic mineralising event at NKM.
directly have carried the sulphur for metal precipitation. Hydrocarbons with high sulphur content are known in many basinal environments (e.g. Baskin and Peters, 1992). Diagenetic processes may result in reduced sulphur being directly fixed onto kerogens and this chemically bound sulphur then migrates with the hydrocarbons (Orr, 1974). The sulphide precipitation would have resulted by the simple reaction of reduced phases, such as H₂S (sour gas) liberated from hydrocarbons with soluble metals.

The ability of low to moderate temperature (120 to 180°C) brines to transport Cu as chloride complexes at a moderate pH and intermediate redox conditions has been demonstrated by Rose (1976). Within the Katangan Sequence, the MCF (which lies below the NKM mineralised horizon) is the only significant red-bed sequence through which a copper-bearing fluid, as oxidizing as described by Rose (1976), could migrate (i.e. log aO₂ = 0). However, if as proposed earlier, the source of the metals was fluids migrating through and leaching the whole Katangan sequence (sandstones, shales, carbonate) as well as the basement, it is likely that any fluid in contact with the sedimentary rocks was more reduced than that modelled by Rose (1976). Therefore, one of the most efficient mechanisms for the transportation of copper and cobalt in an ore fluid at moderate pH and low to moderate temperatures (~120 to 180°C), is a Cl-rich brine of intermediate redox state (Sverjensky, 1984; Rose, 1989). In this a model, the deposition of the copper occurred by the interaction of the oxidizing metalliferous fluids with shale-siltstone rocks containing abundant carbonate, reduced organic matter, and in situ biogenically-derived sulphide formed during early diagenesis. Under such a scenario, the resulting changes in H₂S and pH would likely cause orders of magnitude decrease in metal solubility resulting in the precipitation of copper.

The transportation of Co in moderate temperature fluid suggests the fluids would have been highly oxidizing and have a lower pH than would be required for the transportation of only a copper rich fluid, as cobalt is soluble as Co²⁺ in most of the transport field, except where pH values of 7.6 or greater exist. (Haynes, 1986b, 1987). For example, for a fluid to transport 1000 ppm Cu and 200 ppm Co, Haynes (1987) indicates the fluid must be more oxidizing, as well as have a lower pH than would be required to transport copper alone at an approximate log fO₂ between 10-55 and between 10-35 bars. The solubility of copper and cobalt are both dependent on oxygen fugacity and, importantly, the oxygen fugacity state of a fluid can be increased by the dissolution of evaporites (Sverjensky, 1984). Strong complexes are formed between Cl⁻ and Cu⁺ (e.g. CuCl₂ and CuCl). These Cl⁻ complexes are stable under intermediate redox conditions and allow fluid concentrations in excess of >100ppm Cu. Crerar and Barnes (1979) and Xiao et al. (1998) documented the solubility's of chalcopyrite and chalcocite at temperatures from 40⁰ to 300⁰C and concluded that at temperatures of 350⁰C, in near-neutral to mildly acid pH conditions, Cu and Fe will dissolve in Cl⁻ rich fluids at concentrations of ~1000ppm (Fig. 7.4). Additionally, Xiao et al. (1998) indicate that only an unusually oxidized fluid can transport Cu at temperatures below 250⁰C because the cooling of a fluid to < 250⁰C will cause metal precipitation.

Without detailed fluid inclusion studies at NKM, it is difficult to comment on the possible effect on the mineralisation process from decreasing the effective salinity of the mineralising fluid, by bonding cations such as Ca²⁺ with Cl⁻, or the dilution of the mineralising fluid(s) by a significantly lower saline fluid phase or CO₂. The documented presence of Ca- and Mg-bearing daughter minerals in fluid inclusions (e.g. Greyling et al., 2005) supports the interpretation for fluid originating from evaporite dissolution. Although the presence of calcium and magnesium will have limited effect on the solubility of metal in the fluid.

The observation of cleavage parallel, coarse-grained Cu and Co sulphide and cross-cutting sulphide veins (formed during deformation and metamorphism) could indicate that an increase in aS²⁻ is responsible, in part, for the precipitation of sulphides in these veins. This is supported by the fact that the sulphide hosting veins are confined within the limits of the stratabound ore envelope (corresponding to the presence of fine-
grained sulphide in the adjacent wall-rock). In addition, the release of sulphur during the thermochemical reduction, replacement of diagenetic sulphate and conversion of pyrite to pyrrhotite, would release $H_2S$, thereby promoting the Cu-sulphide precipitation. The formation of later phases of chalcopyrite (syn-tectonic) may have resulted from the hydrothermal fluid having a component of $H_2S$ and not just using the pre-existing the sulphides as source for sulphur, however this process will result in the dissolution of host rock carbonate which was not observed at NKM.

The association of chalcopyrite with microfractures and rimming carbonaceous clasts in localised breccias (50 cm thick), confined to the high strain domain, suggest that localised reduction of the syn-tectonic metalliferous fluid was a mineralising process. Additionally, the presence of pyrrhotite replacing pyrite within the high strain domain at NKM suggests that the temperature has exceeded $\sim 300^\circ C$ during prograde metamorphism (Hall, 1986) resulting in the remobilisation/syntectonic mineralising event. This process of pyrite to pyrrhotite transformation occurs at temperatures in excess of $300^\circ C$ and at oxygen activities ($\log aO_2$) of about -30, when in the presence of a carbon reductant. This reaction is also likely to release sulphur (Craig et al., 1979). This process was important during the deformation of the NKM orebody, enrichment of ore zones and the accompanying local remobilisation of the main pre-tectonic orebody to structural sites such as fold hinges. Additionally, at these high temperatures, sulphate can be reduced to $H_2S$ through the interaction with $Fe^{2+}$ (Barnes, 1979). However, similarly as described for lower temperature fluids, given the abundance of organic matter at NKM, carbon is likely to have played a role in the high temperature reduction of sulphate. This process can be achieved quite rapidly where both a $H_2S$ catalyst and organic carbon are present (Ohmoto and Rye, 1979). At NKM, $H_2S$ derived from either the reduction of organic sulphur or hydrolysis of diagenetic sulphides could have aided the reduction of sulphate and the formation of sulphur compounds of intermediate valency (e.g. $NaSO_3$), with further reduction achieved by utilising organic carbon. Once $H_2S$ is in the system, sulphate reduction would have been a self-perpetuating process, at least until the sulphate supply became exhausted.

The mechanism(s) outlined above resulting in the transportation and precipitation of the metals from the moderate temperature basinal brines (pre-tectonic) and higher temperature syn-tectonic fluids were likely to have been significantly controlled by the presence of in situ organic component on a local scale depending on the host lithotype (facies associations) of the COM, as well mobile hydrocarbon reductants, if occurring at a stratigraphic/structural trap site (Basal Quartzite Orebody). Such mechanisms are also dependant on temperature and pH, both of which are in some ways problematic particularly for pre-tectonic fluids. The precipitation of disseminated copper from at higher temperatures was facilitated by an increase in $aS^2-$ where fluids were in contact with diagenetic sulphides, or where thermolytic reduction of diagenetic sulphate has occurred.

### 7.2.5 Source of Metals

The NKM deposit contained in excess of $>15Mt$ Cu metal prior to mining, while the ZCB contained in excess of $>190Mt$ of Cu metal. Therefore the discussion of possible sources for the metal is crucial when developing a genetic model for the system. Proposed sources for the metals have included magmatic (e.g. Darnley, 1960), metamorphic (e.g. McNaughton and Whitnall, 1990), rift-induced exhalations (e.g. Annels, 1989), erosion of basement enriched in copper (e.g. Garlick, 1961), leaching of the basement (Sweeney et al., 1986), deep-derived circulating hydrothermal fluids (Raybould, 1978), basin circulating fluids throughout the whole of the Kangan Sequence (Hitzman et al., 2005; Selley et al., 2005) and leaching of the footwall red beds (Hoeve and Quirt, 1989). In addition, the source of cobalt has been singled out for special attention by several authors who have
proposed varying models including leaching of basement (e.g. Sweeney and Binda, 1994), basalinal derived (e.g. Sweeney et al., 1986) and from ore fluids circulating through the mafic volcanics in the Upper Roan (e.g. Annels and Simmonds, 1994). Wakefield (1978), based upon observations at the Samba and Lumwana prospects/deposits, suggested pre-Katangan porphyry copper deposits as potential sources. However, Sillitoe (pers comm., 2002) and Bernau (2007) suggest that the mineralization hosted in the basement rocks at these prospects are very similar to ‘typical’ ZCB style mineralised systems, although have a strong Lufilian age structural control.

Shales normally contain between 0 to 300 ppm Cu, with average copper content in carbonaceous shales between 80 and 100 ppm Cu (Wedepohl, 1970). Although black shales are commonly present in the vicinity of stratabound copper deposits and contain Cu, they are rarely considered as a source of the metals (Haynes, 1987). This is because at temperatures of about 80 to 120°C and in the presence of both reduced carbon and sulphur, shale is more likely to act as a metal sink rather than a metal source (Gustafson and Williams, 1981). At higher temperatures, typically of those experienced at NKM during metamorphism (~350 to 400°C), the extraction of metals from a black shale can result from a weakly acidic fluid formed by the oxidation of a shale precursor (Barrett and Anderson, 1982). However, based on elevated Cu concentration levels (> 500 ppm Cu) throughout economic and uneconomic zones of the COM at NKM and across the Chambishi Basin, there is no supporting evidence for this process occurring on large-scale.

The transformation of smectite to illite is a complex process which may release metals into a basin. There are a number of variables, including original starting composition of the smectite, rates of burial, temperature change and fluid flux in the sedimentary sequence (Lydon, 1986; Primmer and Shaw, 1991). The process of smectite-illite transformation commences at temperatures of 80-100°C and continues up to ~180°C (Colten-Bradley, 1987). Significantly the process of smectite-illite transformations are inhibited in environments with high pore fluid pressure and low rates of fluid throughput (Colten-Bradley, 1987). Therefore, if high pore-fluid pressures are achieved and maintained, a potential source rock for metals can be buried to greater depths and experienced higher temperatures than expected before metal release occurs (Primmer and Shaw, 1991). However, the influx in high salinity fluid (i.e. from the dissolution of evaporites) or dramatic loss of pressure (i.e. overpressured development; early tectonic dislocation) within a sequence may result in the rapid progression of smectite-illite reactions and the release of metals. Typically such a process produces low salinity fluids with low capacity to effectively transport copper, however an increase in the salinity of the fluid (from mixing with highly saline basinal brine) significantly enhances the concentration to ore fluid levels (Lydon, 1986).

Despite no direct evidence pointing to one particular source for the metals, the geological framework and geochemical results presented here (when considered within the framework documented by previous authors such as Annels (1989), Hoeve and Quirt (1989) and Selley et al. (2005)) suggest the most plausible source for the copper is leaching by long-lived, basalinal fluids circulating throughout the whole Katangan sequence (including the basement). Such a model differs from that of many sediment-hosted copper systems in which the copper is most probably only derived from the leaching of early rift-cycle clastic and mafic volcanic beds (Jowett, 1989). Aside from Mg-, K- and Na- alteration throughout the Katangan Sequence (e.g. Selley et al., 2005), numerical modelling of fluid flow based on estimated conditions in the ZCB (Kosi et al., 2003) supports this interpretation. Additional, the relatively thin MCF (red-bed sequence) on the ZCB has been interpreted to be of the incorrect composition and of insufficient volume to be the sole source for the Cu and/or Co metal (Hitzman et al., 2005).

7.2.6 Summary
The disseminated sulphides of the main Cu orebody at NKM are hosted within reducing carbonaceous argillite,
dolomite-argillite and argillite rocks overlying an arenite sequence of rocks. The confinement of the main Cu orebody at NKM to a halo surrounding the MCF-COM contact, the distinct upward vertical zonation of the sulphides (Cu-sulphides to pyritic hangingwall), the lateral zonation of Cu grades away from interpreted syn-rift basin structures, the presence of organic matter and in situ sources of sulphur as well as potentially those associated with ore fluids, is interpreted to indicate that the precipitation of sulphides from the moderate temperature ore fluids was largely controlled by the reduction of oxidized metal-bearing brines by thermochemical processes and temperature decreases in the fluid. Additional, decreasing fluid Eh and changes in pH played a role in the deposition of the copper during the later, high temperature mineralising events (remobilisation) related to peak deformation and metamorphism.

7.3 GENETIC MODEL FOR COPPER MINERALISING EVENTS

The observations and evidence collected during this study of the NKM have resulted in a significant improvement of the geological evolution of the deposit by documenting multistage mineralising events, spanning early diagenesis to peak metamorphic (Section 7.2). These are summarised below (Fig. 7.6):

• Early diagenesis resulted in the precipitation of evaporite minerals and framboidal pyrite within the Copperbelt Orebody Member (first mineralising event).
• The generation of saline basinal fluids, possibly sourced from the dissolution of evaporitic units higher in the Katangan Sequence. These fluids migrated throughout the whole of the lithified Katangan Sequence below the evaporitic units, as well as basement rocks using basin faults to circulate between impermeable and permeable horizons.
• The convection of the fluids through basin aquifers and along syn-rift fault systems was long lasting (in excess of 100 Ma years) prior to the onset of the Lufilian Orogeny (D2 to D4).
• The dissolution of evaporite sequences was the source of Cl, salinity, Mg2+, Ca2+, Na+ and SO42- and logfO2 resulting the basinal fluids being highly saline and oxidised. The diagenetic, moderate temperature (~100 to 180°C) fluids were capable of leaching metals from the country rock (Katangan Supergroup and basement), as well as transporting both copper and cobalt in high enough concentrations to be considered an ore forming fluid.
• The migration of the moderate temperature basinal fluids was confined by key stratigraphic horizons and were focused towards basin structures or the edges of zones of fault cross-over or relay ramp. The fluids migrated to the upper parts of the permeable MCF, with the overlying COM providing the first effective stratigraphic seal in the Katangan sequence; this was only breached by major basin faults and during the later stage of basinal fluid flow (as the scale of the basinal fluid flow increased) (Hitzman et al., 2005) and at the onset of the Lufilian Orogeny.
• The reduction of the ore fluids and the precipitation of copper associated with the main pre-orogenic mineralising event resulted from the interaction with organic and early diagenetic sulphides contained within upper MCF and basal COM. However, arenaceous or massive carbonate facies at the base of the COM did not provide of the required chemical conditions nor stratigraphic/structural traps for sulphide precipitation. The position of the ore varies from upper MCF to lower COM, indicating that local variation in the
mineralogy, available local sulphur sources (anhydrite and early diagenetic pyrite), chemical conditions and permeability of the COM were important factors in controlling sulphide precipitation (second mineralising event).

- The onset of deformation (D₂) resulted in enhanced fluid flow along basin structures and adjacent to contrasting permeable horizons (i.e. MCF-KF contact), as well as the development of bedding parallel veins hosting sulphides, which were subsequently folded and cross-cut by late-stage sulphide bearing vein sets during progressive deformation (D₂-D₄). The circulation of syn-tectonic fluids was enhanced by the development of structural permeability during deformation (continuation of the second mineralising event).

- With the progression of the Lufilian orogeny, higher temperature metamorphic fluids migrating through the Katangan Sequence were expelled. These fluids resulted in the local remobilisation of sulphides precipitated during the main stage of ore precipitation prior to deformation. (final mineralising event). The Nkana-Mindola Deposit has evidence for multi-stage, diagenetic to syn-tectonic, long lived mineralisation events which were each significantly influenced at different stages and in varying ways by the depositional environment, basin structure and the REDOX Mindola Clastic Formation – Kitwe Formation boundary.

7.4 DEPOSIT COMPARISON

Despite not being a focus of this study, it is worth briefly discussing the debate as to the relationship of the NKM deposit to other Cu deposits in the world beyond those of the ZCB. This debate surrounding NKM has arisen primarily due to the intense deformation in portions of the system and the fact that copper sulphides are aligned to cleavage and in syn-tectonic veins within black argillite rock. At a very high level, these characteristics share similarities with the Mt Isa and Nifty Cu deposits. The sole syn-orogenic mineralising event envisaged by Stephens (1999) for the NKM deposit has close affinities to syn-metamorphic mineralizing models proposed for the Nifty Cu deposit in Australia by Anderson (1999) and Anderson et al (2001), and the Mt Isa Cu deposit by Waring et al. (1998a and b) and Valenta (1994). The proposed similarities were based upon the comparison of characteristics of only the high strain structural domain at NKM to these deposits. As documented in this study, the Cu orebody at NKM has been significantly deformed and remobilized in the high strain domain during orogenesis and it is proposed that a syn-tectonic remobilisation/mineralising event did occur. However, the evidence presented for the whole of the NKM disputes a close relationship with the structural-metamorphic Nifty and Mt Isa style of deposits and instead supports a closer affinity with the widely accepted sediment-hosted copper mineralisation style, such as the Kupferschiefer and other well documented deposits on the ZCB, such as Chambishi and Chambishi SE (Annels, 1989; Hitzman et al., 2005; Selley et al., 2005).

Table 7.2 lists a basic summary of the characteristics of ZCB argillite-hosted deposits in comparison to the Mt Isa and Nifty deposits. The Mount Isa and Nifty Cu deposits have several features in common as well as unique characteristics between each deposit. Importantly, the majority of these features are not characteristic of the main mineralising event NKM deposit and include:

- Well defined deposit specific syn-tectonic alteration textures and zonation patterns at Mt Isa Cu and Nifty Cu deposits;
- the timing of the main Cu mineralising event as syn-tectonic;
- the lack of evidence of regional scale alteration associated with basinal ore fluids; and
- Fluid inclusion data for the Mt Isa and Nifty deposits suggest primary ore fluids are high temperature.

A sediment-hosted copper model for the Nifty and Mt Isa deposits is inappropriate as such a model does suggest a diagenetic timing of mineralisation and low to moderate temperatures of formation. Although both deposits do have one similarity to NKM in that early frambooidal pyrite is replaced by later phases of
Fluid flow promoted within permeable horizons in Katangan strata and main basin margin and subsidiary basin faults.
chalcopyrite. The fundamental difference between the NKM deposit and the Nifty and Mt Isa deposits is that main mineralising events at Nifty and Mt Isa were synchronous with peak deformation and are a product of structural controlled, syn-metamorphic fluids. These deposits have closer affinities to the syntectonic Kansanshi Cu deposit on the ZCB (Broughton et al., 2002). Although the NKM deposit has been deformed and subsequent remobilisation/syn-orogenic mineralising events have occurred, the main Cu-Co mineralisation event took place prior to peak deformation from moderate temperature basinal fluids, unlike the main mineralisation events at the Mt Isa and Nifty deposits (which are modeled as being synchronous with peak deformation, as previously stated).

7.5 CONCLUSION

The genesis of large stratiform-stratabound copper deposits remains a controversial subject with the debate largely focused around a diagenetic versus epigenetic timing for mineralisation. Large fluid flux(s) severely modify and often destroy primary textures thus inhibiting a complete understanding of the deposits and relative timing. In this study of the argillite-hosted Nkana-Mindola (NKM) Cu-Co deposit it has been possible to document from deposition to deformation key characteristics of the system and to place the Cu distribution within a stratigraphic and structural framework suggesting long-lived, multi-stage copper mineralising events.

The primary copper and cobalt sulphide mineralisation at the NKM Cu deposit has in excess of ~650 Mt @ 1.8% Cu and 0.1% Co. The deposit is dominantly hosted in the folded Neoproterozoic dolomite-argillite and carbonaceous-carbonate argillite rocks of the Copperbelt Orebody Member, Lower Roan Group. The Lower Roan unconformably overlies basement rock. The maximum depositional age of the Katangan Supergroup is constrained by a 877 ± 11 Ma U-Pb zircon date of the Nchanga Red Granite (Armstrong et al., 1999), while the minimum age is constrained by correlation of the Lower Kundelungu Group with the Sturtian glaciation at ~740 Ma (Key et al., 2001). The regional metamorphic grade is upper greenschist facies and is related to the Lufulian Orogeny.

The host strata of NKM deposit are Neoproterozoic meta-sedimentary rocks of the Lower Roan Group. This ~400 m thick package records the early stages of rift development, and can be broadly subdivided into two mappable units: the basal fluvialite-dominated Mindola Clastic Formation (MCF), and overlying marginal marine-dominated Kitwe Formation (KF). In detail, five depositional stages are defined, constituting packages of member status, which reflect cyclical shoreward facies shifts. These include 1) the Basal Sandstone Member, a sub-aerial, alluvial fan and braided fluvial assemblage, 2) the Kafue Arenite Member, a sub-aerial to subaqueous alluvial fan, fan delta to braided deltaic assemblage, 3) the Copperbelt Orebody and Rokana Evaporite Members, an upward-shoaling marginal marine argillite-sandstone-carbonate package deposited under local evaporitic conditions, the 4) Nchanga Quartzite Member, a sandstone-argillite assemblage deposited in braided deltaic environment; and 5) the upper Chambishi Dolomite Member, a carbonate-evaporite assemblage deposited in a shallow marine to deltaic environment.

The fine-grained siliciclastic-carbonate-bearing KF has, in the main, laterally persistent beds and facies to the kilometre scale. However local facies, if not thickness, variations occur in its basal ore-bearing unit, the Copperbelt Orebody Member (or so called Ore Shale). These facies variations at the level of ore coincide with more pronounced thickness anomalies in footwall MCF strata. Specifically, lateral transitions from richly mineralised argillaceous facies of the Copperbelt Orebody Member to poorly endowed arenaceous or carbonate facies, correspond to abrupt ‘pinch-outs’ of the underlying MCF. The overall change in stratal architecture across the MCF-KF interface records an expansion in depocentre dimension and accommodation development, during the transition from rift initiation to rift climax. Despite not being able to directly reconstruct
Table 7.2. Summary data for copper deposits from the Zambian Copperbelt, Paterson Orogen and the Mount Isa deposit.

<table>
<thead>
<tr>
<th>ZAMBIAN COPPERBELT</th>
<th>PATTERSON OROGENY, WA</th>
<th>MOUNT ISA, QLD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age of Host Rocks</strong></td>
<td>Neoproterozoic</td>
<td>Palaeo-proterozoic</td>
</tr>
<tr>
<td><strong>Deposit Size</strong></td>
<td>Nikana 178.2Mt @ 3.37% Cu (P), 81.7 @ 2.38% Cu (R), 303.3 @ 2.22% Cu (R); Konkola – 53.5M @ 4.06% Cu (P), 51.8M @ 3.62% Cu (R), 421.0Mt @ 3.06% Cu (R) Nchanga – 203Mt @ 5.03% Cu (P), 112.2Mt @ 3.96% Cu (R), 197.0Mt @ 2.22% Cu (R)</td>
<td>Nifty – oxide 12.2Mt @ 2.52% Cu and sulphide 26.3Mt @ 4.6% Cu Telfer Maroochydore – oxide 14Mt @ 1.6% Cu and sulphide 140Mt @ 0.5% Cu</td>
</tr>
<tr>
<td><strong>Basin Architecture</strong></td>
<td>Continental rift</td>
<td>Overall plate convergence but with possible local rift-basin development.</td>
</tr>
<tr>
<td><strong>Host Rock Lithology</strong></td>
<td>Katanga System of pyritic, marine to Cc, bn, cpy, py</td>
<td>Lampl and Throssell Group of the Yeneena Supergroup. Cu mineralisation only in carbonaceous pyritic shales and dolostone of the Broadhurst Fmn.</td>
</tr>
<tr>
<td><strong>Metamorphic Grade</strong></td>
<td>ZCB dominantly greenschist facies – to amphibolite facies</td>
<td>Lampl and Throssell Gp sub-greenschist and Rudall Complex amphibolite retrogressive to greenschist</td>
</tr>
<tr>
<td><strong>Basement</strong></td>
<td>Lufubu system comprising mica schists extensively intruded by granites, clean quartzite of the Muva system and a range of granites</td>
<td>Unknown, possibilities include orthogeness and schists of the Rudall Complex or granite-greenstone and volcanic rocks of Pilbara Supergroup</td>
</tr>
<tr>
<td><strong>Volcanics</strong></td>
<td>Gabbroic intrusions high in sequence.</td>
<td>No volcanic rocks</td>
</tr>
<tr>
<td><strong>Styles of Mineralisation</strong></td>
<td>Sediment hosted strataform Cu – arenite and argillite hosted; Cu Vein (eg Kansanshi) Stratiform U near granite and U vein</td>
<td>Metamorphic Cu – Nifty; Epigenetic Cu – Maroochydore; U unconformity – Kintyre Cu-Au – Telfer; Pb-Zn – Warrabarty, Moses Chair</td>
</tr>
<tr>
<td><strong>Mineralogy</strong></td>
<td>Cb, bn, cpy, py</td>
<td>Oxide – az, ma, Cu Primary – cpy, sp, gn, py</td>
</tr>
<tr>
<td><strong>Alteration features</strong></td>
<td>K, Mg, Ca, and Na – variation depends on location within the basin. Large scale alteration.</td>
<td>Nifty – Zoned quartz-dolomite with highly silicified central core</td>
</tr>
<tr>
<td><strong>Carbon Isotope</strong></td>
<td>Nikana - Ore Shale ~5 to -200‰ Footwall ~5 to -10‰</td>
<td>Host rock +0.4 to +4.9%, Pre-min -7.5 to 3.8%, Syn-min -10.3 to 2.4%, Post-min -9.9 to 6.7%,</td>
</tr>
<tr>
<td><strong>Oxygen Isotope</strong></td>
<td>Nikana - Ore Shale ~10 to 17‰ Footwall ~18 to 25‰</td>
<td>Host rock +18.8 to +21.4%, Pre-min +13.5 to +20.1%, Syn-min +14.3 to +21.5%, Post-min +13.6 to +21.6%,</td>
</tr>
<tr>
<td><strong>Sulphur Isotopes</strong></td>
<td>Nikana~ +2.9 to 11.7%, avg +6.7± 3.4%; (See chapter 6 for details) Konkola -1.0 to +4.0%, avg +1.1%; Cpy -7.0 to +1.2% Chambishi-7.5 to +3.1%, avg -2.3±4.4%</td>
<td>fram py +16 to +27%, cpy +6 to +6%,</td>
</tr>
<tr>
<td><strong>Geochemical associations</strong></td>
<td>Cobalt + Mo, Zn See chapter 6 for details at NKM.</td>
<td>Enriched in Cu, SiO2</td>
</tr>
<tr>
<td><strong>Fluid Inclusion</strong></td>
<td>See Table 7.1</td>
<td></td>
</tr>
<tr>
<td><strong>Deformation</strong></td>
<td>All deposits hosted in synclinal, anticlinal or domal structures</td>
<td>Nifty and Maroochydore hosted in synclinal (thrust?) structures</td>
</tr>
</tbody>
</table>


Abbreviations: avg-average, az-azurite, Ba mica-barium rich white mica, bar-barite, bn-bornite, ca-calcite, e.g.-coarse grained, cym-cymrite, disseminated, dol-dolomite, f.g.-fine grained, Finn, Formation, fram-framboidal, gn-galena, Gp-Group, ma-malachite, min-mineralisation, org-organic matter, po-pyrrhotite, py-pyrite, s-salinity, sp-sphalerite, Temperature of homogenisation, Tr-trapping temperature.
the basin evolution and basin geometry of the Lower Roan Group at Nkana-Mindola, the ability to document small, yet significant pieces of the puzzle demonstrate that the sedimentation of the Lower Roan Group resulted from rift basin evolution and not from passive basin development. The significance of the rift initiation fault array on sediment dispersion during the sedimentation of the MCF is recognised, along with the influence of portions of the rift initiation fault array during the onset of sedimentation of the KF at the rift climax phase. The change in basin configuration between the MCF and the KF influenced subsequent basin inversion, basinal fluid migration and ultimately the distribution of copper sulphide minerals.

Three deformation stages, formed during the ~560Ma to 520Ma Lufilian Orogeny, are recognised from underground mapping, core logging and analysis of pre-existing surface geological map datasets. The northeast-southwest directed compressional deformation, defined here-in as D₂, D₃ and D₄ resulted in sub-regional to regional scale folding of the sedimentary and mafic volcanic rocks of the Katangan Supergroup, forming northwest-southeast trending structural fabric throughout the southeast portion of the Lufilian Fold Belt.

The 2nd order F₃ Nkana Syncline is one of the dominant structures in the southeast corner of the ZCB and the penetrative S₃ cleavage is related to this event. The F₃ folds are open to isoclinal and predominantly plunge northwest, with local plunge reversals. Numerous 3rd and 4th order parasitic folds to the Nkana Syncline are recognised within the NKM deposit. Axial-planes vary from upright to steeply dipping to the northeast or southwest. No large scale decollement was observed nor interpreted from sedimentological and structural data, occurring at the contact between the MCF-KF.

The analysis of the fold patterns and geometries at NKM show that the nucleation sites, wavelengths, and attitudes of macroscopic folds are significantly influenced by the original basin architecture, in particular the position and morphology of MCF depocentres. With progressive amplification and tightening of folds, rheological contrast between the MCF and KF increasingly influenced the mechanics of folding and the style of deformation partitioned along the contact of these two units. While localised veining and more regional decoupling are both characteristic of this stratal interface, there is little evidence of significant displacement. The structural complexity observed at NKM is small scale, related in part to inheritance from the complex syn-rift basin architecture, strain partitioning and rheological differences between key units. The three compressional deformation events (D₂, D₃ and D₄) defined at NKM are related and represent progressive deformation which was significantly controlled by the pre-existing basin architecture and rheological contrasts in the sedimentary rocks of the Lower Roan Group.

Although data at NKM is locally sparse, the analysis of the broad scale fold patterns and geometries at NKM does allow for the conclusion that the location and wavelength of folds appear to be influenced by the original basin architecture and more precisely the syn-rift basin architecture. Evidence for this conclusion includes the primary thickness changes of the MCF about the profiles and coincident changes in the fold attitude with facies changes in COM. Changes in the fold plunges which are commonly coincident with thickness and/or facies changes are possibly associated with original basin simple fault cross-over zones and/or relay ramp zones. Based on this conclusion, the paucity of F₃ folds on the NE limb of the Nkana Syncline may well be indicating a simpler syn-rift basin architecture compared to the syncline keel which could be interpreted as the core of narrow graben system.

Veins stages observed at NKM are divided on the basis of relative timing to D₃ deformation. Pre D₃ veins consist of bedding parallel quartz-carbonate veins (VI) which have a restricted distribution to the base of the COM and are more typical in carbonaceous argillite host rock. Syn D₃ quartz-carbonate-mica-sulphide veins (VII) are S₃ parallel to sub-parallel and are only observed in the high strain structural domain and predominately
confined to the argillaceous units, however are also observed in the MCF. Late stage veining, peak D₃-D₄ deformation cross cut S3 cleavage and are similarity predominately occurring in the argillaceous units. All VII and VIII veins have some proportion of sulphide, however no mineralised veins were observed outside the disseminated copper orebody.

The northern and southern copper orebodies are hosted in the upper portion of the MCF and the lower portion of the COM. The copper sulphide minerals are laterally zoned across the NKM deposit with a bornite-chalcopyrite dominant assemblage in the north and a chalcopyrite-pyrite assemblage in the south. The zonation coincides with a change from the northern dolomite-argillite facies association in the north to the carbonaceous-carbonate facies association in the south. Vertical zonation is variable, however a uniform, stratabound, pyritic hangingwall to the copper orebody occurs across the deposit. High grade Cu intervals correspond to fringes of MCF depocentres and local lateral facies boundaries in the Copperbelt Orebody Member. The relationships suggest that mineralising fluids were directed along the base of the host horizon, through tapering MCF packages. Relatively high permeabilities within the MCF, both primary and reaction-enhanced, coupled with fault- and facies controlled cross-stratal fluid pathways, and partitioning of in situ sulphur sources (anhydrite±pyrite) within the Copperbelt Orebody Member, all contributed to the distribution of primary Cu-Co ore.

The continuous and transgressive character of the orebody across the MCF-COM stratigraphic boundary, the folded orebody geometry and the observed textures suggest that the majority of copper sulphides pre-dated the development of S₃ cleavage and peak metamorphism, while localised sulphide remobilisation occurred during deformation in high strain domains. However, ambiguous textural relationships of the ductile sulphides and recrystallised of gangue mineralogy obscure original diagenetic related timing relationships. Deformation caused remobilisation of sulphides at various scales, predominately resulting in the local remobilisation of sulphides into cleavage and cleavage parallel veins.

Potassic and sodic alteration is recorded mineralogically by authigenic K-feldspar, sericite, albite and metamorphic phlogopite. These phases form part of an alteration assemblage which includes quartz, dolomite/ calcite and varying amounts of tourmaline and rutile. Phlogopite (Mg#>0.7) has consistently high K₂O/Al₂O₃ values (>0.68), a feature interpreted to record metamorphism of argillaceous strata affected by pre-existing potassic alteration. There is broad variation in the intensity of potassic alteration throughout the deposit, with weakly mineralised strata positioned on the SW limb of the Nkana Syncline possessing significantly lower levels of K₂O compared to the NE limb. Carbonaceous-carbonate argillite has TOC values varying between 0.01 to 3.54%. Ag, Bi, Cu, Co and Mo are significantly enriched relative to ‘average shale’ abundances.

Barren gap massive carbonates possess C-O isotopic signatures (δ¹³C values ~+3.2‰, and δ¹⁸O ~+23.4‰) that are largely indicative of precipitation from Neoproterozoic seawater. There is a trend towards depleted δ¹³C and δ¹⁸O values (average values of δ¹³C = -14.5‰ and δ¹⁸O = +13.8‰) in strata closely associated with argillite, indicating additional contribution of organic carbon. All mineralised syn- and post-cleavage vein sets (VII and VIII) have C-O isotopic values that are indistinguishable from their host strata, suggesting that no new reservoirs of carbon or oxygen were introduced during orogenesis. Sulphur isotopes of various anhydrite phases indicate a consistent seawater source for sulphur contained in sulphate phases at least. ⁸⁷Sr/⁸⁶Sr values (0.7183 to 0.7413) of carbonates are more radiogenic compared Neoproterozoic carbonate.

Sedimentology, structural, paragenetic and stable isotopes data suggest that Cu mineralisation at the NKM deposit occurred in a multi-stage basin process, including early diagenesis (framboidal pyrite), late diagenesis (main Cu-Co phase) and syn-orogenic (remobilisation of Cu-Co sulphides). It is proposed that the metals hosted within the Copperbelt Orebody Member are best explained by moderate temperature (~120 to
200°C), oxidized, evaporite derived basinal brines circulating though the lower parts of the Katangan Super-group, with copper precipitation resulting from fluid reaction with organic material hosted within the COM and/or mixing with sulphides or sulphide solutions. The circulation of Mg-, K- and Ca-rich fluids formed large scale basin wide alteration patterns extending beyond the NKM deposit itself. Remobilisation of the pre-tectonic ore and the likely addition of further metals occurred during metamorphism.

The Zambian Copperbelt, though well explored, still holds high potential for additional ‘ore-shale’ hosted Cu orebodies similar to NKM and/or Cu mineralisation hosted at other levels of the Katangan Super-group (e.g. Broughton et al., 2002; Hitzman et al., 2005; Selley et al., 2005). The NKM mineralised system is unique as both ‘ore-shale’ (main Cu orebody) and ‘arenite-hosted’ (Basal Quartzite Orebody) styles of mineralisation are identified at the one deposit, further adding weight to the suggestion that stacked, stratabound Cu mineralisation systems may occur in a productive basins. Importantly this study has contributed understanding by the detailed documentation of a complex sediment-hosted stratabound copper deposit and providing links to the broader, basinwide framework and fluid events. Despite extensive modification during basin inversion, this study has shown that a multiple disciplinary study, using sedimentological, structural and geochemical databases, can unravel some of the key characteristics resulting in the formation of the Nkana-Mindola deposit, a world-class sediment-hosted Cu deposit.

7.6 IMPLICATIONS FOR EXPLORATION

The ZCB is a highly mineralised province and sections of the ZCB have been well explored. However, all exploration has been focused around outcropping copper occurrences. Areas of the ZCB covered by shallow cover have been subject to less intense exploration.

The implications for future exploration on the ZCB based on findings from this study include:

• A well developed understanding of the stratigraphic sequence is required. Changes in thickness and facies should be accurately mapped and then related to the structural geometry of folds and Basement-Lower Roan geometry. Changes in the geometry of folds are directly influenced by the basin architecture and therefore provide a mechanism for targeting potentially inverted ore trap sites. In addition, high strain domains have the potential to host structurally thickened and remobilized copper orebodies within a known mineralised basin.

• Local exploration of the deeper levels of the NKM deposit should consider Cu targets hosted within the lower portion of the Mindola Clastic Formation, particularly in the vicinity of changes in fold geometries, as well as structurally controlled (folded) exploration targets hosted within the COM. For example, to the west of the ‘C’ anticline.

• Exploration should target key stratigraphic boundaries at different levels of the stratigraphic sequence.

• Where available, C-O isotopes will provide a further tool for understanding fluid migration within a host sequence and/or structural trap site.

Broader scale critical factors in the exploration for economically significant sediment-hosted stratiform deposits have been documented by Kirkham (2001) and Hitzman et al. (2005). The most important factors include:

• Multistage or prolonged brine circulation to produce an ore fluid;

• The availability of sufficient reductant and reduced S;
Regional scale alteration of the sedimentary package indicating basinal fluid flow; and
An appropriate structural and stratigraphic architecture to focus the fluid.

7.7 RECOMMENDATIONS FOR FUTURE RESEARCH

The following research suggestions are to be considered for future work at NKM and elsewhere on the African Copperbelt (Zambian Copperbelt and DRC Copperbelt). Some of these suggestions arise from a number of limitations of this study or are potentially complimentary follow-on studies using the proposed geological framework of this study. Suggestions include:

- Dating of hydrothermal alteration minerals associated with mineralisation (phlogopite ± sericite) by Ar-Ar methods at low and high strain deposits. This work should be done in conjunction with the dating of sulphides from weakly deformed deposits along with mineral specific sulphur isotopes;
- The study was limited by the inability to undertake detailed CL imagery and mineral chemistry of carbonates. Such a study, when combined with isotopic information would provide further understanding of the carbonate gangue and vein phases associated with diagenetic and/or metamorphic processes;
- A major limitation of this study was the inability to completely sample the Lower Roan Group at several key localities at NKM. Future studies should undertake geochemical sampling of the MCF and KF at NKM beyond that of just the immediate orebody (COM), to better understand the geochemical alterations patterns surrounding key basin structural zones interpreted to be possible fluid pathways (i.e. sampling of the MCF and KF in the immediate vicinity of barren gaps or anomalously thin sequences of MCF, as well as distal to these zones). Specific studies at NKM or at other deposits should attempt to identify evidence of reaction-enhanced permeability about barren gaps (sandstone and carbonate lithotype);
- Stratigraphic and mineral-specific strontium isotope studies of gangue and vein minerals to further understand the evolution of basinal fluids.
- The understanding of changes in the porosity and permeability of the Lower Roan Group from sedimentation, through late diagenesis to metamorphism is poorly documented and understood and could provide further understanding of alteration distribution;
- Fluid inclusion studies (ideally from weakly deformed deposits) focusing on K-feldspar, quartz and carbonate mineral phases in conjunction with boron isotope analysis of tourmaline could determine the role of marine and non-marine fluids; and
- The significance of cobalt and the reason why cobalt has been found in low concentrations (100-500ppm) in all host rocks is unknown. The use of in situ LA-ICPMS trace element and sulphur isotopes analysis to document the chemistry of the different sulphide phases and in particular develop a better understanding of the paragenesis of cobalt rich and cobalt poor sulphide phases and associated alteration across one or two key sections at NKM, as well as at several other argillite-hosted copper deposits on the Zambian Copperbelt.