Chapter 4

Structural Evolution of the Lower Roan Group at Nkana-Mindola

4.1 Introduction

The Nkana Mindola (NKM) Deposit is located in the southeast corner of the Lufilian Fold Belt (LFB), an overall northwest-southeast trending orogen. The LFB is a Pan-African (Neoproterozoic) fold and thrust belt occurring between the Kalahari and Congo Cratons. Numerous structural studies of the LFB have divided the region into four north verging tectonic domains and these were discussed in detail in Chapter 2.

The Kafue Anticline dominates the regional structure in the central and southern corner of the ZCB (Fig. 4.1). To the east is the Mufulira Syncline while on the western flanks are the Chambishi and Roan-Mulashi Basins (synclines). Within the Chambishi Basin, the metasedimentary rocks of the Katangan Supergroup are enclosed by basement granites, the Lufubu Schists and the Muva metasediments, and intrusive, sill-like gabbroic bodies. The Chambishi Basin is host to 6 significant Cu deposits with the largest being the Nkana-Mindola Mine.

Existing geological maps of the Chambishi Basin were used to define macroscopic structural domains. The south-eastern corner of the basin is dominated by the NW striking Nkana Syncline, while in the northern area of the basin WNW trending folds are common. The fold patterns exhibit evidence of inheritance from pre-existing basement structures, including partitioning of strain, nucleation of folds parallel to inverted rift margins, and deflected orientations of the Lower Roan - Basement contact above inverted growth faults. In the northern and western areas of the basin, the broad WNW striking synclines are separated by fault bounded basement inliers (Selley et al., 2003, 2005).

Relative to other Cu deposits within the Chambishi Basin the NKM deposit is a unique record of deformation and provides an opportunity to locally constrain the deformation history occurring during the Pan-African orogeny at one of the highest grade ZCB copper deposits. In this study particular importance is placed on documenting and understanding the relative changes in the intensity of deformation between different areas of the Nkana Syncline and examining evidence for the existence or not of regional decoupling occurring at the base of the Copperbelt Orebody Member within the context of the previously documented sub-basin configuration and inversion related strain patterns.

Previous work on the Zambian Copperbelt (ZCB) by Mendelsohn (1961), Annels (1984, 1989), McGowan et al. (2003) and more recently as part of the AMIRA P544 project Selley and Bull (2001), Selley (2002), Selley et al. (2003) and Selley et al. (2005) has produced descriptions and interpretations of the main structural features occurring within low to moderate deformation structural domains on the ZCB. Understanding the structural history at NKM is important for a number of reasons:
Figure 4.1. Geological map of the Chambishi Basin with an overlay of the interpreted inherited structures from Selley (2005).
Firstly, previous published literature has suggested that a regional extensive decollement exist between the MCF and KF across Zambia (e.g. Sweeney and Tembo, 1987; Tembo, 1994; McGowan et al., 2003), however not all interpretations support this conclusion (e.g. Annels, 1984; Sweeney and Binda, 1994; Selley et al., 2005). In Chapter 3, the identified sedimentary facies and basin architecture characteristics at NKM also disputed the existence of a major decollement at the level of the KF-MCF. The analyses of structures related to the Lufilian Orogeny in this chapter will present further evidence that mitigates against a major decollement at the base of the Copperbelt Orebody Member, the level of the ore, at the NKM deposit;

Secondly, the understanding of the basin architecture at NKM as describe in Chapter 3 provides a framework for which to interpret the possible influence that these features may have upon the geometry of structures formed during inversion; and

Thirdly and of most significance from an economic and ore genesis point of view is to provide a framework to document the relationship and relative timing of deformation to the Cu-Co orebodies at NKM.

Historically NKM has been classed as a disseminated stratiform copper deposit, with the majority of copper sulphides which form the economic orebody occurring at the base of the COM. However observations have shown copper sulphides are also occurring in veins, as massive blebs and remobilised/recrystallised sulphides suggesting a potential for syn-deformation sulphide association. The characterisation of the vein types at NKM, their paragenetic relationship and timing to structure and mineralisation provides information on the geochemical and physio-chemical conditions at the time of vein formation. Veining may also provide information on interlayer slip processes and metamorphic fluid flow during greenschist facies metamorphism (Ramsay, 1982; Tanner, 1989).

This chapter examines the deformation history of the Nkana-Mindola (NKM) deposit. Emphasis is placed upon the documentation, and causes of, significant variation in the state of strain throughout the deposit. The very high strains that characterise the southern part of the deposit are particularly at odds with most of the spatially related ores of the Chambishi Basin, wherein deformation is weak, or at best moderate in its intensity. By developing the structural framework of NKM, this allows for the identification of relationships between basin structures, inversion related deformation, Cu orebody geometry and the sulphide species distribution to be further explored in Chapter 5.

4.2 DATASETS AND NOMENCLATURE

Structural analysis was based on both new data sourced mainly from the northeast limb of the Nkana Syncline, and compilation of historical underground and surface mapping datasets. The data acquired as part of this study were collected from five key areas of underground and open cut exposure, and drill core from the Nkana Synclinorium Area (NSA) at SOB Shaft (Fig. 4.2). Mapping sites were chosen partly on their accessibility, and principally to provide insight to the variation in strain about the enveloping surface of the Nkana Syncline. Of these sites, the NSA, located within the core of the syncline, provided the most comprehensive and modern datasets. Along the west limb of the Nkana Syncline no field work was possible within this area as part of this project, however an analysis of existing surface mapping and geological logs, within the context observations and interpretations from accessible areas on the NE limb of the syncline, provides insights into the structure of this area.

During the field work for this research, the NSA was the focus of underground exploration allowing access to rehabilitated and new underground workings as well as new drill core. Furthermore, access to most stratigraphic levels from basement to the geological hangingwall of ore (i.e. upper COM), a rare occurrence
Figure 4.2. Location of the areas of where structural traverses were undertaken and the position of the 1:5000 broad structural sections compiled from historic mine data to document the gross geometry of the Nkana Syncline.
at NKM, provided important constraints on the geometry and nature of stratal boundaries, and in turn, macroscale fold geometry. The NSA area examined, including drill core coverage, measures approximately 2.5 km along the axis of the fold by 1 km in width, and extends from ~150 m above the 3360 L to ~250 m below the 3360L (this equates to approximately 800 m to 1300 m below topographic surface). Underground mapping was conducted at 1:500 scale on the 3360L, with broader-scale (1:1000 scale) structural traversing on the 3030 and 3270 levels. A series of interpretative cross sections, oriented normal to the average trend of the Nkana Syncline, were constructed at ~70-80 m spacings (Digital Appendices 3 to 6). The series of new geological cross-sections were primarily constructed over a 6 month period while in Zambia using underground mapping and drill core logging datasets collected during this study, pre-existing geological logs of drillcore and by the photo relogging and physical summary logging of holes. This work was undertaken in collaboration with Mopani Copper Mines geologist Mr Giddy Mwale and included definition of the geometry of the copper orebody in this region. Digital Appendix 3 contains scans of the original draft of these cross sections and maps as submitted to Mopani Copper Mines.

The newly acquired data were integrated with historical surface geological maps to produce 1:5000 scale serial sections through various profiles of the Nkana Syncline in the southern region of the deposit (section traces shown in Fig. 4.2). The surface mapping was conducted between 1940 to 1980 by company geologists in areas that are now caving. Projection of lithological boundaries defined the author’s underground mapping to the surface indicates that the historical mapping was both comprehensive and accurate. Digital Appendices 4 and 5 contains scans of key maps, sections and traverses compiled and modified for use in this study. Portions of the surface geological maps have been reproduced and are referenced where appropriate.

Mesoscopic structural data were analysed stereographically using GEORient (Holcombe, 1999) and DIPS (Roscience). All geometric measurements were made with reference to magnetic north. Drill cores were in each case unoriented, however -angles of planar elements were recorded. The downhole structural analysis of drillhole focused on the identifying stratigraphic contacts, shear and fault zones, bedding (S₀) and cleavage (S₁) angles relative to core axis.

Throughout this chapter, a standard form of annotation (e.g. Hobbs et. al., 1976; Ramsay and Huber, 1983) is used for the structural events and fabrics. Subscript number represents the chronological order of events; hence ‘D₂’ follows ‘D₁’. D₁ is herein defined as the extensional basin-forming event that accommodated deposition of the Katangan Supergroup. A subscript number followed by a letter (e.g. ‘A’ or ‘B’) defines a stage within the event (e.g. D₂₃ is distinct but related later stage of D₁₃). Present-day geographical coordinates are used when discussing the principal orientations of stress and strain.

4.3 PREVIOUS WORK

Regional studies documenting the structural history of the Chambishi Basin and further afield within the ZCB were reviewed in Chapter 2 (e.g. Davidson, 1931 [Chambishi]; de Swardt, 1964; Voet and Freeman, 1972 [Chingola]; Whyte and Green, 1974 [Chibuluma]; Daly et al., 1984; McGowan, 2003 [Nchanga]; and Selley et al., 2005). Here a summary of previous work specific to the NKM deposit is given.

The broad geometry of the main fold structures at the NKM deposit has been well documented since the early 1940’s in the form of company maps, reports, and physical 3D orebody model. However, to the best of the author’s knowledge, no comprehensive structural study has been undertaken since those of Richards (1965). This study focused on a small area immediately adjacent to SOB Shaft and primarily documented structures occurring within the COM. Unfortunately, only a summary document of this work remains, documenting the
intense deformation affecting the COM argillite and development of tight folding.

Jordaan (1961) documented the broad variation in the deformation over the full extent of the NKM deposit. In this study tight to isoclinal folding was identified within the hinge region of the Nkana Syncline, with a transition to more open and slightly asymmetrical folding towards the north at Central Shaft. At Mindola, the orebody was shown to occur on the upper limb of the structure, where strata dip westward from 25° to 50°. There has been one recent study which examined ore-related veining. Greyling et al. (2005) undertook a fluid inclusion-based study of a limited selection veins at NKM, identifying two main vein generations (pre-and syn-tectonic generations). Brems et al. (2009) completed a detailed study of the vein paragenesis at SOB Shaft in combination with a focus structural study based on key underground exposures.

4.4 STRUCTURAL SETTING AT NKANA-MINDOLA

The Nkana Syncline is one of several large-scale, north-northwest- to west-northwest trending, generally upright folds, which contribute to the macroscopic synformal geometry of the Chambishi Basin (Fig. 4.2). Several detailed deposit-scale studies from the ZCB have demonstrated that depositional trough axes formed the loci for synclines during inversion, with variable hinge line plunge linked to the attitude of the basement-cover unconformity prior to compressional deformation (Whyte and Green, 1971; Voet and Freeman, 1972; Selley et al., 2005). The characteristic non-cylindrical form of these folds has been attributed to inheritance from a complex sub-basin geometry that initiated and evolved during deposition of the Lower Roan Subgroup (as discussed in Chapter 3.8). It should be noted, however, that whereas a systematic geometric relationship between sub-basin and fold geometry is widely demonstrable at the deposit scale, it remains unclear as to whether the macroscale west-northwest-trending synclinal form of the Chambishi Basin is itself directly inherited from a larger-scale, similarly oriented, sub-basin depocentre.

The influence of a complex sub-basin geometry lessens the need for multiple, superposed fold generations to account for the locally complex, non-cylindrical fold geometries. Only one penetrative foliation is observable within Katangan strata (although, as shown below, multiple fabric development occurs locally within NKM), supporting interpretations of a single phase, or at least simple, folding history. Breccia horizons are known from NKM, however occur above the stratigraphic interval examined in this study. However layer-parallel zones of high strain occur at deeper stratigraphic levels, in particular at the Mindola Clastic Formation-Copperbelt Orebody Member interface, but unlike the breccias, these zones are characterised by ductile fabrics and no evidence of significant displacement can be seen. Decoupling at this stratal interface has been documented at several ZCB deposits, where a 3 m thick shear zone is developed (e.g. Molak, 1995). Arguments for a pre-folding phase of broadly layer-parallel decoupling within the Katangan Supergroup, have been presented by several workers (Binda and Mulgrew, 1974; Binda and Porada, 1995; Molak, 1995; Porada and Berhorst, 2000; Selley et al., 2005). Evidence for this event comes principally from laterally extensive, dominantly stratabound breccia horizons, located in the main within evaporative carbonate-dominated strata of the Upper Roan Group. These breccias are traceable throughout limbs and hinge regions of major folds. At several localities within the ZCB, including the south-western margin of the Chambishi Basin, the basal brecciated detachment surface appears to cut down-section in a westerly direction to the level of the COM, thus forming a regionally transgressive ramp. Most workers have attributed breccia development to a thrusting episode, juxtaposing allochthonous carbonate-dominated stratigraphy within para-autochthonous siliciclastic-dominated stratigraphy (Binda and Porada, 1995; Porada and Berhorst, 2000). By contrast, Selley et al. (2005) favoured an extensional origin for
the detachment surface, based largely on the apparent ‘removal’ of stratigraphy across the surface, as opposed to thrust-repetition.

### 4.4.1 Macroscopic Form within the Nkana Syncline

The Katangan Sequence of sedimentary and volcanic rocks at NKM have experienced compressional deformation which can subdivided based upon cross-cutting relationships and variations in geometrical relationships between structures (Table 4.1). \(D_3\) is widely recognised as forming the dominate \(F_3\) folds regionally prevalent across the LFB (i.e. Nkana Syncline; Fig. 4.2) and resulted in the main penetrative cleavage (\(S_3\)) forming event at NKM. In addition to cleavage formation, pre-, syn- and post-tectonic (post \(D_3\)) veining and bedding and cleavage parallel transposition and dissolution occurred during \(D_3\). \(D_4\) structures are only observed in the higher strain regions within the hinge zone of the Nkana Syncline and are moderately dipping faults and shears, oblique to sub-parallel to \(S_3\) and confined to the argillite rocks of the COM. The dip direction of the faults rotates about the mesoscopic folds. The crenulation of \(S_3\) cleavage occurs in the immediate vicinity to the moderately to steeply dipping faults.

### 4.4.2 Structural Domains

As is the case for most large scale folds in the ZCB, the axial surface of the Nkana Syncline is non-planar, varying in strike from north-northwest to northwest and has an upright to steeply south-westerly dip at progressively higher levels (Fig. 4.2). Where observable in mining operations, the hinge region of the COM comprises numerous parasitic closures that define complex 3\(^{rd}\)-order enveloping surfaces. The interlimb angle

### Table 4.1. Structural fabric elements used in this study for the Nkana-Mindola Deposit.

<table>
<thead>
<tr>
<th>Regional defined events (Daly et al., 1984)</th>
<th>Relative Age</th>
<th>Structure (Fabric, fold)</th>
<th>Defined by</th>
<th>Lithology / Stratigraphy</th>
<th>Description</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_1) - Rifting (~750Ma (Rodina Break-up))</td>
<td>(D_1) (lifting)</td>
<td>Faulting (ripping)</td>
<td>Syn-depositional faulting associated with basin formation</td>
<td>Lower Roan - particularly controlling the localised deposition of the MCF in small basin compartments.</td>
<td>Inferred from facies type and distribution</td>
<td>Moderate</td>
</tr>
<tr>
<td>(D_2) (~ onset of NE-SW directed compression)</td>
<td>(L_1)</td>
<td>Mineral elongation on (S_0)</td>
<td>Argillite-sandstone of the Kitwe Formation (Nchanga Quartzite Member)</td>
<td>Ball and pillow, dewatering structures</td>
<td>Moderate (confined to specific horizons)</td>
<td></td>
</tr>
<tr>
<td>(D_3) (compressional deformation during the Lufilian Orogeny (~560 to 520Ma))</td>
<td>(S_3)</td>
<td>First-axial plane cleavage</td>
<td>COM; Well developed in fine-grained argillite.</td>
<td>Closely-spaced, smooth continuous cleavage</td>
<td>Strong</td>
<td></td>
</tr>
<tr>
<td>(F_3)</td>
<td>(L_1)</td>
<td>Mineral stretching lineation on (S_{31})</td>
<td>Argillite, carbonaceous argillite</td>
<td>Alignment of the phyllosilicates minerals and calcite</td>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>(F_3)</td>
<td>Open to isoclinal folding</td>
<td>Throughout stratigraphy</td>
<td>Observed at all scales</td>
<td>Moderate to intense in high strain domains.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_4)</td>
<td>(F_4)</td>
<td>Moderate angle faults and shears</td>
<td>Argillite, MCF; sandstone-siltstone.</td>
<td>Discrete moderate to steep angle anastomosing</td>
<td>Moderate (however localized to high strain zones) and only developed in high strain zones within fine grained lithologies.</td>
<td></td>
</tr>
<tr>
<td>(S_4)</td>
<td>Crenulation of (S_4) forming localised weak (S_4) cleavage development</td>
<td>Argillite, carbonaceous argillite</td>
<td>Smooth disjunctive cleavage</td>
<td>Weak (confined to high strain zones, associated with shearing)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
and wavelength of parasitic folds decrease progressively towards the southeast. Such characteristics, coupled with different structural levels of the mining operations, provides the basis for distinguishing three structural domains within the deposit (Figs 4.3 and 4.7) which are introduced briefly here.

Four orders of magnitude of $F_3$ folding have been identified in the Chambishi Basin. First order $F_3$ folds are of regional importance and can be traced for kilometres to tens of kilometres, such as the Kafue Anticline. The Nkaña Syncline is a second order regional fold (Fig. 4.1). Third order folds are parasitic upon first order folds and are important at the deposit scale. Third order $F_3$ folds can be traced for hundreds of metres to several kilometres at NKM and are well defined on the mine plans and sections by tracing the basement-MCF, Basal Sandstone Member-Lower Conglomerate unit (where available) and the MCF-KF stratigraphic contacts. Laterally discontinuous mesoscale (metre to tens of metres) 4th order $F_3$ folds are locally developed in the hinge zones of these 3rd order $F_3$ folds and are only of local significance to mining operations on one or two
particular working levels. The 4th order folds are prevalent within the argillaceous rocks of the COM within the high strain structural domain and are characterised by tight to isoclinal, inclined or upright folds, with southwest and northeast dipping axial surfaces.

For the purpose of describing and interpreting the mesoscopic and macroscopic structure at NKM, the area has been divided into three structural domains, each defined by differences in observed deformation intensity based on the relative development of cleavage, pebble elongation, fold profile changes and fault intensity (Fig. 4.3). Overall there is an increase in observed deformation from northwest to southeast, toward the hinge zone of the Nkana Syncline. The following section will briefly introduce the structural domains and each of these will be discussed in further detail in later sections of this chapter.

**Domain One**
Domain one is located on the upper portion of the north-eastern limb of the Nkana Syncline (Fig. 4.3) and records the lowest deformation at NKM. While low amplitude mesoscopic folds affect strata on a local scale, the macroscopic geometry of the fold limb is simple, involving a relatively uniform moderate dip of Lower Roan Group strata towards the southeast. A primary depositional contact between the MCF and COM, largely unaffected by strain, is also preserved throughout the domain. Evidence of macroscopic parasitic folding occurs at the higher stratigraphic level of the Upper Roan and Mwashia groups to the west. Historical ZCCM maps reveal apparent fold repetition of breccia-mantled, stratabound gabbroic bodies that occur at this level (Fig. 4.4). These structures were not revisited during this study, but potentially represent fold nucleation above the regional brecciated detachment surface in the Upper Roan.

**Domain Two**
Domain two, located to the SE of domain one, is defined as the transition from low deformation (domain one) to high deformation (domain three). It includes the deeper levels of the Mindola Shaft (4440 L; 4480L and 5520L) and in plan extends from the southern edge of the Kitwe Barren Gap to the Central Shaft headframe (Fig. 4.3). Within this domain, the attitude of the northeast limb steepens dramatically, with upward facing, yet uniformly steeply dipping (750 to 850 west) strata passing to overturned strata (750 to 850 east and northeast) on the deeper levels of Mindola Shaft. Towards the southern margin of the domain, in the vicinity of Central Shaft, strata are affected by macroscopic parasitic folding as the hinge region of the Nkana Syncline is approached. Individual parasitic hinge lines can be traced over distances of 1 km. Fold profiles vary from open to tight and wavelengths range from less than 100 m to several hundreds of metres.

**Domain Three**
Domain three, the highly deformed area occurs on the southern side of Central Shaft, continuing southward to include the hinge region and western limb of the Nkana Syncline. Tight parasitic fold closures are ubiquitous, the hinge lines of which can be confidently projected either up- or down-plunge between successive sections through the mining operations (Fig. 4.5). This allows for the three-dimensional form of the folds to be determined, which reveals variable plunge towards the northwest, and locally south-eastward (Figs 4.5 and 4.6). In general, hinge lines display a stepped or sigmoidal form, shallowing, or locally reversing their plunge in the NSA (Fig. 4.6). Inflection points of some hinge lines, such as the ‘C’ Anticline in the NSA, correspond spatially to facies variation within the COM and MCF.

Previous geological investigations at NKM and those undertaken as part of this study have identified 10 mappable 3rd order F3 folds within the hinge zone of the Nkana Syncline at SOB Shaft (Fig. 4.5). These
Figure 4.4. Modified surface geological maps showing the distribution of gabbroic units near the base of the Mwashia Group within the low strain structural domain, west of the Mindola Pit. No 3rd order $F_3$ folds were recognised within the Mindola Pit, however previous surface mapping by company geologists to the west of the pit, near to or within the hinge of the NKM syncline identified $F_3$ folds within the Mwashia Group.
Figure 4.5. Detailed surface geological map of the hinge zone of the Nkana Syncline (modified from ZCCM maps). The hinge zone comprises several 3rd order F3 folds. The trace of the larger folds is mapped using the MCF-KF contact, as bedding transposition and post-cleavage shearing complicates the fold patterns within the argillite beds of the KF. The location of the large scale (1:5000) sections are marked as well as the Nkana Synclinorium Area (NSA). Detailed underground geological traverses were conducted within the NSA.
Figure 4.6. Simplified projection of hinge lines onto a common long section oriented parallel to the axial surface along the NE limb of the Nkana Syncline of the area from south of SOB Shaft to the southern edge of the Kitwe Barren Gap. The folds are parasitic 3rd F3 folds on the Nkana Syncline and have a dominant moderately NW plunge with localised plunge reversals (modified and developed from historic map sheets). The fold profiles are constructed based upon the geological contact between the MCF and the COM.
have been named A-F from east to west using accepted mine terminology at SOB Shaft. The ‘E’ anticline corresponds to the previously named Chamboli anticline. Further to the west of the ‘F’ fold, the Luanshimba syncline-anticline and the Mushila syncline are recognised. To the north of SOB Shaft, outside the immediate hinge zone of the Nkana Syncline, several other 3rd order F3 folds are recognised along the northeast limb of the Nkana Syncline between SOB Shaft and the Kitwe Barren Gap. These are once again named using mine terminology and include the J, JA, Zero and North folds moving from south to north, however only surface expression of the ‘J’ fold is observed at NKM deposit.

The geometry of the western limb of the Nkana Syncline is constrained only by historical surface mapping (Fig. 4.8). Strata are again affected by parasitic folding with the Luanshimba anticline forming the most conspicuous structural element (Figs 4.5 and 4.8). The enveloping surface of parasitic folds and sub-parallel basement-MCF contact exhibit an abrupt anticlockwise deflection in strike moving northwestward of the Nkana Syncline hinge region (Figs 4.5 and 4.8). Deflection of parasitic fold axial traces from northwest to west-northwest is broadly paralleled by that of the Nkana Syncline. At the northern end, an abrupt change in the orientation of the F3 fold axis of parasitic folds is coincident with a change in the strike of the basement-MCF contact. The F3 fold axis trend west-northwest. Stepping out to a larger scale, there is a coincident subtle shift in the orientation of the 2nd order F3 Nkana Syncline, from northwest to west-northwest trending.

4.5 MESOSCOPIC FABRIC DEVELOPMENT

Penetrative and locally non-penetrative planar and linear fabrics are developed throughout each of the three structural domains (Table 4.1). The intensity of fabric development increases towards the hinge region of the Nkana Syncline, particularly within the KF.

4.5.1.1 \( L_2 \) evaporite nodule lineation

Elongate aggregates of prismatic dolomite/albite crystals, interpreted to represent modified pseudomorphs after anhydrite or gypsum, were observed at the base of the KF at the southern of the Mindola Pit in domain one (Figs 4.9a and b). Preserved or developed only in the low strain domain, the lineation plunges consistently towards the south-southwest with the plane of bedding, oblique to the trend of both mesoscopic and macroscopic fold axes in domain one (Fig. 4.9d). The development of this lineation appears restricted to a narrow zone, positioned immediately above the MCF-KF interface. At similar stratigraphic levels within domains two and three, the Schistose Ore and Contact Ore Shale, respectively, dolomite/albite pseudomorphs after sulphate are recognised and appear flattened, although there is no evidence of overprinting by a shear fabric.

4.5.1.2 \( S_3 \) regionally developed foliation and local stretching lineation

A dominant penetrative foliation, \( S_3 \), is observed in all structural domains. This fabric is particularly well developed within the finer-grained rocks of the Lower Roan Group, and intensifies in the moderate to high strain structural domains. Within argillaceous lithotype of domain one, \( S_3 \) occurs as continuous growth aligned biotite, flattening quartz grains and preferential segregation of quartz and mica into different layers within the argillite lithotype (Figs 4.10a and b). The cleavage is very closely spaced at \( \sim 0.1 \) to \( 1 \)mm (Figs 4.10b and 4.10c). Within high strain structural domains the carbonaceous argillite may exhibit foliation resembling anastomosing and lensoidal appearance and layer transposition and dissolution is common (Fig. 4.10c). Within the low strain domain \( S_3 \) cleavage is only clearly observed in the lower portion of the COM, immediate adjacent to the MCF-
Figure 4.7. Simplified stacked schematic geological cross sections across the Nkana Syncline, constructed around the basement-MCF and the MCF-KF contacts. The Nkana Syncline plunges moderately to the NW and several parasitic F3 folds can be traced for kilometres within the hinge zone. The red line marks contact between the basement and MCF and the top of the yellow unit (MCF) is the contact between the MCF-KF. Examples of the variation in the structural intensity are shown on several of the sections. The contact between the Lower Roan Group and Upper Roan Group has not been depicted accurately on the sections due to the lack of intersection points. Detailed geological maps and sections will be shown for the Nkana Synclinorium Area in the following sections of this chapter (sections are modified and simplified from compilation of company geological cross sections and plans at Mopani Copper Mines).

Figure 4.8. Detailed geological map of the west limb of the Nkana Syncline (modified and simplified from compilation of historic ZCCM geological maps (1974 to 1980)). The mapped fold geometries of the west limb are similar to those observed on the northeast limb. There is a considerable greater thickness on MCF, which is interpreted to be unrelated to the structural thickening during D3 to D4. The dominant NW trending F3 folds abruptly change to west, west northwest trending along the northern portion of the west limb. This change in strike is coincident with a shift in the orientation of the basement-MCF contact.
Figure 4.9. Two lineations have been identified on bedding plane surfaces in the low strain domain at NKM.  

a). The moderately, west dipping contact between the Mindola Clastic Formation and the Kitwe Formation in the Mindola Pit.  

b). Elongate dolomite crystals on bedding plane surface within 40cm of the MCF-KF contact. The L3 lineations are plunging shallowly to the south-southwest, oblique to the axial trend of the Nkana Syncline (lens camera cap for scale - 5cm diameter). This fabric was only observed within the low strain domain.  

c). Slicken-slide lineations define west-southwest plunging L3 lineations.  

d). Equal area stereographic projection of L2 and L3 lineations measured in the Mindola Pit, at or just above the contact between the MCF and CCM.  

e). Mesoscopic F3 folds developed only within the dolomitic argillaceous rocks in the low strain domain.
Figure 4.10. Examples of $S_3$ cleavage development. a). Underground photo clearly showing $S_3$ fabric well developed in carbonaceous argillite lithotype in the high strain domain (3360L, NSA, SOB Shaft; scribe for scale). b and c). Photomicrographs of $S_3$ cleavage developed in carbonaceous argillite lithotype from the high strain domain. Significant $S_3$ parallel transposition is evident (Drillhole NS015; sample no 284). d). Photomicrograph of $S_3$ cleavage weakly developed in the basal portion of the MCF from Mindola North Shaft, low strain domain (underground sample - 1050L - Mindola North Shaft). e). Photomicrograph of biotite/phlogopite defined $S_3$ cleavage developed within argillaceous sandstone of the upper MCF at Central Shaft (underground sample, 2030L- Central Shaft). f). Photomicrograph of biotite and muscovite defined $S_3$ cleavage in sandstone-argillite lithotype of the MCF. There are small changes in the mineralogical and grainsize across the sample which influences the development of the $S_3$ fabric.
KF (Fig. 4.10d). Elongation of the quartz grains parallel to the cleavage may occur in high strain structural domains suggesting different magnitudes of stretch in X and Y directions. A stretching lineation is observed by elongate quartz grain aggregates, mica beards or fibrous strain shadows around rigid particles occurring down-dip on the cleavage. Strain shadows have developed around pre-existing grains such as quartz and pyrite (Fig 4.10c). Such features are not observed in low strain zones.

In the coarser grained units such as the sandstones of the MCF, S\(_3\) cleavage is discontinuous and widely spaced and not always readily recognisable (Fig. 4.10f). Within some of the coarse-grained quartz rich sandstones well developed shape preferred orientation of quartz grains and quartz-mica beards extending from grain boundaries locally develop (Fig. 4.10f). The micas may form envelopes around the lenslike and sometimes trapezoidal grains of quartz grains, and more rarely feldspar grains. No evidence of flatten or elongation of pebbles were observed in the low and moderate strain structural domains (Fig. 4.10a). Within high strain structural domains, the pebble to cobble conglomerate unit of the MCF has a well developed dimensional fabric defined by the preferred alignment of clasts parallel to that of the S\(_3\) cleavage (Figs 4.10a, c and d). The conglomerates will have the appearance typical of flattened-pebble foliation, however later stage anhydrite crystallisation may obscure the foliation. Some clasts have been cross-cut by shears sub-parallel to the regional S\(_3\) fabric, while small brittle fractures occur in some clasts at a high angle to S\(_3\) fabric (Figs 4.10b and c) and the principle shortening direction was orientated orthogonal to the S\(_3\) cleavage.

4.5.1.3 S\(_4\) - localised crenulation cleavage

S\(_4\) is locally overprinted by a crenulation cleavage, S\(_4\), within argillaceous lithotype in the high strain structural domain. Development of S\(_4\) is highly domainal, and restricted to a 1 to 3 m wide halos to fault zones (Figs 4.12b and c). In thin section, S\(_4\) is defined principally by the hinges of microfolds (Fig. 4.12e and f) however may be accompanied by growth of rare fine biotite or pressure-solution related re flattening of quartz grain aggregates.

4.5.1.4 D\(_4\) faults

D\(_4\) is characterised by metre to hundreds of metre scale faults predominately confined to the fine-grained units of the KF and to a lesser extent within the underlying MCF (Figs 4.12a to d). The structures are commonly discrete 2 to 5cm wide zones with curvilinear surfaces oblique to near parallel to the S\(_3\) cleavage and commonly result in the crenulation of S\(_3\), forming S\(_4\) fabric. No crenulation of S\(_3\) fabric is observed near the D\(_4\) faults in coarser grained lithotypes, however intense fracturing is common within the immediate hanging- and footwall to the structures. Larger structures are characterised by intense biotitic zones up to several metres in width, however these are uncommon and confined only to the very high strain structural domains (domain 3) and are in close proximity to the MCF-KF contact (Fig. 4.12d). The larger scale structures are laterally continuous over several hundreds of metres (Fig. 4.22). This localised faulting confined to the high strain structural domain resulted in minor modification of F\(_3\) folds, however the overall F\(_3\) fold geometries and trends of syncline and anticline structures can still be mapped for hundred's of metres across the deposit. Displacement along the faults zone is difficult to constrain within the argillite rocks due to the propensity of good marker beds. No evidence was observed of greater than ~ 20 to 30 m vertical and lateral displacement along these structures.

4.5.2 Fracture and joints

No distinction is made here between fractures and joints, and the terms are used interchangeably. Limited attention was focused toward the understanding of the late brittle structural development at NKM during this study. The more competent units such as the sandstones of the MCF are well jointed, with minor localised
Late stage anhydrite cement.

Stretched and flattened clast in high strain domain.

Figure 4.11. Examples of the varying degrees of deformation in the Lower Conglomerate unit of the MCF. a). Low degree of clast flatten or modification occurring in moderate strain domain (drillhole CE 490, Central Shaft). b) Moderate degree of clast flatten and late stage veining cross cutting clast (drillhole NS 68, SOB Shaft). c and d). Examples of clast flatten and deformation of the unit within the Nkana Synclinorium Area, high strain structural domain (drillholes NS 79 and NS 30).
Figure 4.12. Examples of $D_4$ faults occurring within the high strain domain and the development of localised $S_4$ cleavage. Dip-slip and strike-slip movement along all faults varies from centimetres to only 10's of metres.

a). $D_4$ fault cross cutting COM on the 3360L SOB Shaft.

b). 50cm wide $D_4$ fault, sub-parallel to $S_3$ cleavage on the 3360L SOB Shaft.

c). 5 to 10cm width, anatomising $D_4$ fault cross-cutting $S_3$ cleavage at a moderate angle.

d). Large scale $D_4$ fault occurring at the western end of the of NSA, 3360L, SOB Shaft. This structure could be traced for several hundreds of metres. Typically $D_4$ faults can only be traced over 10's of metres.

e). Photomicrograph of small scale $D_4$ fault (3360L, SOB Shaft).

f). Photomicrograph of $S_4$ cleavage, only developed immediately adjacent to $D_4$ faults in high strain domains (3360L, SOB Shaft).
movement (in the order of 5 to 10 mm) along some of the joint planes. Within the argillite rocks of the COM there is little evidence of consistent fracturing, however fracturing is well developed in the immediate hanging and footwall to D₄ faulting. The main joint set in the COM strikes ~310° degrees dipping to the east and west at ~70° degrees and joint spacing is variable between 7 to 10 cm apart. Late-stage cross cutting joints striking ~220° have similar spacing and the joint surfaces are rarely coated. Within the high strain structural domain (Domain 3) and restricted to the carbonaceous argillite lithologies a fracture cleavage was observed. The fractures strike ~190° slightly oblique to the main D₃ and D₄ structures and are steeply dipping to the east and west. There fractures cross-cut D₃ cleavage and D₄ structures interpreted to indicate that the structures formed during the later stages of D₄.

### 4.5.3 Veining

The characterisation of the vein types at NKM and their paragenetic relationship and timing relative to deformation and mineralisation provides important information on the geochemical and physio-chemical conditions at the time of vein formation. The majority of observed veins at NKM are restricted to the high strain structural domain. Table 4.2 summarises the vein characteristics as defined by this study.

#### 4.5.3.1 Bedding-parallel to -sub-parallel veins (VI) – early/pre-S₃ or D₃

Bedding parallel carbonate-quartz dominant fibre veins containing minor trace quantities of pyrite, chalcopyrite and bornite, occur commonly in the basal portion of the carbonaceous argillite lithotype of the COM at SOB Shaft, and more rarely in the dolomite-argillite lithotype in the northern area of NKM. Within the southern high strain domain, this generation of veins is overprinted by the S₃ foliation and folded about micro- and

<table>
<thead>
<tr>
<th>Vein Stage</th>
<th>Composition</th>
<th>Morphology</th>
<th>Location / Host</th>
<th>Relative Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI – Bedding parallel</td>
<td>ca ± dol-qtz and trace ccp, py, muscovite</td>
<td>Deformed bedding-parallel to sub-parallel fibre veins. Fibre growth, 1 to 5cm in width, only occurring at the base of COM in carbonaceous argillite lithologies; laterally continuous for 10% of metres; folded and disrupted during cleavage formation.</td>
<td>Basal portion of the COM mainly within the carbonaceous argillite</td>
<td>Pre- to early D₃</td>
</tr>
<tr>
<td>VII – Foliation Parallel</td>
<td>qtz-ca-dol-phzmica-kf-ccp-py-po-car</td>
<td>S₃ parallel, minor pinch and swell, localized boundinage, cut by shearing. Laterally discontinuous – 5 to 10m; 1 to 3cm in width; locally warping and rough margins resulting from transposition/dissolution. Mineralogical composition similar to immediate host lithology.</td>
<td>COM in high strain zones. Syn-S₃ - foliation development</td>
<td></td>
</tr>
<tr>
<td>VIII – Foliation parallel</td>
<td>qtz±ca-dol-ph-ab±ccp-py-po-car</td>
<td>S₃ parallel, sharp edges, cut by shearing. Mineralogical composition similar to immediate host lithology.</td>
<td>COM in high strain zones, minor in basement and MCF</td>
<td>Late D₃ (post main S₃ development)</td>
</tr>
<tr>
<td>IVV– Tension gashes, fracture veins and massive cleavage cross cutting veins</td>
<td>Qtz±ca</td>
<td>Tension gashes and irregular fracture vein network, locally developed in vicinity of D₄ faults</td>
<td>COM, confined to immediate vicinity of D₄ shearings/thrusting. Confined to contact zone</td>
<td>Post D₄ – syn D₅</td>
</tr>
</tbody>
</table>
Folded bedding parallel veins

Deformed V1 veins; VII veins and late stage cross-cutting VIII veins.

Deformed bedding parallel veins (VI) and S3 parallel syn-tectonic qtz-carbonate-mica veins (VII) (3360L SOB Shaft). Tightly folded VII veins in the high strain domain. Late stage qtz-carbonate + sulphides S3 sub-parallel and cross cutting veins (VIII and IV) only occur in the high strain domain and predominantly only within the COM, near the contact with the MCF. Hand specimen of folded VI vein sets with disseminated sulphide occurring along the vein margins. Hand specimen VII (S3 parallel veins). Hand specimen of VII and small VIII veins. V3 veins cross cut S3 cleavage.
mesoscopic F$_3$ closures (Fig. 4.13a, b and d). Individual veins range in thickness from approximately 5 mm to 3 cm, and have lateral extents mainly within the range of 1-7 m. Collectively, they form sub-parallel arrays with spacings of 10 to 30 cm and at NSA, vein arrays can be traced about the profiles of macroscopic closures, such as the ‘C’ Syncline-Anticline pair.

Many veins have sharp contacts with the host rock, however these boundaries are more diffuse if the veins have experienced higher strain during the subsequent deformation. Trace quantities of authigenic quartz, feldspar, and sulphide occur within vein selvages that are unmodified by later deformation. The main stage of calcite and/or dolomite growth exhibits syntaxial and composite growth textures, with prominent median line, localised fibre curvature characteristic and dominant orientation of fibres perpendicular to bedding. Destructive recrystallisation of the fibrous textures occurs locally in the hinge regions of macroscopic folds, and also within limbs affected by transpositional S$_3$ development. The vein array is thought to be related to the D$_2$ mineral lineation only observed in the Mindola Pit, marking the onset of compressional deformation.

4.5.3.2. S$_3$-sub-parallel and -parallel veins (VII and VIII) – syn-D3

S$_3$-sub-parallel and –parallel vein arrays are largely confined to the basal argillaceous unit of the COM (~10 m thick) in structural domain three. Less commonly such veins occur in the MCF close to the contact with the COM and upper stratigraphic levels of the KF. At all levels, the density of veins increases towards the hinge regions of macroscopic F$_3$ folds. The veins do cross-cut vein set VI, however the veins have not been observed crossing the MCF-KF contact itself.

Two morphologically distinct generations of S$_3$-sub-parallel and –parallel veins are distinguished, both of which are cross-cut by low angle shear fractures. VII veins have a complex mineralogy of k-feldspar+quartz+calcite+dolomite±albite±biotite±pyrite±chalcopyrite with accessory hematite and chlorite. The veins range from 3 mm to greater than 2 cm in width and have an apparent lateral extent of metres to tens of metres. The veins regularly have a pinching and swelling morphology, interpreted as boundinage and their margins exhibit dissolution textures associated with S$_3$ foliation seam development. Internal textures within the veins are complex suggestive of episodic fluid pulse during the main D$_2$ event. Slivers of host rocks are incorporated within the vein. VIII veins have the same complex mineralogy as VII veins, however are not boudinaged, nor are they cross-cut by S$_3$ dissolution seams. VII and VIII generations are thus considered temporally distinct, the former forming syn-kinematically with S$_3$, the latter post-dating foliation development. However, the common mineralogy of both vein generations is interpreted to indicate involvement of fluids with similar chemical and physical properties. As such VIII are considered to have formed during the D$_3$ event, but after considerable fold tightening.

4.5.3.3 Post-S$_3$ veins (VIV) – late D$_3$ to syn D$_4$

Two compositionally distinct generations of veins were observed to cross-cut S$_3$, both of which occur within a halo to the MCF-KF interface. The first include rare, quartz±carbonate tension gash arrays, that are oriented at various angles to S$_3$. Low angle varieties occur in association with D$_4$ faults within the COM, suggesting a temporal relationship with this phase of faulting. En-echelon arrays of quartz-filled tension gashes are common in the sandstone of the MCF in domain three. The veins are ~5 cm in width and up to 50 cm in length and are spaced ever 20 cm over 2 to 3 m.

The second variety of post-S$_3$ veins are texturally massive and composed of muscovite, calcite, dolomite, quartz, albite, anhydrite, pyrite, chalcopyrite, bornite and carrollite. These are confined to hinge regions of tight to isoclinal F$_3$ folds in the high strain structural domain, and typically occur within ~10 m above or below the MCF-KF contact (Fig. 4.13e). Slivers of the host rocks may also occur within the veins. Alteration selvages to
the veins are 10-50 cm wide, and typically contain Cu-Co sulphide minerals, regardless of whether the host strata contain pre-existing stratiform or structurally controlled sulphide phases. These irregular veins can be traced for tens of metres and vary in thickness from 50 cm to in excess of 3 m.

4.6 FOLD AND STRUCTURAL DOMAIN ANALYSIS

As previously introduced, three structural domains have been identified at NKM based on the variation in strain intensity between location. In the following section the geometric characteristics of fold and fault development within each structural domain will be discussed to highlight the similarities and differences between each structural domain. More specifically this section will address reasons for the apparent abrupt change in fold geometry from high amplitude/wavelength folding affecting domains 1 and northern portion of domain 2 compared to the more complex low wavelength folding further south in the high strain structural domain, document the relationship between the fold geometry and variations in facies architecture and discuss the influence of rheological variations in the stratigraphy on the fold profile geometry.

4.6.1 Mesoscopic Analysis Domain One - Low Strain Zone

The structural style in domain one is best illustrated in the exposures of Lower Roan Group strata in the Mindola Pit (Fig. 4.14). This highest preserved structural level of the north-eastern limb of the Nkana Syncline involves uniform bedding dips of ~30° to the southeast. At deeper structural levels exposed in underground operations at Mindola North Shaft, the limb dip increases progressively to between 40° and 45° east.

Despite the preservation of a primary depositional contact between the MCF and overlying COM, this level of the stratigraphy forms the locus for most complex fabric development (Fig. 4.15). The form and composition of two lineations, L₂ and L₃S, both of which are contained within the bedding surfaces close to the MCF-COM interface, have been described above. The L₂ nodule lineation plunges shallowly to the south-southwest, at an angle to both the hinge lines of mesoscopic F₃ folds and the macroscale homoclinal axis defined by S₀ variation in domain one. Obliquity between L₂ and the various proxies for F₃ fold axis orientation is consistent with the interpretation that L₂ stretching is unrelated to the principal folding phase. By contrast, the more steeply southwest plunging L₃S quartz-calcite fibre and groove lineation is oriented at ~90° to F₃ fold axes (Fig. 4.9d). This geometric relationship, coupled with consistent top-to-northeast displacement sense indicated by the fibres, is interpreted to record flexural slip associated with F₃ fold tightening.

4.6.2 Mesoscopic Analysis - Structural domain 2 and 3

The majority of second and third order F₃ folds commonly plunge between 15° to 35° degrees to the northwest however local plunge flattening and reversals do occur (Figs 4.16 and 4.17). At a mesoscale, fold wavelength decreases within the COM when compared to the underlying competent sandstones of the MCF. The moderate and high strain structural domains are restricted to the southern side of Central Shaft, continuing southward towards the hinge zone of the Nkana Syncline and along the western limb of the Nkana Syncline.

Geological observations for domain 2 were made from the deeper levels of the Mindola Shaft (4440 L; 4480L and 5520L) and from the southern edge of the Kitwe Barren Gap to the Central Shaft headframe. On the deeper levels of Mindola Shaft the stratigraphy dips 70° to 85° to the west and west-northwest and no parasitic folding on the eastern limb of the Nkana Syncline is recognised in this zone However to the south of the Kitwe Barren Gap, parasitic folding on the northeast limb of the Nkana Syncline is clearly recognised with such folds as the Zero Syncline-Anticline and the North Syncline (Figs 4.16, 4.17 and 4.21). The Nkana
Figure 4.14. a). Photograph of the southern wall of the Mindola Pit, the strata is dipping ~30° to the east. The contact of the Mindola Clastic Formation and Kitwe Formation is the dip slope of the western pit wall.  b). Kitwe Formation occurring in the Mindola Pit (looking to the east). The upper portions of the Kitwe Formation is weathered obscuring some of the sedimentary features.
Figure 4.15. a). Contact between the MCF and KF in the moderate strain structural domain at Central Shaft (2030L). No evidence of movement along the contact. b). Contact between the MCF and KF in the Mindola Pit, low strain structural domain. Localised evidence of movement, defined by L3, however displacement is only in the order of metres. c and d). Contact between the MCF and KF at Mindola Shaft, moderate strain structural domain. No evidence of movement along surface. S3 cleavage is developed in the argillaceous rocks of the KF resulting from the partitioning of strain into the KF relative to the underlying MCF.
Figure 4.16. Detailed surface geological map of the hinge zone of the Nkana Syncline (modified from ZCCM maps). The hinge zone comprises several 2nd order F₂ folds. The trace of the larger folds is mapped using the MCF-KF contact, as bedding transposition and post-cleavage shearing complicates the fold patterns within the shale-siltstone beds of the KF. The location of the large scale sections and the Nkana Synclinorium Area (NSA) are marked. Detailed underground geological traverses were conducted within the NSA.
Figure 4.17. Simplified projection of hinge lines onto a common long section oriented parallel to the axial surface along the NE limb of the Nkana Syncline of the area from south of SOB Shaft to the southern edge of the Kitwe Barren Gap. The folds are parasitic 3rd F3 folds on the Nkana Syncline and have a dominant, moderate NW plunge with localised plunge reversals (modified and developed from historic map sheets). The fold profiles are constructed based upon the geological contact between the MCF and the COM.
Table 4.3. Key characteristics from analysis of fold profiles at NKM.

<table>
<thead>
<tr>
<th>Fold Profile Analysis</th>
<th>Figure References</th>
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<tbody>
<tr>
<td>• The 2nd order enveloping surface defined by major parasitic folds defines a series of box-shaped closures and in some cases more rounded closures. This association of subvertical limbs and intervening broad, flat-lying hinges is demonstrated in sections 7300mS SOB, 2000mN SOB, 4800mS central, 2000mS central, and 4200mN central while the intervening sections involve more rounded hinge and uniformly dipping limbs.</td>
<td>Figs. 4.16 and 4.18</td>
</tr>
<tr>
<td>• The classical box-shaped form of the folds is shown by the section and plan of the Zero Anticline.</td>
<td>Figs. 4.20 and 4.21</td>
</tr>
<tr>
<td>• Major folds have relatively consistent wavelengths of roughly 200 to 300m</td>
<td>Fig. 4.18</td>
</tr>
<tr>
<td>• The wavelength of folds diminishes (coupled by increasing amplitude) in areas where the MCF is thin and overall antiforms are nucleated on the crests of basement horsts.</td>
<td>Figs. 4.16 and 4.18</td>
</tr>
<tr>
<td>• There is decreased fold wavelength and increased fold amplitude within the synformal box hinges relative to outer limbs is demonstrated in sections 4800mS, 2000mS.</td>
<td>Figs. 4.16 and 4.18</td>
</tr>
<tr>
<td>• The wavelength of the 2nd order box folds changes along the strike of the Nkana Syncline, which is coincident with the progressive eastward migration of the fold nose from the Luanshimba syncline at the south, into the 'C-D' synclinal core to the north and then a shift to a westward migration at approximately the position of Central Shaft.</td>
<td>Fig. 4.18</td>
</tr>
<tr>
<td>• The wavelength of these main synclinal increases progressively from the Luanshimba syncline on section 7300mS, to the 'C-D' core in 4800mS to 4200mN central.</td>
<td>Fig. 4.18</td>
</tr>
<tr>
<td>• The transition from domain 2 to domain 1 involves the shift from box-shaped, broad synformal hinge into a curvilinear simply deformed homoclinal limb.</td>
<td>Figs. 4.16 and 4.18</td>
</tr>
<tr>
<td>• There is an increased thickness of the MCF northward of 2000mS central, which corresponds with broadening of the main synformal core and overall profile is disharmonic, with generally higher amplitude, lower wavelength folding partitioned into the KF, compared to MCF (basal contact at least).</td>
<td>Figs. 4.16 and 4.18</td>
</tr>
<tr>
<td>• Thickening of the MCF within the hinges of many closures is also apparent – however this is not consistent – in general, greatest thicknesses occur in synformal hinges, while many antiformal closures correspond with anomalously thin MCF – eg 6900mS, 4600mS, 1000mN, 1250mN. These relationships are interpreted that the thickness variation is unlikely to be a response to the folding process, and is in part at least inherited from primary depositional thickness variation</td>
<td>Figs. 4.16 and 4.18</td>
</tr>
<tr>
<td>• Thickness variation in the MCF occur about fold profiles. There is apparent thinning occurring along several major fold limbs, most notably along the eastern flank of the 'C'-anticline between 4600mS and 2000mN however, this relationship does not persist to the north, where the limb involves an anomalously thick MCF package and of significance is that this change in thickness is coincident with the appearance of the more steeply plunging 'J' fold couple.</td>
<td>Figs. 4.16, 4.18 and 4.22</td>
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Table 4.4. Key characteristics from analysis of hinge line at NKM.

<table>
<thead>
<tr>
<th>Fold Hinge Line Analysis</th>
<th>Figure References</th>
</tr>
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<tbody>
<tr>
<td>Folds are non-cylindrical with local plunge variations.</td>
<td>Fig. 4.17</td>
</tr>
<tr>
<td>The trace of hinge lines and degree of non-cylindricity is systematic with an overall sigmoidal, echelon pattern. These is a flattening of hinges in the NSA and notably a down-plunge 'death' of the 'B' fold couple and up-plunge 'death' of the 'J' fold pair, corresponds to this change in plunge and also broadly with the SOB barren gap.</td>
<td>Figs. 4.16 and 4.17</td>
</tr>
<tr>
<td>Fold deaths occur along their axes. These include folds 'A' and 'B' at ~3600mS, 'J' couple coming in at roughly 0m SOB, 'D' couple (NSA) and the Mushiula-Luanshimba fold couple dies out progressively northward to produce a homoclinal hinge at 2000mN SOB.</td>
<td>Figs. 4.16, 4.17, 4.18 and 4.22</td>
</tr>
<tr>
<td>Corresponding to the along trend 'death' of the folds is a progressive change in the plunge of the folds based on the assessment of the basement-MCF contact.</td>
<td>Figs. 4.16, 4.17 and 4.18</td>
</tr>
<tr>
<td>The hinge of the Luanshimba anticline plunges NW fairly steeply from 700mN to 0m SOB. North of this section, as the interlimb angle progressively increases and a homocline is formed with the hinge exhibiting a shallow plunge to SE.</td>
<td>Figs. 4.16, 4.19</td>
</tr>
<tr>
<td>Abrupt anticlockwise swing in fold axial traces from the main synclinal embayment.</td>
<td>Figs. 4.17, 4.19 and 4.22</td>
</tr>
<tr>
<td>Successive fold couples can have very different plunges as in the example of 'J' fold couple and 'C' fold couple. This can be interpreted to indicate different dips on ramps at relay ramp sites (i.e. greater NW dip on ramp associated with 'J' couple, and shallower dip on main inverted graben along 'C' couple)</td>
<td>Fig. 4.17</td>
</tr>
<tr>
<td>Overall antiforms are nucleated on the crests of basement horsts.</td>
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Table 4.5. Key structural characteristics of Nkana Synclinorium Area.

<table>
<thead>
<tr>
<th>Analysis of the Nkana Synclinorium Section (NSA).</th>
<th>Figure References</th>
</tr>
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<tbody>
<tr>
<td>The eastern margin of the NSA area is bordered by quartz-biotite schist and gneissic rocks of the basement complex. Unconformably overlying the basement are the quartz-mica-sericite quartzites and feldspathic arenites rocks (facies association MCF 1, MCF 2 and MCF 3) of the Basal Sandstone Member. MCF: These rocks have a weak, biotite defined northwest striking S cleavage. At the southern end of the area (X-Section 700N), a small basal breccia unit (facies association MCF1) directly overlies the basement and is itself overlain by the Basal Sandstone member. The Kafue Arenite Member is identified throughout the NSA however thickness changes are notable.</td>
<td>Figs. 4.22 to 4.26</td>
</tr>
<tr>
<td>The total thickness of the MCF along the eastern limb of the 'C' Syncline is relatively thin (0 to ~50m) compared to other areas at NKM where the thickness exceeds 100m (i.e. Central Shaft; Mindola Shaft). MCF does thickening within synformal cores and progressive thinning onto the upper flanks and crests of antiforms is also shown unequivocally on several of the NSA sections (700Nm). However most notable are the flanks of the 'C' syncline in section 700mN and a prominent basement high on the eastern side of sections from 700mN to at least 2350mN.</td>
<td>Figs. 4.21 and 4.27.</td>
</tr>
<tr>
<td>The box-shaped profile of the main synclinal core in the NSA is comparable to the zero syncline, in that it comprises 2 pinched synclines flanking a central basement-cored dome (C antcline).</td>
<td>Fig. 4.27</td>
</tr>
<tr>
<td>Basement highs occur from 700mN, 1550mN, 1750mN and the amplitude of the original basement high relative to neighbouring depressions decreases northward and further north, the plunge reversal appears to relate to a broader basement-cored antiform appearing at section B. This is interpreted to be possibly link with inheritance of relay-ramp geometries, with accommodation becoming transferred into the 1° fold couple depocentre to the east.</td>
<td>Figs. 4.22 and 4.27</td>
</tr>
<tr>
<td>The profile is characterised by upward converging synformal axial surfaces above the central antiform. This asymmetry across the profile appears in part generated by a conjugate array of moderately to steeply dipping D shear zones which are shown on stereoplots as striking parallel to the axial surfaces of the folds.</td>
<td>Figs. 4.23, 4.25 and 4.27.</td>
</tr>
<tr>
<td>Late stage faults are demonstrably reverse faults, with offset of the MCF-COM contact and where preserve apparent normal displacements down-dip – for example, the flanks of the small basement pinnacle immediately east of the C syncline on section 2150mN. These geometries can only be explicable by pre-existing basement highs, with either thinning and onlap of the BQM, or partial reactivation of original normal faults.</td>
<td>Figs. 4.22 and 4.26</td>
</tr>
</tbody>
</table>

Synclinorium Area (NSA) was of particularly focus due to underground access and the ability to document a high strain structural domain. For the purpose of this discussion of the moderate and high strain structural domains, Tables 4.3, 4.4 and 4.5 has been constructed to document the key characteristics from analysis of fold hinge line/trace geometry and fold profiles.

Within structural domains 2 and 3, macroscopic (3rd order) F3 folds are open to tight, upright to moderately inclined and plunge to the southwest and the trend of the hinge lines are near parallel to the strike of the axial surfaces, however localised variations occur. The axial planes are curved and vary from steeply inclined to the west or east. The variation in the axial plane appears to also be influenced by the proximity to basement and the shape of the basement-MCF surface and partly due to the partitioning of strain into the finer grained rock units. Steeply inclined to upright folds are commonly observed in areas in close proximity to basement blocks on either side of a synclinal structure. Within the finer grained rock units folding has resulted in attenuated limbs, bedding plane crumpling, axial plane cleavage and axial plane shearing. Interlimb angles to F3 folds vary from 0° (isoclinal) to about 60° (close) with a decrease in interlimb angle in the vicinity of the hinge zone of the Nkana Sycline (deeper level – 3360L Nkana Synclinorium Area). Fourth order, mesoscopic F3 folds have only been observed within the moderate and high strain structural domains and are characterised by tight to isoclinal, inclined or upright folds and with southwest and northeast dipping axial surfaces.

4.6.2.1 Nkana Syncline and West Limb (Figs 4.16, 4.18 and 4.19)

The geology of the western limb of the Nkana Syncline is relatively poorly understood compared to that along the NE limb of the Nkana Syncline. The analysis of the fold geometries is documented in Tables 4.4 and 4.5. Within the hinge zone area of the Nkana Syncline, two key 2nd order F3 folds are identified, these being...
the Luanshimba Syncline-Anticline and Mushila Syncline (Fig. 4.16). These folds can be traced for several kilometres on surface. The Luanshimba Syncline and Anticline plunge to the north-west and the axial plane varies from near vertical dipping to approximately 70° to 80° to the east (Fig. 4.18). The axial trace trends at ~308° degrees, however significant local variation in the trend of up to 15° degrees has been mapped. The Mushila Syncline is outside the immediate fold nose area and is a parasitic fold on the western limb of the Nkana Syncline trending ~310° and has a steep to near vertical axial plane. Further to the NW and along the west limb and away from the Nkana Syncline hinge zone, a series of parasitic folds occurring only within the lower portion Katangan Supergroup have been defined.

At the north western end of the west limb (Fig. 4.19), beyond the 8000N (Central) section axial trace of the F3 folds identifiable within the Kitwe Formation rotate from trending ~310° trending to ~340° (Fig. 4.19). All folds plunge consistently plunge to the NNW, west of this marked changed. The change in the trend of the fold axial trace is coincident to a similar significant change in the strike of the contact of the basement-Lower Roan Group which was discussed in chapter 3 and interpreted as a significant basin controlling structure based of facies variations and associated facies thickness variations of the MCF.

4.6.2.2 Nkana Synclinorium Area (NSA) (Figs 4.22 to 4.27)
This section describes the structure of the Nkana Synclinorium Area (NSA) and key are summarised in Table 4.5. The NSA is situated in the hinge zone of the F, 2nd order Nkana Syncline (Figs 4.16 and 4.22) at depth of ~800 m to ~1300 m below ground surface on the northern side of SOB Shaft. The northwest-southeast trending F, 3rd order ‘C’ syncline and anticline are the dominant structures within the area (Fig. 4.22).

The ‘C’ syncline is easily recognised from geological mapping along the 700-1250N and 2800N cross cuts based upon stratigraphic contacts between the basement-MCF, Basal Sandstone Member and Lower Conglomerate unit and the MCF-COM (Figs 4.23 to 4.26). The stratigraphic contacts between the MCF and KF within the NSA are either conformable or marked by localised shearing however there is no evidence of significant structural displacement (defined as in excess of ~30 m) along this contact was recognised (Figs 4.23 to 4.26). S3 cleavage is well developed throughout the area and S4 cleavage is identified adjacent to D4 faults (Figs 4.23 and 4.25). Along the 2800N cross-cut, numerous 3rd order F3 parasitic folds and extensive D4 faulting within the finer-grained units of the MCF and the carbonaceous argillite rocks of the COM result in further localised complication of the fold geometry of the ‘C’ syncline-anticline (Figs 4.23 and 4.25). The moderately to steeply dipping D4 faults can only be traced along strike for tens to several hundreds of metres within the argillaceous units of the COM. The faults do cross cut the MCF, however are difficult to correlate between drillholes. A significant D4 fault is recognised at the western end of both the 700-1250N and 4700S cross-cuts (Figs 4.23 to 4.26). This structure is traced cross cutting the basement and Lower Roan Group rocks. Towards the south, this structure is sub-parallel to the basement-MCF along the western limb of the ‘C-D’ syncline (Figs 4.22 and 4.25). Intense biotite alteration of the hangingwall and footwall rocks occurs immediately adjacent to the larger D4 structures. Field observations and geological interpretation suggests dip-slip and strike-slip movement along this structure is only in the order of tens of metres.

The conjugate geometry of the faulting is largely influenced by the geometry of the central anticline, with shear zones principally dipping parallel to the respective limbs of this structure (Figs 4.23, 4.25 and 4.27). This indicates that the peripheral synclines were progressively superimposed over the antiformal hinge and this geometry/kinematics is consistent with a flexural slip process. Such a process will involve slip towards antclinal hinges and when layer parallel slip can no longer be accommodated faulting will develop. Furthermore this process is likely to be complicated by the influence of retightening of pre-existing structures (i.e. retightening...
of folds initially inherited from horst and graben configurations; type 0 fold interference patterns). Both mechanisms are interpreted to have been at play in the high strain structural domain, highlighting the difficulty in distinguishing between the different phases of folding. Such a fold mechanism may never generate obvious fold interference and it would be difficult to distinguish more than one cleavage forming event, as the cleavage would be have simply been reactivated.

No attempt has been made to use the classification of fold profiles based on dip isochrons patterns from Ramsay (1982) due to the variability in strain and the effects of rheological differences. In sedimentary rocks of component, homogenous compositions such as the sandstone of the MCF, near symmetrical folds are type 4B-4C folds, based upon the visual classification of Hudleston (1973). Fold profiles near the hinge zone typically are in class 5B to 5E (after Hudleston, 1973) with variation relative to level of strain and lithotype. The limbs of the folds in high strain structural domain are steeply dipping to sub-vertical and are characterised by intense flattening, as well as dissolution and transposition. Folding of the more competent sandstone strata rarely demonstrate thickening in fold hinges. Thickening of the carbonaceous argillite within the fold hinges can be accommodated by delamination along bedding planes and flexural slip. Within structural domain 2 at Central Shaft, in an area where the COM is composed of interbedded dolomite-argillite rocks the fold profiles exhibited in the COM are typically 4D-4E/5D-5E (after Hudleston, 1973).

Although data at NKM is locally sparse, the analysis of the fold patterns and geometries at NKM does allow for the conclusion that the location and wavelength of folds are significantly 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 (Fig. 4.28). Based on this conclusion, the paucity of folds on the NE limb of the Nkana Syncline may well be indicating a simpler basin architecture compared to the syncline keel which could be interpreted as the core of a narrow, complex, syn-rift graben system. 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.

4.6.3 Decoupling at the MCF-KF interface
Localised decoupling at the contact between the MCF and KF occurs within the low, moderate and high strain structural domains, however there is no evidence of movement along this contact in excess of tens of metres (Figs 4.22 and 4.27). This is supported by the sedimentology and basin architecture studies described in Chapter 3, in particular the apparent direct association of the facies associations COM 3 and COM 4 with facies and thickness changes in the underlying MCF, as described in section 3.8 as well as evidence drawn from the analysis of fold profiles and geometries in this chapter.

4.7 DISCUSSION

The following section is a discussion of the development of the key structural features observed at NKM, which have been outlined in the previous sections. Importantly the NKM system provides the opportunity to document the transition from low to high strain structural domains.

4.7.1 Pre lithification –
Pre lithification structures, as described in chapter 3 are suggestive of basinal seismic activity and sediment pile dewatering prior to lithification (e.g. Margara, 1976; Demounlin, 1996). All pre-lithification structures
Figure 4.18. Simplified stacked schematic geological cross sections across the Nkana Syncline, constructed around the basement-MCF and the MCF-KF contacts. The Nkana Syncline plunges moderately to the NW and several parasitic 3rd F folds can be traced for kilometres within the hinge zone. The red line marks contact between the basement and MCF and the top of the yellow unit (MCF) is the contact between the MCF-KF. Examples of the variation in the structural intensity is shown on several of the sections. The contact between the Lower Roan Group and Upper Group Roan has not been depicted accurately on the sections due to the lack of intersection points.
Figure 4.19. Detailed geological map of the west limb of the Nkana Syncline (modified and simplified from compilation of historic ZCCM geological maps (1974 to 1980). The mapped fold geometries of the west limb are similar to those observed on the northeast limb. There is a considerable greater thickness on MCF, which is interpreted to be unrelated to the structural thickening during \( D_2 \) to \( D_4 \).
Figure 4.20. Geological sections of the broad Zero Syncline at Central Shaft depicting the broader open F3 folding within the moderate strain structural domain as well as smaller 3rd order folds (note small antiform structure in hinge). Section constructed from underground mapping and interpretation of drillholes.

Figure 4.21. Plan map. All development is within the MCF and COM inhibiting the ability to document the relationship of the basement-MCF contact in this region. The plan map is located about 500m north of the sections, due to access restrictions on the 2140L 200 to 300S cross cuts.
Figure 4.22. Simplified geological plan of the 3360L at SOB Shaft, constructed from underground mapping and logging of drillholes. The northwest plunging C syncline and anticline are the dominant 3rd F3 folds identified at this location. Figures 4.23 through to 4.26 document in detail the geological mapping of the 4800S and 750N-1250N access drives. The D1 syncline-anticline in the southeast of the area have been further complicated by significant faulting associated with D4, however these structures can only be traced over several hundreds of metres and no significant horizontal or vertical movement has been identified nor interpreted. The location of the cross sections is marked and these are shown in figure 4.27 and a copy of the original A0 hand drawn geological plan map and sections are in Digital Appendix 3.
Anhydrite Flooding within Lower Conglomerate unit and upper contact with Kafue Arenite Member sheared.

Biotite rich shear zones

Massive biotite and anhydrite interval associated with thrusts.

Biotite rich zone

Strongly foliated rocks

Fault, localised chlorite and calcite

Figure 4.23. Geological map of the 2800 mN cross-cut.
Fault zone

Biotite rich shear zones

Massive biotite and anhydrite interval associated with thrusts.

Fault, localised chlorite and calcite

GFW

AFW

AHW

Faulting/Shearing (D4)

Bedding (S0)

Cleavage (S3)

Folded V1 bedding parallel vein sets and V2 syn tectonic veins occurring within carbonaceous argillite of the COM.

Kitwe Formation

Rokana Evaporite Member

Copperbelt Orebody Member

Kafue Arenite Member

Footwall sandstone unit - Kafue Arenite Member

Basal sandstone Member

Basement granite and schist

GFW

AFW

AHW

Copperbelt Orebody Member

Geological Footwall

Assay Footwall

Assay Hangingwall

Footwall sandstone unit - Kafue Arenite Member

Copperbelt Orebody Member

Rokana Evaporite Member

Contact between the Lower Conglomerate Unit (facies Association MCF 4) and the Kafue Arenite Member.

Anhydrite flooding within Lower Conglomerate unit. This is only seen within the high strain domain.

Mainly foliated rocks

Fault, localised chlorite and calcite

D4 fault sub-parallel to the dominant S2 cleavage filled by anhydrite.

Contact between the Lower Conglomerate Unit (facies Association MCF 4) and the Kafue Arenite Member.

Folded V1 bedding parallel vein sets and V2 syn tectonic veins occurring within carbonaceous argillite of the COM.

Figure 4.24. Geological map of the 2800N cross-cut on the 3360L at SOB Shaft with the position of the 'C' syncline and anticline clearly marked.
Figure 4.25. Geological map of the 700N cross-cut on the 3360L at SOB Shaft with the position of the 'C' syncline and anticline clearly marked.
Figure 4.26. Geological map of the 700N cross-cut on the 3360L at SOB Shaft with the position of the 'C' syncline and anticline clearly marked.
Figure 4.27. Stacked, ~70m spaced simplified geological sections for the Nkana Synclinouirium Area (looking northwest) constructed from geological map data and drillhole interpretation. The ‘C’ syncline and anticline are well defined. Significant structural thickening of the COM occurs in the hinge zone of the folds and late stage faulting further complicates the mesoscale fold geometry. The original scans of the A0 hand drawn sections are in digital appendices 3 and 4. They show geological units logged for each drillhole as well as the copper and cobalt grade information. The relationship of the copper orebody geometry to the structural evolution of the NSA will be discussed in chapter 5. Please refer to Figure 4.22 for the location of the sections. The sections are displayed from bottom left to top right moving from SE to NW, down plunge of the ‘C’ syncline.
Figure 4.28. Schematic diagrams depicting the proposed fold geometry relationship to original basin architecture. The structural synthesis presented in this chapter shows that there is significant complexity in the F3 Nkana Syncline, however the majority of this complexity is small scale and observed mainly within the argillaceous rocks occurring in the high strain domain. The broad, large-scale structure in the NKM deposit is dominated by D3 folding. 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 (drawn with the assistance D. Selley).
observed at NKM are evidence of ongoing tectonic activity during the deposition of the Lower Roan Group and were discussed in Chapter 3. Sedimentary compaction and diagenesis contributed little to the formation of a preferred orientation in the grains, as observed by the lack of preferred orientation in the weakly foliated rocks of the COM in low strain domains.

### 4.7.2 Structural elements associated with folding ($D_2$, $D_3$, $D_4$)

$D_2$ to $D_4$ deformation at NKM has resulted in the pervasive deformation of the Lower Roan Group with the physical characteristics of the sedimentary rocks and the basin architecture influencing the style and geometry of $D_3$ structures. $F_3$ folds are predominantly northwest plunging, open to isoclinal with upright to moderately northeast and southwest-dipping axial planes. Folding was accompanied by the development of penetrative $S_3$ cleavage during overall NE-SW shortening. Strain has been partitioned into particular units, with increased deformation of the COM relative to the underlying MCF.

Identified $L_2$ lineations, oblique to the $D_3$ fold axis and occurring at the base of the COM in only the low strain domain are interpreted to have resulted from north northeast – south southwest shortening. No definitive age constraints can be placed on this structural event. Importantly, these lineations have not been identified at higher stratigraphic levels in the KF nor within the higher strain domains.

There are two conceivable interpretations for the development of this lineation. One possibility is resulting from the limited decoupling at the base of the KF associated with a shortening event which was unrelated and occurred prior to $D_3$. The second and favoured interpretation is for the lineation development to have occurred at the onset of the $D_3$ shortening event. This event was responsible for generating $D_3$ folds (i.e. Nkana Syncline) with ongoing progressive deformation and a shift in the far-field stress field resulted in the development of the main $D_3$ structures, oblique to this early lineation. Apart from a shift in the far field stress, the fact that the original basin and facies architecture are intact, the oblique orientation of the $L_2$ relative to $D_3$ may have resulted from a localised change in stress orientation associated with a change in the geometry of the basement-Lower Roan contact. Despite the poor temporal control and definitive connection to a specific tectonic episode, the onset of any compressive event at NKM may have resulted in local decoupling at the stratigraphic boundaries where two distinctly contrasting lithologies are in contact, such as the MCF-KF contact.

The accommodation of plastic strain does not have to be consistent throughout a sedimentary sequence (O’Dea and Lister, 1995). At NKM the fold geometry varies where sedimentary packages containing rocks of contrasting competency have been deformed. The more competent units, such as the MCF, normally maintain close to their original thickness, even at locations of tight folding (i.e. NSA). However unlike the sandstones of the MCF, thickening of the fold hinges and dissolution is common in argillaceous units. Less is known about the deformation of units higher in the stratigraphy of the Kitwe Formation as no accessible underground exposures or intact drillcore were available.

The initiation of the $S_3$ fabric at NKM occurred after the formation of the bedding parallel fibre veins, however prior to dissolution and transposition. $S_3$ cleavage is proposed to have developed by a simple passive Marchan model, parallel to the X-Y principal plane of the finite strain ellipsoid. The foliation within the COM is parallel to sub parallel to the fold axial surfaces and is interpreted as an axial surface foliation since the cleavage has an overall consistent geometrical relationship with the axial planes of the folds, accounting for localised changes due to $D_4$ faults.

Localised anastomosing $S_3$ cleavages, plunge reversals and changes in the axial trace of the fold were observed within tightly folded carbonaceous argillite rocks in high and moderate strain structural domains. $S_4$ cleavage refraction across layer-ductility boundaries is evident, while layer-parallel slip is common at the
interface between competent and incompetent sedimentary units and is commonly accompanied by refraction of the S\textsubscript{3} cleavage to a low angle relative to bedding orientation. Crenulation of S\textsubscript{3} is common in the vicinity of moderate to steeply dipping anastomosing D\textsubscript{4} faults/shears which are predominately confined to the COM. It is proposed that the progressive deformation during D\textsubscript{3} – D\textsubscript{4} shortening resulted in the development of these structures as folds progressively tightened, strain was partitioned preferentially to the argillaceous units and buckling inherited the original basin architecture. The reduction in the interlimb angle of the D\textsubscript{3} folds in these high strains domains also resulted in the partial rotation of the earlier formed foliation planes out of the plane of maximum compressive stress at the same time as the localised D\textsubscript{4} faulting and shearing were initiated resulting in an anastomosing S\textsubscript{4} cleavage pattern observed only within the argillite rocks of the COM.

4.7.3 Relationship of structural style and stratigraphic/basin architecture

The extent to which an individual sedimentary layer or package has been deformed by each mechanism is a function on the relative composition of adjacent strata. The geometry and frequency of F\textsubscript{3} folding, the position and extent of D\textsubscript{4} faulting and the location of each of the vein sets are all strongly affected by rheological differences between the stratigraphic units and the original basin architecture of the syn-rift phase. In the high strain structural domain, the degrees of structural complexity is directly proportional to the amount of argillite and the heterogeneity of the sedimentary succession. Also rather than being distributed evenly throughout a unit, strain appears to also be concentrated at the interface of adjacent sedimentary rock units demonstrating competency differences (Ramsay and Huber, 1987).

Evidence of localised decoupling at the basement-MCF and the MCF-KF contacts were observed, however the extent of slip along these contacts is by no means of regional significant and is typically only accommodating tens of metres of movement based on structural observations. Furthermore, when considered in the context of the basin architecture discussed in Chapter 3, particularly the location of facies associations COM 3 and COM 4, all evidence suggests no regional scale decoupling.

The geometry of shortening-related folds and faults resulting from tectonic inversion of a complex extensional basins is heavily influenced the geometry of pre-existing basin architecture and has been documented in numerous basins (e.g. Bulter, 1989; Pomtma and Betts, 2006). Furthermore it has been identified that the miss interpretation of multiple bulk-shortening directions may occur if little consideration is given to the pre-existing basinal fault architecture.

The classical interpretation of inversion geometry will involve the development of thrusts during compression, with these thrusts localised along pre-existing faults, however O’Dea and Lister (1995) consider that the classical interpretation fails to offer a link between fault displacement, distribution of strain and the composition of the rock. In a revised model for the Crystal Creek block of the Mt Isa Inlier (O’Dea and Lister, 1995) suggest that thrusting is more related to localised buckling rather than through going structures soling out at depth and that strain is partitioned at basement-cover sequence contact and in faults. Typical inversion models result in the development of two structural levels, each characterised by its own deformational style and apparent different deformation (McClay and Buchanan, 1992; Bailey et al., 2002).

Pomtma and Betts (2006) showed that folding proximal to the basement buttress (i.e. basin fault block) is intense and symmetrical, while folding above and distal to the buttress is highly asymmetrical. Bailey et al., (2002) suggest that the rheological contrast between a rigid basement block (fault block) and layer cake stratigraphy may results in the buckling of the cover sequence during deformation rather than the re-activation of pre-existing faults. However they also acknowledge that basement buttressing has been rarely documented apart from a few studies (for example Bulter, 1989). Buttressing against a pre-existing basement block may
lead to the partitioning of the deformation and the development of localised deformation pattern in the separate zone (O’Dea and Lister, 1995) and thus not the result of regional scale changes stress regimes at the time of deformation. O’Dea and Lister (1995) document the orientation of the S₁ cleavage at different transfer and influence of original extensional faults within the Crystal Creek block, Mt Isa concluding that local orientations of fabric need not represent regional shortening directions and such variations may have arisen from heterogeneities in boundary conditions rather than from different deformation events.

Stephens (2001) correctly defined the structural in high strain structural domain. However Stephens (2001) interpreted tight D₁/D₂ synforms (herein called D₁ folds) as being separated by thrust formed antiforms. This interpretation failed to recognise that the pre-existing facies architecture of the MCF and KF are still intact, thus precluding the proposed large-scale thrusting. Furthermore the differences between the interpretation proposed by Stephens (2001) and presented here has a significant impact on the proposed structural controls on mineralisation as will be discussed in the forthcoming chapters.

Daly et al. (1984), Molak (1995) and McGowan (2003) recognized major compression related shear-zones within the Katangan sequence at Nehanga and concluded significant thrusting of the KF over the MCF across the ZCB. McGowan (2003) interpret layer-parallel detachments at three main stratigraphic points at Nehanga: (1) at the top of the arkosic unit; (2) the top of the ‘Lower Banded Shale’ and (3) at the top of the ‘Upper Banded Shale’ unit and concluded that the structural geometry was in part strongly controlled by competence contrasts between different lithologies. Atkinson and Wallace (2003) documented a similar scenario and highlighted the importance of component and incompetent units in a stratigraphic sequence in controlling the position of thrusting and subsequent formation of detachment folds. In the case study of the Nehanga deposit there appears to be no dispute that thrusting has occurred however the application of such a model across the whole ZCB appears to be incorrect based on results of this study.

Additional Hitzman (2000) interprets a large scale decollement surface based on the tectonized contact between the weakly deformed MCF and folded KF observed in the Chambishi Pit. However the close proximity of the Chambishi deposit to the NKM deposit and in light of sedimentological and structural results from this study and those of Selley et al. (2003, 2005) documenting the intact basin architecture at Chambishi SE, the contact zone of apparent increased strain can be plausibly explained in terms of localised decoupling along the stratigraphic boundary and the partitioning of strain into the argillite rocks of the KF, without the need for invoking a regional scale decollement surface as this level of the stratigraphic package.

Previous workers across the Zambian Copperbelt have documented the relationship between “basement highs” and associated anticline-syncline formation (e.g. De Swardt, 1962, 1965; De Swardt et al., 1964). De Swardt (1962) documented the deflection in the axial planes of the primary folds around basement domes which extended to higher structural levels. Recently Selley and Bull (2001) and Selley et al. (2003) documented the structural observations from several weakly deformed deposits in the Chambishi Basin (e.g. Chibuluma West, Chambishi SE and Mwambashi B), clearly demonstrating the geometry of the structures generated during the Lufilian orogeny have inherited the pre-existing early basin rift architecture, particularly the fold geometry development during the Lufilian Orogeny. These works documented examples of partitioning of strain and nucleation of folds parallel to inverted rift shoulders in the Chambishi open pit and at the Chibuluma West deposit. At Chibuluma West high amplitude, low-wavelength basement cored anticlines represent inverted tilt-blocks developed within the footwall of west-northwest-trending half-grabens (Selley and Bull, 2001). To extend this work further it can be concluded that the regional fold patterns, particularly within the northern area of the Chambishi Basin, indicate the geometry of the early basin architecture and particularly the interference of west-northwest and north-northwest trending folds.
Despite the relatively poor 3D control on the basement-MCF across the whole NKM system, several important features can still be concluded about the relationship of fold geometry to original basin architecture from windows into the NKM system. At the scale of the NKM deposit individual stratigraphic boundaries have influenced the style of deformation, as has the syn-rift basin architecture. The lithological variations between the basement and MCF compared to the KF strongly influence the distribution of strain between the different units and the variations in fold geometry. The recognition of the effects of the strain partitioning and pre-existing basin architecture on fold geometry is very significant particularly as other studies have placed a large significance on the geometry and relationship of mesoscale structures observed only within the COM and applied these observations when discussing the deformation of the Roan Group. This study has been able to document that the location and wavelength of folds are directly inherited from original basin architecture by documenting that primary thickness changes of the MCF about the profile and the coincident of changes in the fold attitude with facies changes in the COM. This evidence strongly suggests that the changes in the fold style between domains and even within the high strain structural domain is significantly controlled by the original sub-basin geometry (Fig. 4.28). In such a model the sub-basins are inverted by buckling as opposed to reverse activation of normal faults.

Pre-existing weakness (i.e. faults) are commonly reactivated during deformation, however this may not always be the case. For example, if the dip of the original basement blocks/rift margins at NKM is interpreted to have been approximately $50^\circ$ to $70^\circ$ degrees and that during subsequent sub-horizontal compression the normal stresses may have been greater than the shear stress acting across these faults, than significant slip along these pre-existing structures is unlikely and buckling is more likely to have occurred in the overlying sequence.

NKM is dominated by the NW trending Nkana Syncline, however upon closer analysis subtle changes in the fold geometry are evident from surface mapping data. The change in the fold geometry is interpreted to be related to the position basement blocks and/or inverted faults, particularly as depicted along the western limb of the Nkana Syncline. These changes can be observed from surface mapping and the changes in the fold geometry are coincident with changes in the strike of the basement-MCF contact and/or facies and thickness changes of the MCF and/or rapid facies in the lower most portion of the COM.

The shortening at NKM is interpreted to have been accommodated by two mechanisms, firstly the inversion of original basin margins and secondly the folding of basement and cover sequence with the location of the basement buttresses (i.e. rift fault blocks, margins) controlling the partitioning of strain between such mechanisms. The full restoration of the original rift basin architecture was not possible for NKM, however by documenting similarities between the NKM deposit and studies by Selley et al (2003, 2005) of weakly deformed deposits within the Chambishi Basin as well as published examples documenting the inversion of rift systems (i.e. Bulter, 1989; Bailey et al., 2002; Pomtma and Betts, 2006) it is concluded that original rift basin architecture at NKM significantly influenced the geometry and location of structures formed during orogeny.

4.7.4 Strain Partitioning – Significance

As previously mentioned, strain has been focused within particular units and at the interface between adjacent sedimentary units of contrasting competency. Assessment of the structures solely within one of these units without consideration or context to the immediately underlying and overlying rock packages will result in a distorted understanding of the deformation history of the area (Ramsay and Huber, 1983; O’Dea and Lister, 1995). Mechanisms controlling the degree and influence on fold geometries related directly to rheology contrasts have been presented by Ramsay (1982), Ramsay and Huber (1983), Davis and Reynolds (1996) and Lan and Hudleston (1996) including the mechanical properties of the surrounding layer, cleavage development, crystal
plasticity, grain boundary sliding, pressure solution mechanisms and flexural-slip processes in multilayered sequences. Hobbs et al. (1976) use the term competence to describe a relative brittle or ductile strength, while the term ductility is a measure of the ability of the rock to undergo permanent strain without failure. Variations in the dominant fold wavelengths, shapes of folds and cleavage refractions can result from layer competence contrast and all of which are observed to varying degrees at NKM.

The massive and thickly bedded sandstone dominated MCF has poorly developed penetrative cleavage. Typically arenaceous rocks with less than 10% clay contact do not commonly form disjunctive cleavage as shallow crustal levels (Engelder and Marshal, 1985). Furthermore such packages of rocks behave as stress guides, which when considered in the context of NKM include the rocks of the MCF and basement, whereas the more ductile argillite of the KF will have further ductility enhancements resulting from cleavage formation. The mechanical differences between the basement lithologies and the MCF compared to the layered KF played a significant role as the cover rocks are more likely to have buckled and formed penetrative foliation.

The partitioning of strain into the dolomite argillite and carbonaceous argillite lithotype resulted in flexural slip, pervasive foliation, bedding dissolution and transposition occurring only within these lithotype. The textures and dimensional preferred orientation patterns of silica phase minerals in the high strain structural domain are interpreted to result from the concurrent processes of transposition on a microscale and dynamic recrystallization. The segregation of quartz into layers particularly in the high strain structural domain resulted from dynamic recrystallization with dissolution and precipitation creep most likely to have continued operating on a more restricted basis (Fowler and Winsor, 1997). This can be seen at NKM where the effects of dissolution (pressure solution) are restricted to the margins of quartz-rich layers and early vein generations. There is no evidence of collapsed F3 fold hinges suggesting mineral precipitation in the hinge zones was able to keep pace with deformation.

Davis and Reynolds (1996) indicate that typically the planes of transposition and dissolution are parallel to foliation if not indeed foliation. Transposition was only observed within the argillite units in the high strain structural domain. The process of transposition and dissolution, which only develops in areas of highest strains in multilayered rocks occurs as fold amplification reached maximum, resulting in folds lock up and the process of flexural-slip ceasing (Ramsay and Huber, 1983). Davis and Reynolds (1996) recognised that flexural-slip folds lock-up at an interlimb angle of \( \sim 60^\circ \) as a result of an increase in the frictional resistance between beds. Furthermore within tight to isoclinally folded strata bedding transposition and the formation of a pseudo stratigraphy is common (e.g. Davis and Reynolds, 1996). The hinge zones of the 3rd order folds, such as the ‘C’ anticline at NKM such features. The extent of solution transfer associated with S3 foliation development is likely to have caused a change in volume of COM, particularly in high strain structural domains.

Conglomerates may show significant strain variations relative to surrounding lithologies (e.g. Ramsay and Huber, 1987; Treagus and Treagus, 2002). Within the MCF, the rheological difference between the Lower Conglomerate unit (Mine terminology) and the overlying and underlying sandstone units of the MCF is significant. Within the high strain structural domain, a high degree of shortening occurs in the conglomerate unit, with the level of strain observed being partly a function of the structural position relative to the hinges of synclines and anticline, the matrix-cement component and the internal differences in clast types and sizes. Relatively undeformed conglomerate clasts observed in the low strain domains at Mindola Shaft and these clasts are spherical, sub-rounded to rounded varying in composition from gneissic, granite and quartzite while deformed clasts of the same composition are elongate and sometimes fractured with aspect ratios of 5:1 to 10:1. Despite no detailed assessment of strain within this unit across the three structural domains at NKM, simple observational comparison of this unit between the high and low strain structural domains suggests a
recognisable degree of partitioning of strain into the Lower Conglomeratic unit and that deformation of the clasts formed an axial fabric parallel to $S_3$, during $D_3$ shortening.

4.7.4.1 Role of bedding-Plane Slip

Bedding-parallel slip commonly refers to flexural slip occurring on all bedding surfaces or in the minimum case along the contact between incompetent and competent surfaces within a well bedded sedimentary sequence (e.g. Ramsay, 1982; Tanner, 1989). However in many cases slip in folds is thought not to be equally distributed along all bedding surfaces with localisation of slip occurring while other surfaces appear to be welded together (Tanner, 1989; Couples et al. 1998). Such a mechanism will result in layers of slip having different elongational and contractional fabrics to those beyond intervals of active bedding parallel slip. When considering the Lower Roan Group at NKM slip has been almost entirely confined to the beds within the KF. As Gessner et al. (2006) noted at Mt Isa, shales commonly deform by layer-parallel shearing whereas siltstones have a greater tendency to selectively fracture which will ultimately result in significant variation in deformation behaviour and changes in deformation-related permeability. Multilayer flexures is cumulative process which superimposes different stress states at different times and the slip zones themselves can act as barrier to fluids beyond that expected for the stratigraphic sequence (Couples et al. 1998). Evidence for bedding-parallel slip influencing syn-tectonic fluid dispersal at NKM is not conclusive, however it is a plausible mechanism controlling to fluid circulation and dispersion during deformation due to the development of fractures and subsequent veins.

4.7.5 Vein Development

4.7.5.1 Bedding Parallel Veining (VI)

Bedding parallel veins occur in the low and high strain domains within the basal portion of the COM. Bedding parallel veins can be formed pre- or early-folding where differential movement along bedding surfaces or there has been an associated build up of high fluid pressure until a state of over pressure is reached (Ramsay and Huber, 1983; Fitches et al., 1986; Gavigilio, 1986; Tanner, 1989; Henderson et al., 1990; Jessel et al., 1994; Sibson, 2001). For example, bedding parallel veins occurring in the Wenlock slates of Wales have been described as forming by pre-folding hydraulic jacking by an over pressured pore-fluid (Fitches et al., 1986; Cosgrove, 1993, 2001). However, fibrous carbonate veins can form during late diagenetic history of a sedimentary basin (Ramsay and Huber, 1987). The formation of bedding-parallel veins during compaction indicates that there was a significant quantity of fluid still within the sedimentary pile an with the reduction in pore spaces, this results in zones of increased pore fluid pressures knows as geopresseded zones (Ramsay and Huber, 1983). Such late diagenetic veins formed result from fluid expulsion which could not keep pace with volume reductions due to the reorientation of the sedimentary grains.

Annels (1989) and Greyling et al. (2005) documented sub-concordant veins occurring at the base of the COM at the Chambishi SE deposit. These veins were interpreted to have formed during late diagenesis, and the vein emplacement resulted in the lateral secretion of disseminated Cu-sulphide mineralisation from the host lithotype into the quartz vein. This interpretation was based on the fact the subconcordant veins have the same sulphide mineralogy as the adjacent argillite and that there was a halo depleted of mineralisation immediately surrounding the vein. Another feature identified by Annels (1989) suggesting vein formation during diagenesis is that vein minerals have penetrated and enclosed some of the host grains, however such a texture was not identified at during this study. However the enclosing of host rock within a vein is not considered conclusive evidence for diagenetic vein formation. Similar quartz-dolomite (+-sulphide) bedding parallel to sub-parallel
veins have been described at Nchanga (McGowan et al., 2003).

At NKM, it is interpreted that the onset of shortening (D₂) resulted in an increase in the lithostatic pressure and associated localized decoupling along the MCF-KF stratigraphic contact which is interpreted to have been accompanied by extension in the immediate hangingwall (i.e. basal portion of the COM). It is envisaged that the essentially undeformed package of Roan Group rocks underwent compression resulting in layer parallel shortening prior to the onset of fold amplification (e.g. Jessell et al., 1994). The significant competency contrast between the MCF and KF and the differences in bedding thickness between the two units has controlled the amount of shortening prior to buckling and the rate of amplification of a single layer (e.g. Hudleston and Stephansson, 1973; Crespi and Chan, 1996). Flexural-slip folding commonly has associated slip on bedding planes and the slip process is concentrated on the limb of the folds, preserving the bedding parallel veins, while the curved fibres observed in some of the bedding parallel veins are explained by fibre deformation and grain boundary migration (Williams, 1980). Whether the shortening event forming the bedding parallel veins and the later S₃ cleavage formation are directly related was not resolved in this study, however it is clear that the folded bedding parallel veins were generated prior to the main amplification of the D₃ folding phase. Neither has it been conclusively shown that the oblique lineation and bedding parallel veins were initiated during a separate pre-D₃ event or were formed at the onset of D₃ and record a change in far field stress during D₃. It is highly plausible the oblique mineral lineation and bedding parallel veins record an earlier and distinctly separate compressional event.

4.7.5.2 Syn-tectonic veins (VII, VIII, IV)

Syn-tectonic veins provide important information on metamorphic fluid flow, fluid-rock interactions and deformation conditions during an orogenic event. The D₃ to D₄ deformation of sedimentary rocks at NKM resulted in the formation of cleavage parallel and cross-cutting veins. The frequency of axial-planar veins increases toward the hinges of D₃ fold and are most prevalent in the carbonaceous argillite rocks within high strain structural domains. Arrays of variably deformed sub-vertical, cleavage parallel veins occur near the basal contact of COM within the high strain structural domain. The vein complexity is results from ongoing vein reactivation during progressive deformation particularly influencing the morphology of veins. Vein formation during cleavage development likely involved the progressive opening of pre-existing NW-SE striking veins as well as the formation of new cracks and subsequent veins. The generation of these new veins resulted from a change in the tensile strength of the rock during cleavage development (Crespy and Chan, 1996). The composition of the cleavage parallel and post-cleavage developed veins are similar to the composition of the host sedimentary rocks suggesting the components were from the dissolution of silica and carbonate-bearing minerals during deformation. As such it is interpreted that the mineral assemblages of the veins were derived through dissolution of silica and carbonate-bearing minerals originally contained in the host or immediately underlying sedimentary sequence and possibly related to the structural thinning of the COM on limbs to F₃ folds.

4.8 SUMMARY

This chapter described and interpreted the key structural fabrics, fold morphologies and structural relationships at NKM formed during the ~560 Ma to 520 Ma Lufilian Orogeny. Three deformation stages are recognised from underground mapping, core logging and analysis of pre-existing surface geological map datasets. The northeast-southwest to north-northeast- south-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.

Competency differences between adjacent sedimentary units, particularly between the MCF and the overlying KF, have locally influenced the fold morphology, the later development of faulting and the formation and distribution of veining. Compositional layering within the argillites and shales rocks of the COM has also significantly influenced the mechanical behaviour and strain. This was an important control on the syn-tectonic fluid flow and subsequent vein formation. The partitioning of strain to the finer grained units of the Kitwe Formation resulted in mesoscopic scale complex structure in these units, however this is somewhat misleading to the overall folded structure of the NKM deposit as defined by the key stratigraphic contacts of basement-MCF and MCF-KF. Within the high strain structural domain components of coaxial and none coaxial strain were likely to be operating during progressive deformation and the geometry of the inherited basement structure and syn-rift basin architecture strongly influenced the variation in strain.

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.

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.

The defining of three separate deformation events does not necessarily mean each of these deformation events were the result of three distinctly separate shortening events, especially if as interpreted in this study Type 0 folds formed. Furthermore there is no evidence that the three deformation episodes were separated by significant time interval. It is most probable that 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. The structural synthesis presented in this chapter shows that there is significantly complexity in the F₃ Nkana Syncline, however the majority of this complexity is small scale, related to inheritance from the complex syn-rift basin architecture, strain partitioning and rheological differences between key units. The NKM deposit is dominated by D₃ folding.