Chapter Four - Structure

4.0 Introduction

This study is the first structural analysis to be undertaken in the central to northern regions of the Paterson Orogen and has only been possible because open pit mining at Nifty has created new exposures. Previous structural studies in the Paterson Orogen (Hickman and Clarke, 1994; Hickman et al., 1994; and Bagas and Smithies, 1995; Reed, 1996) have concentrated on the areas of well exposed Thrussell and Rudall Complex rocks in the Sunday Creek. Studies undertaken to the south of Nifty have identified two deformation events that are interpreted as occurring pre-Thrushall Group deposition (Hickman and Clarke, 1994; Hickman et al., 1994; Bagas and Smithies, 1995). To aid comparisons between these earlier workers and the interpretations of this study, structural events observed at Nifty have been designated as “Nifty De” and abbreviated to DDe. Regional events are noted as “Rudall Dr” and DDr.

This chapter describes the deformation sequence observed at the Nifty Cu deposit. The aims of examining the structure of the deposit are:

1. Identify pre, syn-, and post-mineralisation structures and deformation and establish their relationship to the sites of mineralisation and alteration.
2. Recognise the deformational evolution and the effect that deformation has had on the present localisation of mineralisation.
3. Develop a model for the structural evolution.

This structural synthesis has been made from an analysis of bedding, cleavages, lineations and folds from the Nifty open cut mine, the surface outcrops that form the Nifty syncline to the local mine area, and the more distant outcrops known as A, B, C and D beds (Norris, 1987, 1987b). All bearings given in this chapter are in mine grid. Mine grid is 23.5° east of true north. When compass quadrants such as north, south, or north-east etc. are used, the direction is with respect to true north. Stereoplots presented in this chapter are equal-area lower hemisphere projections and have been prepared using a computer program, GEOrient (Holcombe, 1995). Local outcrop mapping used 1:500 scale maps prepared by WMC Resources Ltd (Mazzoni, 1982; Norris, 1985). The location of drill hole collars and the surface trace of the drill holes were taken from WMC Resources Ltd. plans (Brooke, 1989; Carmichael, 1990).

4.1 Overview of Deformation Events

This section presents an overview of the deformation events observed at Nifty and will provide the base for later descriptions. Four deformation events are recognised from bench mapping in the open pit at Nifty.
4.1.1 \( D_{31} \)

Two styles of early folding are observed in the open pit and diamond drill core (Fig. 4.1A-E). Centimetre scale, angular, polycrinal folds (Fig. 4.1A-C) with horizontal axial planes occur on the western wall of the open pit at the contact of the pyrite marker bed with the upper shale. The folds are transected by a slaty \( S_2 \) cleavage at approximately 90° to the fold axial plane. The fold is confined between planar beds that show no obvious signs of shortening. Figure 4.1C shows an equal-area stereonet plot of structural data from the fold at 260°F=88m. The fold axis and axial plane are flâ© lying. Although this fold is presently recumbent the original orientation was probably steeper as the structural history indicates that this fold occurs on the steep limb of an \( F_1 \) fold. It is interpreted that these are \( F_1 \) folds that formed along discrete zones of slip before rotation to a recumbent orientation.

A second style of early folding occurs as centimetre scale, isoclinal folds that are observed in laminated shales in eastern area domain and also in diamond drill core (Fig. 4.1D-E). Examination of this fold style in thin section and hand specimen shows a poorly developed axial planar cleavage that is cross-cut by \( S_2 \) at high angles (Fig. 4.1E). The true orientation of isoclinal folds in diamond drill core cannot be determined but they are sub-parallel to nearby bedding and are interpreted as early recumbent folds. Bedding parallel isoclinal folds have also been recognised in diamond drill core from Warnaby and Fisch (P. Dare, pers. comm. in Canniched, 1993).

4.1.2 \( D_{32} \)

\( D_{32} \) is a regional faulting, folding and cleavage-forming event during which the Nifty syncline formed (Fig. 3.2). Faults occur as north-west to south-east striking, north dipping thrusts with the northern block upthrusted. Folds are upright and open, doubly plunging structures with axes trending north-west to south-east. Considerable complexity exists associated with the differences in plunge direction of fold axes and cleavage-bedding lineations within individual domains. The change in fold plunge onto the overturned limb suggests that the fold is partly non-cylindrical and perhaps tightened in association with high angle reverse faulting. A penetrative slaty cleavage axial planar to \( F_{32} \) has developed (Fig. 4.2) and is north-west to south-east striking and steeply north-east to north-north-east dipping. \( S_{32} \) cleavage is best developed in fine-grained carbonaceous shale and dolomitic marlstone as shown in Figure 4.2. This cleavage is dominant throughout the open pit but is often obscured in surface outcrop due to weathering. In localised areas \( S_{32} \) has been folded during \( D_{33} \).

4.1.3 \( D_{33} \)

Rare occurrences of folded \( S_3 \) were observed in the open pit at 280/D=42m (Fig. 4.3A-B) in the hinge zone of a large \( F_{32} \) fold in the western wall (1996). At this site \( S_{32} \) cleavage is folded and a second slaty cleavage has formed in the core of \( F_3 \) folds. The \( F_3 \) axis as calculated from poles to bedding is 26°/297°. The \( S_{32} \) slaty cleavage has also been folded with the fold axis plunging 33° toward 277° (Fig. 4.3B inset). A \( S_3 \) cleavage occurs in localised zones in the hinge of \( F_{32} \) folds where it is a slaty cleavage axial planar.
Figure 4.1A, B, C, D. A, B, fold in laminated shales of the upper shale unit on the western face of the open pit (1996). This fold style occurs as centimetre-scale, angular, polyhedral folds with a horizontal axial plane. Slaty S_2 cleavage cuts the fold axial plane at approximately 90° (note pen for scale in A and D). B. Sketch of F_1 showing orientation of bedding, F_1 fold axis trace and S_2 cleavage. C. An equal area stereoplot of an F_1 fold at 250/F+8m. The calculated fold axis plunges 03° towards 087°. Symbols: bedding (○), measured fold axis (■), measured cleavage bedding intersection lineation (©), pole to the measured fold axial plane (+). D. Plane polarised photomicrograph of an isoclinal F_1 fold in interbedded dolomite mudstone and carbonaceous shale. Note the weakly developed S_1 axial planar cleavage.
Figure 4.2: $S_{\alpha}$ is a north-west, south-east striking, steeply north-east to north-north-east dipping, penetrative slaty cleavage developed during regional folding. $S_{\alpha}$ cleavage is best developed in fine-grained carbonaceous shales and dolomitic mudstones (THRD635, 319.4m).
Figure 4.3A-B: Rare examples of folded \( S_3 \) cleavage are observed in the western wall of the open pit (1996). A slab \( S_3 \) cleavage occurs in the centre of these \( F_3 \) folds. A. Photograph of Site 260/F+44m, note hammer for scale. B. Sketch of photograph shown in (A) with structural data and as an inset stereoplote of dip data and \( S_3 \) cleavage.
to F3. Elsewhere, S3 occurs as a spaced cleavage with 1-5cm between cleavage planes. Figure 4.4 shows a hand-specimen of hangingwall shale from the open pit (101880mE, 59620mN, 250mRL) showing L3 and L4 bedding cleavage intersection lineations. The difference in orientation between the two lineations is approximately 15°. Associated with F3 are faults that are parallel to the fold axial plane and are likely to have formed as accommodation structures during folding.

4.1.4 D9a

D9a occurs as open folds at mesoscopic scale with generally horizontal axial planes but with highly variable axial trace trends (Fig. 4.5). Figure 4.5 shows a series of open folds with horizontal axial planes on the northern wall of the stage 1 open pit. No cleavage was observed associated with this style of folding. Also associated with D9a are small scale (<1m) folds and associated faulting (Fig. 4.6). This occurs in an area confined to the northernmost western wall and the northern wall of stage 1 open pit. Bedding parallel shortening has ramped approximately 60cm thick shale beds and zones of altered and mineralised rocks (Fig. 4.6). As this fold style offsets rocks that have undergone silicic alteration associated with mineralisation, a post-D9a timing is interpreted. Carmichael (1993) interpreted these ramp structures as D9a.

Figure 4.6: Shale beds and bands of mineralised and altered rocks in the corner of the western and northern open pit walls have undergone layer parallel shortening that has resulted in thrust-ramp style faulting and folding (3000/A+8m).

4.1.5 Post D9a

Subsequent to D9a there has been several brittle faulting events and the intrusion of dolerite. The dolerite dyke shown on the eastern edge of Figure 3.2 is not exposed at surface but has been intersected at shallow depths in RC and diamond drilling and in the eastern pit wall. This dyke has been offset by a series of normal faults. The timing of the faulting can be constrained as post-mineralisation and post-D9a deformation as 1) a mineralised xenolith was found in diamond drill core TND 14, and 2) no cleavage has developed in the dolerite of the dyke. A poor, two-point Rb-Sr date of 700-750Ma is reported for this dyke in WMC Resources Ltd. records but no details on sample location, methods or results have been published.

40
Figure 4.4: The orientation of \( S_{01} \) cleavage varies from \( S_{02} \) cleavage by approximately 15°. This example shows \( L_{01} \) and \( L_{04} \) cleavage bedding intersection lineations in hangingwall carbonaceous shale (sample from the open pit 1996, 10180mE, 506200mN, 250RL).
Figure 4.5: $F_3$ folds are exposed in the northern wall of the open pit (looking north, 1996) as a series of open folds with generally horizontal axial planes but with highly variable axial trace trends. No cleavage is associated with this style of folding.
4.1.6 Fault History

This fault history was developed from bench mapping in the open pit, outcrop mapping in the local area, and logging of structures in diamond drill core. The correlation between faults that are observed in outcrop and those in diamond drill core is difficult. Correlations between surface exposures and drill core were made by projecting measured fault planes from surface to drill holes. Deformation in drill core at the estimated intersection depth were examined for consistency in the sense of movement, apparent timing relationships with respect to established vein stages and alteration textures, and the style of deformation.

Several cross-sections have areas unconstrained by drill core or surface exposure and faults in these areas have been projected along section.

Faults shown in Figure 3.2 have been labelled R-Z. Cross-section 101700mE (Fig. 3.2, A-A') extends from TND3, which is located north of the open pit, to outcropping Nifty member in the mine south domain. TND3 intersects a major fault between 98-103m and this fault is labelled T1 on Figure 3.2. Above this fault, bedding and cleavage in the diamond drill core is sub-vertical and below the fault they are sub-horizontal. The orientation of bedding and cleavage cannot be determined exactly because the drill hole was drill vertically and no orientation data measured during drilling. The stratigraphic succession in TND3 consists carbonaceous silt and shale above 153m and beds of carbonaceous shale containing evaporitic mineral pseudomorphs below. This succession is different from that exposed in diamond drill holes through the main primary ore body suggesting that faulting has juxtaposed footwall beds from deeper in the basin. The amount of offset is difficult to estimate because of the poor exposure and lack of drilling in the footwall. The deepest diamond drill hole (THRD780) at Nifty finished at 814m (approximately 360m below the Nifty member-footwall beds contact) and no correlation can be made between footwall exposed in THRD780 and TND3, suggesting the potential for a large offset. The dip direction of T1 is interpreted as north dipping because of if this fault dipped south then it would be observed in other diamond drill holes. Fault T1 is interpreted as a north-dipping thrust fault related to D12 deformation.

Two small (~50m wide), fault bounded blocks containing the pyrite marker bed were observed during rip mapping in the open pit floor ([996] Fig. 3.2; cross sections A and B; and Figure 4.2). The western-most block has is bounded to the north-east and south-west by faults S and R respectively. Sinistral offset by fault S has occurred resulting in the blocks current position close to the northern wall of the open pit. Fault S is exposed in the northern wall of the open pit and strikes approximately 118° and dips steeply (>70°) to the south. Projections of the fault plane were intersected in TND16 and TND18 at 154m and 168m respectively where disrupted intervals occur. Fault S has been offset by later north-east to south-west trending faults and the extension of S, between W1 and W2, has not been observed. The other block containing pyrite marker bed occurs in the stage 2 shale domain, south of a line projected from the upper contact of pyrite marker bed in the western end of the open pit. This block is bounded to the north-east by fault T2 and to the south-west by fault R. No pyrite marker bed is exposed east of the two offset faults.
bounded blocks however as shown in cross-sections B-E the pyrite marker bed occurs at depths below this area. The omission of the pyrite marker bed in the eastern end of the open pit is interpreted here as a result of movement on a T2 thrust. T2 is interpreted as a north-dipping thrust associated with D12 deformation and may be a splay from the T1 fault. The T-series of faults form part of a regional fault pattern of north-west to south-east striking, north dipping thrusts that were first recognized from geophysical images (Carmichael, 1993).

The north-east to south-west striking faults (labelled U-W in Fig. 3.2) have sinistrally offset outcropping pyrite marker beds and Nifty member rocks in the open pit and mine south domain. These faults are exposed in the western and southern walls of the open pit. Faults U and V dip approximately 70° to the north-west. Projections along strike of faults U and V are shown in cross-section 101700mE (Fig. 3.2, section A-A'). It is interpreted that faults U and V are younger than faults R, S and T and have offset them. Offsets of the stratigraphy along the northern margin of the open pit are sometimes dextral and the available evidence supports a large component of dip slip movement on these faults.

The W-fault spays (W1 and W2) are close to the edge of the open pit southern wall. The southern splay, W1, occurs as a major shear zone approximately 10m wide that cuts through the eastern end of the open pit. The W2 splay can be traced across the floor of the open pit. Drag on bedding was observed in the stage 2 pit wall and this indicates that the southern side of the fault has been uplifted. Offset of outcropping pyrite marker bed suggests a sinistral component to the movement.

Fault X is a reverse fault that dips steeply to the south. Rotation of bedding in surface outcrops (102100mE, 5060mN) by approximately 40° to the south suggests a dextral component to the movement on this fault. The dextral movement is in agreement with the offset observed in the pyrite marker bed. On cross-section 102000mE fault X is intersected at approximately 230m in THRD640 as a zone of shear that has elongate (strained out) pyrite clots and blebs. This fault is also intersected in TND5 at 349-355m on cross-section 102080mE as a zone of intense shearing. The X fault is interpreted to converge with, and be truncated by W1.

Fault Y is a steeply, south dipping, reverse fault. In cross-section 102080mE (Fig. 3.2, section C-C') fault Y intersects THRD781 at 369m where sub-vertical unasilted carbonaceous shale overlie sub-horizontal silicified dolomite muddstone. As observed in Fig. 3.2 section C-C', fault Y has offset stratigraphy and caused a repeat of upper shale and upper unit rocks in diamond drill holes. Further east in cross-section 102160mE (Fig. 3.2, section D-D'), fault Y is intersected in THRD751 at 180m and THRD755 at 317m, and in cross-section 102240mE (Fig. 3.2, section E-E') fault Y intersects THRD635 at approximately 233m. Above the fault zone a change in the orientation of cleavage occurs between 229-7-231.5m suggesting a post-5 timing for fault Y. Intense biotiterisation and bladed carbonate vein occurs at the base of TND10 and the occurrence of bladed carbonate veins suggest a D1 or post-D4 timing (see Chapter Five, Section 6.4.2). Fault Y also intersects THRD780 at 452m, and on cross-section 102320mE (Fig. 3.2, section F-F') THRD667 at approximately 400m.
Fault Z is steeply north dipping, not seen in diamond drill holes apart from THRD639 where at 404m shearing occurs. In cross-section 102160mE, extensive brecciation occurs at the base of THRD755, from 450m to the end of hole. This brecciation is interpreted to have been caused by fault Z suggesting that Z truncates Y at depth. Fault Y is interpreted as syn- to post-D4b based on fault cross-cutting D4a structures and therefore fault Z is younger.

4.2 Structural Domains in Local Outcrop

Figure 4.7 presents structural orientation data including bedding, cleavage, cleavage bedding intersection lineations, fold hinge lines, fold axial planes, and fault planes measured at Nifty. As can be observed in this figure, individual deformation events have complex geometric relationships (Fig. 4.7) therefore the region was divided into structural domains. Local outcrops occur as three close groups separated by Tertiary laterite, soil and sand dunes. Figure 4.8 shows the extent of local outcrop at Nifty and the three structural domains that were defined as: southern, mine south, and northern. The southern domain consists of outcrops south of the main Nifty-woodie Woodie road. They consist of a series of low rubble strike ridges to the west and a series of small rounded hills toward the east. The mine south domain consists of a group of outcrops to the south and south-west of the open cut pit (Fig. 4.8). As the name suggests the open pit domain consists of all exposures in the open pit and this area is dealt with in a following section. The northern domain consists of a series of outcrops on the northern limb of the syncline not including the open pit area (Fig. 4.8). Stereoplots of bedding, S2 cleavage and L1-2 lineations from southern, mine south and northern domains are presented in Figure 4.8B-D.

4.2.1 Southern Domain

Structural data from the southern domains show shallowly, north-west plunging folds, cleavage steeply dipping to the south-west and calculated fold axes co-axial with L1-2 lineations indicating an axial planar cleavage. The calculated fold axes for the southern domains is 08°5299°. S2 cleavage is typically indeterminate with only five measurements recorded showing cleavage dipping approximately 60° to 230°. L1-2 lineations plunge to the north-west and south east with a spherical mean of 18° to 105°. Outcrop Sth A (101054mE, 49095mN see Fig 4.8 for grid) consists of graded micaceous shale beds outcropping between two sand dunes. The graded bedding dips 70°216° and youngs to the south-west. The younging direction of this outcrop suggests this site is not on the southern limb of the Nifty syncline. Prominent linear outcrops of sandstone and gossanous beds (Sth B) occur close to 101300mE, 49335mN and these beds dip approximately 70°205°. L1-2 lineations can be observed and commonly plunge 20° to 090°220°. Sth C consists of a rugged knoll of fine-grained micaceous sandstone (102240mE, 49350mN, Fig. 4.8) with bedding dipping north at approximately 70°. S2 cleavage dips to the south and south-west between 50°-85° and L1-2 lineations plunge 65°-20° toward 300°.
Figure 4.7: Combined structural orientation data including bedding, $S_1$ and $S_2$, cleavage, $L_1$, and $L_2$, cleavage-bedding intersection lineations, fold hinge lines, fold axial planes, and fault planes measured at NIFS. As can be observed, individual deformation events are not well displayed in these stereoplots therefore the local region was divided into structural domains.
Figure 4.8A-D: Structural domains were established for the local outcrop. These domains shown in (A) and are labelled southern, mine south, and northern. The southern domain consists of a series of medium- to coarse-grained siliceous sandstone with minor silts and shales of the footwall beds, mine south consists of gossanous, silicified shale of the pyrite marker bed and Nilly member, and the northern domain consists of fine- to medium-grained micaceous sandstone interbedded with laminated shales. Stereograms of structural data is shown in B-D. Symbols: poles to bedding (b), poles to cleavage (a) and the trend and plunge of cleavage bedding intersection lineation (o).
4.2.2 Mine South Domain

The Mine South domain was mapped at 1:500 scale by WMC Resources Ltd (Mazzoni, 1982; Norius, 1985) however this mapping was restricted to lithology and the orientation of bedding. Orientation data was recollected during this study using the 1:500 scale outcrop maps as a base. The mine south domain consists of gossanous outcropping pyrite marker bed and laminated shale and dolomitic mudstones of the Nifty member. In outcrop, the contact between the footwall beds and the overlying Nifty member is poorly constrained and the units that make up the Nifty member cannot be identified due to the lack of outcrop and surface weathering. Bedding data defines a shallowly east-south-east plunging fold (127°106°). Cleavage orientation was difficult to determine in outcropping rocks of this domain due to surface weathering however lineation data was measured. L₃ lineations show a spread of trend data from north-east to south-east and appear to be spread about a small circle suggesting folding of these lineations about a steep fold axis.

At site MS1 (100750mE, 50530mN: Figs. 3.2 and 4.8A) a series of folded gossanous beds outcrop. Measured fold hinges plunge approximately 30° to 120° and this direction is coincident with measured L₃ lineations and the calculated fold axis (Fig. 4.9).

![Figure 4.9: Stereoplot of site MS1 (100750mE, 50530mN) shows a shallowly plunging fold with coincident L₃ and measured fold hinges. Bedding (θ), L₃ cleavage bedding intersection lineations (α), measured fold hinge trends (γ), and the calculated fold axis (O).](image)

The gossanous beds at site MS1 form an almost continuous outcrop to site MS2 (101000mE, 50350mN: Figs. 3.2 and 4.8A) where the surface expression of the beds is offset sinistrally by approximately 15m. Outcropping beds of laminated shale have been rotated 45° by drag folding. Between sites MS2 and MS3 (200m) there are two other major faults that have offset outcropping gossanous pyrite marker bed. The sense of movement and magnitude of offset is similar to that observed at site MS2. Site MS3 is centred on a small (30m long), flat topped knoll (101500mE, 50250mN) consisting of well-defined beds, approximately 30cm thick, of Nifty member shale and gossanous pyrite marker bed. Bedding dips approximately 53° to 024° while L₃ plunges approximately 31° to 108° (Fig. 4.10). A difference in trend of the L₃ occurs between that measured at MS1 and MS3. The calculated vector means for sites MS1 and MS3 are 31°/108° and 30°/076° respectively (Figs. 4.9 and 4.10).
Figure 4.10: Stereoplot of site MS3 (100100mE, 5050mN) shows all data plotting on a south-dipping fold limb with coincident L1, bedding (a), L2 cleavage bedding intersection lineations (o).

Site MS4 (Figs. 4.2 and 4.8A) was mapped prior to being covered by heap leach pads in 1997. The area consists of isolated outcrops, each approximately 1m², of weathered shale and dolomitic mudstone with areas of scree and quartz float in surface laterite.

4.2.3 Northern Domain

The northern domain consists of a linear series of isolated outcrops of laminated micaceous shale with laths 3-20mm thick (Fig. 4.3A). Less resistant rocks have been weathered out leaving exposed strike ridges. The outcrop surface has weathered an orange brown and when fresh the shale is light grey. Combined structural data from this domain is shown in Figure 4.8D and three sites, occurring as isolated outcrops (Nth 1-3) are described in more detail. The outcrop extent of site Nth 1 is approximately 100m x30m and consists of a series of linear strike ridges surrounded by weathered rubble and scree. Figure 4.11A shows the orientation of the S0, S2, S3, L1, and L2 from the northern domain and this data forms a complex pattern. The fold axis calculated from bedding plunges 36°/294° (Fig. 4.11A). Slaty, S0, cleavage is overprinted by a second less well developed slaty cleavage (S2), and the difference between S0 and S2 is approximately 20° (Fig. 4.11B).

Figure 4.11A-B: A. Combined bedding, S0, S2 and S3 cleavages and lineation data from site Nth 1 (102100mE, 51450mN). B. Site in Nth 1 outcrops. The difference in orientation between the two generations of slaty cleavage is approximately 20°. Symbols: poles to bedding (a), S2 cleavage (c), S3 cleavage (+), and cleavage bedding intersection lineations (o).
Stereoplot of orientation data (Fig. 4.12) from site Nth 2 shows bedding dipping steeply to the south with cleavage striking anticlockwise of bedding and steeply dipping north. Lineations plunge at shallow angles with a vector mean of 28°7'29"30'. S_{02} cleavage was not observed at site Nth 2.

Figure 4.12: Stereoplot of orientation data from site Nth 2 in the northern structural domain. Symbols are the same as Figure 4.11.

Site Nth 3 is a small knoll (102500mE, 51225mN) that outcrops between two sand dunes. The outcrop extent is approximately 120m x 60m of laminated footwall shales in strike ridges. Orientation data from site Nth 3 (Fig. 4.13) is similar to that of site Nth 1 with the exception that the plunge of E_{02} has a vector mean that is shallower (21° as opposed to 28°).

Figure 4.13: Stereoplot of orientation data from site Nth 3 in the northern structural domain. Symbols are the same as Figure 4.11.

4.3 Open Pit Structural Domains

Details of the open pit and mine south domains is shown in Figure 3.2 as a compilation of outcrop (Mazzoni, 1982; Norris, 1985) and interpreted geology (this study), drill hole collars (Brooke, 1989; Carmichael, 1990), and cross-sections (this study) through the primary ore body along 101700mE, 102000mE, 102080mE, 102160mE, 102240mE, and 102320mE. Outcropping northern limb pyrite
marker bed and Nifty member rocks (Fig. 3.2) have been excavated during mining prior to this study and therefore mapping by WMC Resources Ltd. geologists (Mazzoni, 1982; Norris, 1985) has been used in conjunction with bench mapping (this study) within the open pit for interpretations concerning this area. As shown in Figure 3.2, the only diamond drill hole collared north of the open pit is TND3. A gap in drilling occurs between the open pit and the primary ore body and therefore structural interpretations in this region are less reliable than the area to the south where drill hole control is much better.

The open pit was divided into domains based on the continuity of structural data and these domains are shown in Figure 4.14. Preliminary open pit domains were established from inspection of bedding and S2 cleavage data that was then plotted on stereonets. Data from sites on the margin of the preliminary domain boundaries was added until it distorted the stereonets of the domain. The domain boundaries were then redefined to represent zones of cylindrical F16 folds (poles to bedding on a simple great circle) and constant S2. Names associated with the general geographical location of the domains have been used and these domains are west wall, north wall, eastern area, and stage 2 shales. The west wall domain consists of all levels to the 250m reduced level (Figs. 4.14) and includes a large fold in that face (exposed during 1996). The north wall domain consists of all levels and the stage 1 ramp on the northern face of pit. Some areas within this domain were inaccessible because of unstable slopes (Figs. 4.14). The eastern area consists of benches at eastern end of the open cut in stage 3 to the 280m reduced level bench (Figs. 4.14). The stage 2 shale domain consists of north-west facing walls in the stage 2 shale area (Figs. 4.14). Site locations (eg. 260D+10m) are identified by the reduced level of the bench used for mapping (eg. 260), a letter designation for surveyed markers (eg. D), and the distance from that marker to the site in metres (eg. +10m).

4.3.1 West Wall

The best exposure of the Nifty deposit stratigraphy can be seen in the west wall domain (Fig. 3.4 and 4.14). Hangingwall beds are observed on southern edge and basal lower unit - lowermost footwall on the northern edge. Structural data and stereoplots are shown in Figure 4.15. Poles to bedding from the west wall (Fig. 4.15) show a fold axis plunging 27°/280°. Most of the cleavage poles cluster to the north or south, however, there is a scattered group with dips between 25° and 55° to the west (Fig. 4.15). These westerly dipping measurements were taken from the hinge zone of a large fold that dominates the west wall and shows local refolding of S2. Lm1 (S0/S2) forms a scattered group with the spherical mean plunging at a shallow angle toward 268° (Fig. 4.15). The plot of measured fold axes shows a group of six data points that plunge toward 060°; these trends are interpreted to be F16 folds axes (Fig. 4.15). A second unclassified group of axes plunge at high angles toward the south or south-west.

To examine the generations of cleavage and folding in the west wall, the domain was further subdivided into WWS (west wall south), HIN (hinge zone of large fold), WWN (west wall north), and CNR (corner) (Fig. 4.16). Figure 4.16B-H present stereoplots of poles to bedding and poles to cleavage planes for the west wall sub-domains. The orientation of cleavage in WWS stereoplots (Fig. 4.16B and F) shows a trend
Figure 4.14A-C: Structural domains were established in the Nifty open pit. Domain boundaries are shown in (A) and are labelled west wall, north wall, eastern area, and stage 2 shale. Pit mapping of the structural domains and stereoplots of structural data are shown in Figures 4.15-4.22. B. Key symbols used in Figures 4.15-4.22. C. The colours used in the stratigraphic column (C) are used in Figures 4.15-4.22 to denote the respective units. Detailed descriptions of the stratigraphic units are contained in Chapter Three.
Figure 4.15: Sketch map with structural data from the west wall domain (exposed in 1996). This domain contains an almost complete stratigraphic sequence of the Nifty member. The majority of the face consists of Nifty member with pyrite marker bed and hangingwall shales exposed to the south and footwall beds to the north. See text for a discussion of structural orientation data and Figure 4.14 for legend.
Figure 4.16A-H: The west wall of the Nifty open pit (1996) showing the sub-domain boundaries (WWN -west wall north, HIN-hinges, WWS-west wall south, CNR-corner) and the reduced levels (RL) of the benches. The target fold shown in this face folds S_{13} cleavage and a photograph and sketch of this site 380/D+42m is shown in Figures 4.2 Stereoplots B-E show the orientation of bedding in each of the sub-domains. The calculated fold axis is also shown as a red filled circle. Stereoplots F-H show the orientation of dirty S_{13} cleavage. Note the folding of this cleavage in (G).
consistent with the folding of bedding and conforms to the general strike of regional cleavage poles. Cleavage from the hinge zone sub-domain (HIN) forms a small circle distribution with a group shallowly dipping toward 230° (Fig. 4.16D). The scatter of data reflects the folding of cleavage observed in the hinge zone of the F90 fold. In the sub-domain WWN (Fig. 4.16D and H) the majority of cleavage planes measured have dip directions toward 350°. This pattern may be the result of fold tightening against thrust along the northern side of the open pit.

4.3.2 North Wall

The north wall domain consists of steeply dipping to overturned beds of the basal lower unit and footwall beds. Figure 4.17 shows north wall domain structural data from bench mapping and stereoplots of this data. Bedding is folded about an axis plunging 19°/112° and poles to slaty cleavage are consistent with the trend of the calculated fold axis (Fig. 4.17). The majority of S92 lineations (Fig. 4.17) plunge toward 200° and this is the opposite trend than expected for a fold plunging east suggesting that the cleavage is not exactly axial planar to the folds observed.

An isolated fold occurs at site 280/T+58.6m on the 280RL bench on the north pit wall (Fig. 4.17). This fold is transected by slaty S92 cleavage suggesting a D92 timing. The calculated fold axis plunges 54° to 120° (Fig. 4.18). A major fault (S) occurs approximately two metres to the east of this fold.

![Diagram showing structural data and cleavage](image)

Figure 4.18: Equal area stereonet of structural data from 280/T+58.6m in the north wall domain (Fig. 4.8). Symbols: poles to bedding (●), poles to S92 slaty cleavage (●), and measured fold hinge trends (+).

4.3.3 Eastern Area

Due to faulting and the intrusion of a dolerite dyke the eastern area domain contains a complex pattern of stratigraphic units. To the north are footwall beds, to the east a dolerite dyke intrudes footwall beds, and to the south are overturned laminated shales of an undetermined association (Fig. 4.19). Figure 4.19 shows structural data and stereoplots of the data from the eastern area domain. Stereoplots of poles to bedding in the eastern area of the open pit show a fold axis plunging 27°/110° (Fig. 4.19). The plunge in
Figure 4.17: A sketch map with structural data from the north wall domain (1996). The north wall domain consists of steeply dipping to overturned beds of the lower unit and footwall. See text for a discussion of structural orientation data and Figure 4.14 for legend.
this domain is steeper than the rest of the domains in the pit or syncline limbs. There are insufficient cleavage and lineation (Fig. 4.19) data to determine any trend beyond suggesting that cleavage is steep and the associated lineation is shallow. Fold hinge data is consistent with F_{23} folding (Fig. 4.19).

Figure 4.19 shows details of pit wall mapping and Figure 4.20 a photo-collage and sketch of part of the eastern area domain. Areas of interest in Figures 4.19 and 4.20 have been labelled A–E. Area A consists of steeply north dipping beds of laminated hangingwall shales below a faulted, shallowly dipping dolerite dyke. The dolerite dyke has been offset by a series of normal faults with a throw of approximately five metres. Bedding in Area B has been rotated and now dips steeply to the north-east. Separating Areas B and C are additional minor faults and in Area C the dolerite occurs low on the pit wall. Above the dyke are folded laminated shales with folds plunging 50° to 090°. Graded bedding in Area C indicates that the laminated, hangingwall shales in this area are overturned. Much of Area D is disrupted by the intrusion of the dolerite dyke however grading within bedding suggests that this area is overturned and now faces north. Weathered laminated shales in Area E are intensely folded with folds plunging approximately 20° to the east. These folds are interpreted as localized effects associated with the dolerite dyke and of no regional significance.

4.3.4 Stage 2 Shale

The stage 2 shale domain is located in the core of the syncline and consists of shales of the hangingwall beds. Structural data and stereoplots from the stage 2 shale domain are shown in Figure 4.21. The fold axis calculated from bedding plunges 10°/100° (Fig. 4.21). S_{23} Cleavage, L_{623} lineations and fold axial trends (Fig. 4.21) are consistent with the orientation of the fold axis calculated from bedding and with cleavage being axial planar to F_{23} folds.

Figure 4.22 shows a photo-collage and sketch map of a section of the stage 2 shale domain open pit wall. At the site A (101848mE; 50448mN) a shallowly plunging, open, upright F_{3} fold is observed with axial planar cleavage dipping at high angles to the north. L_{623} lineations plot with the measured fold axis. Three minor faults are shown in Figure 4.22. The southern-most fault dips steeply at 83° toward 040° and the direction of movement of this fault was not able to be determined. The central fault of the three, dips shallowly toward 045° and again no sense of movement was able to be determined. The northern-most fault dips steeply toward 340°, with the southern side downthrown. A thin zone (3cm wide) of breccia occurs on the northern side of the fault plane. The fault truncates an earlier F_{23} fold that plunges 20°/090° (Fig. 4.22).

4.5 Summary of Nifty Structural Data

This section provides a summary of the structural data presented in this study and compares the orientation of structural features from all domains. As more exposure becomes available throughmine
Figure 4.19: Sketch map with structural data from the eastern area domain (1996). This area consists predominantly of steeply dipping to overturned hangingwall shales that have been intruded by a dolerite dyke. Sites labelled A-E are discussed in the text. See text for a discussion of structural orientation data and Figure 4.14 for legend.
Figure 4.28: The eastern area domain consists of predominantly steeply dipping to overturned hangingwall shales intruded by a dolerite dyke. The sediments and dyke have been offset by a series of high-angle faults. Sites labels A-E are discussed in the text. The ground surface is at approximately 360RL, and the pit floor 280RL.
Figure 4.21: Sketch map with structural data from the stage 2 shale domain. The stage 2 shale domain is located in the core of the syncline and consists of laminated carbonaceous and pyritic shales of the hangingwall beds. See text for a discussion of structural orientation data and Figure 4.14 for legend.
excavations the orientation of the faults and other features such as the dolerite dyke can be better constrained.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Bedding Calculated Fold axis</th>
<th>S\textsubscript{D} Slaty cleavage best fit girdle Fold axis</th>
<th>L\textsubscript{02} Cleavage-beding lineation Spherical mean</th>
<th>Spherical mean</th>
<th>Fold hinges</th>
</tr>
</thead>
<tbody>
<tr>
<td>North wall</td>
<td>19/112</td>
<td>88/229</td>
<td>02/099</td>
<td>22/296</td>
<td>16/108</td>
</tr>
<tr>
<td>Stage 2 shale</td>
<td>10/112</td>
<td>71/114</td>
<td>19/294</td>
<td>10/108</td>
<td>06/112</td>
</tr>
<tr>
<td>Eastern area</td>
<td>27/110</td>
<td>89/090</td>
<td>01/270</td>
<td>04/107</td>
<td>03/296</td>
</tr>
<tr>
<td>West wall</td>
<td>02/230</td>
<td>41/092</td>
<td>49/272</td>
<td>23/269</td>
<td>01/100</td>
</tr>
<tr>
<td>Northern</td>
<td>13/297</td>
<td>66/117</td>
<td>24/297</td>
<td>22/296</td>
<td></td>
</tr>
<tr>
<td>Mine South</td>
<td>12/106</td>
<td>59/123</td>
<td>33/303</td>
<td>30/089</td>
<td></td>
</tr>
<tr>
<td>Southern</td>
<td>06/259</td>
<td>59/123</td>
<td>33/303</td>
<td>18/105</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: A summary of structural data from stereonets (Figs. 4.14, 4.13, 4.15 and 4.17). So and Ss are presented as dip and dip direction and lineations and fold axes as plunge and trend. The stereonets and statistical data have been prepared using a computer program GEORient (Holcombe, 1995). The algorithm this program uses to calculate the spherical mean does not account for the non-directed nature of the lines so spherical mean has been recalcualted using a FORTRAN program (R. Berry, pers. commun.).

The data contained in Table 4.1 is also shown as synoptic plots (Fig. 4.23A-C). Figure 4.23A shows the orientation of fold axes calculated from best fit girdles and this shows two groups of fold axes plunging toward 110° and 298° indicative of the doubly plunging nature of the Nifty syncline. The group plunging toward 298° consists of data from the northern and southern limbs of the syncline. The data point for the west wall (*) plots separate from the other domains and this is most likely due to the influence of the F\textsubscript{N}, fold. Figure 4.23B shows the calculated fold axes of S\textsubscript{D} cleavage and suggests the possibility of cleavage transcating folds at shallow angles however there is a problem isolating low angle transcating cleavage from cleavage that has been refurcted or refolded. The variation in best fit girdles of S\textsubscript{D} slaty cleavage may be due to the refraction of cleavage. Cleavage was not measured in surface outcrops in the mine south domain due to the weathering of the outcrops. A combined plot of the spherical mean of L\textsubscript{02} lineations and fold hinge line trends (Fig. 4.23C) show two groups, one group plunges toward the east and is co-incident with the calculated fold axes of bedding. The second group has a greater scatter and plunges toward the west. Within individual domains the relationships are less clear, L\textsubscript{02} lineations and calculated axes from stage 2 shale, north wall, eastern area coincide. However, in the domains mine south, northern, southern and west wall the spherical mean of measured fold axes trends opposite to the spherical mean of L\textsubscript{02}. This also suggests cleavage transsection.

D\textsubscript{sh} is a small scale folding event, during which two fold styles occurs 1) recumbent isoclinal folds, and 2) a poorly defined angular folds with axial planes presently horizontal. S\textsubscript{D} cleavage was not observed with either of the fold styles but has been reported by Carmichael (1993) as best developed in sltitstone units of the footwall beds. Carmichael (1993) defines the Nifty D\textsubscript{3} as a folding and cleavage-forming event during which cleavage formed sub-parallel (up to 10° off bedding) to bedding. Nifty D\textsubscript{3} folds are regional, kilometre to sub-metre scale, upright, open, doubly plunging structures with axes trending north-east to south-east and with axial planes dipping north-east. A well-developed axial planar, penetrative,
Figure 4.23 A-C: Synoptic plots of structural data from the domains within the Niiru open pit and limbs of the Niiru syncline. A. shows fold axes calculated from poles to bedding. B. shows axes calculated from poles to cleavage planes, and C. plots the spherical mean of cleavage-bedding intersection lineations and measured fold axes. Domain symbols: (D)-north wall, (E)-stage 2 shale, (O)-eastern area, (*)-west wall, (B)-northern, (C)-arne south, (C)-southern.
slaty cleavage has formed associated with this fold generation. The cleavage associated with \( D_{20} \) is a fine penetrative slaty cleavage that is dominant throughout the open pit but is often obscured in surface outcrop by weathering. Considerable complexity exists associated with the differences in plunge direction of fold axes and \( L_{20} \) cleavage-bedding lineations within individual domains. The change in fold plunge onto the overturned limb suggests that the fold is partly non-cylindrical and this non-cylindrical character is enhanced near high angle reverse faults that may be causing the overturned limb along the northern side of the open pit. Carmichael (1993) described the Nifty \( D_3 \) event as a macroscopic fold and cleavage forming event during which a penetrative north-west to south-east striking, steeply north-east to north-north-east dipping cleavage and deformation event were formed in silty shales while a spaced cleavage formed in silicous units. Carmichael (1993) considered the fold in the west wall (interpreted as \( F_{22} \) in this study) to be a doubly plunging parasitic \( F_{20} \) fold. He also included disharmonic folds with lift-off or detachment geometries in the \( D_{20} \) event. Norris (1987) records the fold axis of the Nifty syncline as plunging \( 10^\circ/107^\circ \).

In localized areas \( S_{20} \) has been folded during \( D_{20} \). \( D_{20} \) is interpreted as a local folding and faulting event. Fold hinges plunge toward NE at shallow angles. A slaty cleavage is formed in the core of \( F_{22} \) folds. Minor local refolding of \( S_{20} \) has occurred. \( D_{20} \) also appears to have tightened \( D_{20} \) structures. Carmichael (1993) described \( D_{20} \) as a flat-lying, crenulate cleavage that overprinted \( S_{20} \). This description does not match that presented here and no evidence of a flat-lying crenulate cleavage was observed in the open pit or diamond drill core during this study but \( D_{20} \) has a sub-horizontal axial plane and may correlate with Carmichael’s (1993) cleavage.

The folds of the \( D_{20} \) deformation event are characterised by generally horizontal axial planes with hinges co-axial to \( D_{20} \); however there is a high variability in the trend of the fold axes. The folds do not appear to have an axial planar cleavage. Carmichael (1993) recognised this style of \( D_{20} \) as an echelon ramp faulting structures with fault dips of \( 65^\circ/100^\circ \). He interpreted them as extensional faults with an apparent sinistral offset. In his discussion of the ramp-flat fault and folds Carmichael (1993) noted similarities between the structures at Nifty and those of Kimmeridge Bay on the South Coast of Dorset, UK (Ramsay, 1992). The major difference noted by Carmichael was the orientation of the fold axial plane, at Nifty the axial plane is horizontal while at Kimmeridge Bay the axial plane is vertical. Two mechanisms for the formation of this fold style at Kimmeridge Bay have been proposed, 1) volumetric changes occurring in carbonate rocks during dolomitisation (Bellamy, 1977), and 2) tectonic shortening. (Ramsay, 1992). Ramsay (1992) concluded that the Kimmeridge Bay folding and faulting were the result of tectonic shortening associated with the formation of the Purbeck Anticline, and that the structures formed in zones of strongest shear.

\( D_{20} \) is interpreted as representing a period of compression relaxation during which the direction of the maximum compressive stress changed from horizontal to vertical. Subsequent to \( D_{20} \) there has been several brittle faulting events and the intrusion of dolerite.
Faulting shown in Figure 3.2 and the cross section of 101700mE, 102000mE, 102800mE, 103200mE, 102240mE, 102320mE offsets rocks that have been altered, mineralised and folded by F4d, F5b, and F6c. These timing relationships suggest a post D4a timing however it is likely that some of the faults have been active before D4a. In particular, the thrusts T1, T2 tighten D4c and are interpreted to be late-syn-S2. In the eastern end of the open pit a dolerite dyke is exposed. This dyke has been offset by a series of normal faults. The timing of the faulting can be constrained as post-mineralisation and post D2 deformation as 1) a mineralised xenolith was found in diamond drill core TND14, 2) the dyke has a poor Rb-Sr date of 700-750Ma, and 3) no cleavage has developed in the dolerite.

4.4 Regional Deformation

Hickman and Clarke (1994) state that D3b structures (equates to D4a) are mesoscopic isoclines transected by the slaty cleavage (S8a of their D4a). They go on to state that the axial planes of these folds are approximately orthogonal to the S8a of the upright F4d folds and therefore prior to D4a must have been recumbent. They could identify no axial planar foliation (Hickman and Clarke, 1994). Hickman et al. (1994) discuss a regionally based structural evolution and describe D3b structures as 1) recumbent folds, 2) local S8a foliation almost parallel to bedding, and 3) faulting and quartz veining of the Rudall Complex-Yeneena Supergroup unconformity. Bagas and Smithies (1985) interpreted the general orientation of F4d folds to indicate a north-east to south-west oriented compressional regime similar to that of the later D4a event. They also interpreted D3b and D4a to be sequential events related to the Miles Orogeny.

Regional D4a is described as an upright, tight to isoclinal fold with north-west trending axes and with a steeply inclined axial surface cleavage (Hickman and Clarke, 1994). Fold plunges are mainly at a low angle toward the north-west and limbs are often sheared out along faults. Hickman and Clarke (1994) observed S12 in pelitic rocks of the Broadhurst Range locally crenulated by mesoscopic open to tight folds with axial planar cleavage. D3b is described as a sub-vertical crenulate cleavage superimposed on S12 (Hickman and Clarke, 1994). Bagas and Smithies (1985) interpret D4a on the Connaughton sheet to be a conjugate set of north-westly and north-north-westly striking faults and shear zones, and an associated spaced cleavage S8b.

4.5 A Comparison with Other Workers

This section compares the preliminary results of this study with major works from other regions in the Paterson Orogen. Events D3b and D4a can be correlated across the Paterson Orogen (Table 4.2). The direction of isoclinal folding at Nifty is indeterminate and observations suggest that this event is restricted to incompetent beds. D4a (D4a) is the major deformation event during which regional folding and cleavage development occurred (Table 4.2). The direction of compression is consistent throughout the region with a trend of south-west to north-east shortening. D4a is recognised at Nifty and on the Connaughton 1:100,000 map sheet (Bagas and Smithies, 1985) but the differences in the orientation of D4a structures suggest local variations in the direction of compression. D4a is recognised at Nifty and on the
<table>
<thead>
<tr>
<th>Nifty Structure</th>
<th>Regional Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>This study</strong></td>
<td><strong>Carrichael, 1993</strong></td>
</tr>
<tr>
<td><strong>D1</strong></td>
<td>Minor reentrant, clastic and angular</td>
</tr>
<tr>
<td></td>
<td>structural grain</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>D2</strong></td>
<td>Regional development of folding and cleavage in response to NE-SW</td>
</tr>
<tr>
<td></td>
<td>compression</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>D3</strong></td>
<td>Folding and faulting event, Foliation parallel to NNW</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>D4</strong></td>
<td>Folding with generally</td>
</tr>
<tr>
<td></td>
<td>horizontal axial planes</td>
</tr>
<tr>
<td></td>
<td>with folds coaxial to</td>
</tr>
<tr>
<td></td>
<td>Nio. Stress release?</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>D5</strong></td>
<td>Brittle deformation</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: A comparison of deformation events recorded in the Paterson Orogen. Events observed by Carrichael and in this study refer to Nifty and use the first column for deformation event numbers while Hickman and Clarke (1994), Hickman et al. (1994) and Bagaß and Smithies (1995) use deformation event numbers in the last column.

### 4.6 Structural Evolution

The structure evolution of a small area such as the mine site and local outcrops must be considered within the overall deformation environment of the Yenena Basin. In general the deformation observed, and interpreted made by Geological Survey of Western Australia (Hickman and Clarke, 1994; Hickman et al., 1994; Bagaß and Smithies, 1995) and that observed and interpreted for Nifty are in agreement with the exceptions discussed above. This section presents a possible structural evolution model for deformation observed at the Nifty Cu deposit and this model is shown in Figure 4.24A-D.

The Yenena Basin formed with the main sediment sources being the Archiuran Pilbara Craton and the Palaeoproterozoic Rudall Complex (Fig. 4.24A). The earliest deformation event is a small scale, isoclinal folding and the development of a weak axial planar cleavage. It is interpreted that D5 records soft sediment deformation or record the onset of compression in the Yenena Basin. The rare occurrences of D4 folds suggest that these possible interpretations of D5 should be treated as speculation. D4 is a regional north-west to south-east trending compressional event during which thrusting faulting, massive macroscopic folding, slaty cleavage developed, and the maximum metamorphic grade occurred (Fig. 4.24B). This event is interpreted the result of intracratonic thrusting with the Paterson Orogen thrust over
Figure 4.24A-D: Sketch diagram of the structural evolution of the Paterson Orogen. A. Basin development with the main sediment sources being the Archean Pilbara Craton (PI) and the Palaeoproterozoic Budjil Complex (BC). B. North-west to south-east trending compression results in the development of regional folding, thrust faulting, and S5 cleavage. C. During intracratonic thrusting the principal stress axis rotates horizontally by approximately 15° and the tightening of existing structures. D. When the driving force is removed, \( \sigma_3 \) exceeds \( \sigma_1 \), and the orientation of the principal stress direction changes from horizontal to vertical resulting in \( F_\alpha \) folds. Post-collisional granites are intruded into the Lamiil Group.
the Pilbara Craton. It is likely that deformation was continuous during \( D_{92} \) and \( D_{93} \). \( D_{93} \) represents the rotation of the principal stress axis horizontally by approximately 15°. Other features of \( D_{93} \) suggest that compression tightened existing folds and this over-tightening is likely to have caused additional thrust faulting. Finally, when the driving force is removed, \( \alpha_{9} \) exceeds \( \alpha_{8} \) and the orientation of the principal stress direction changes from horizontal to vertical resulting in a short term, rapid extensional period during which folds with horizontal axial planes and variable trend formed. Syn-\( D_{94} \) biotex carbonat veining provides evidence for a rapid drop in fluid pressure at this stage where fractures have opened and fluid pressure has dropped to hydrostatic. Late brittle-style faulting occurred that has offset the ore body and in the Late Group post-collisional granites have intruded.

4.7 Summary

Five deformation events are recognised from bench mapping in the open pit and outcrop mapping in the Nifty Syncline area. \( D_{94} \) is recognised as a minor recumbent isoclinal and angular upright folding event of unknown significance. It could represent the onset of bedding parallel slip in response to north-north-east compression as a precursor to the more significant \( D_{95} \). \( D_{95} \) is a regional folding and cleavage development event that occurred in response to north-east to south-west compression. Folds are doubly plunging with axes trending north-west to south-east. The doubly plunging character may be related to later events but may also include a component of \( D_{94} \) folding that is no longer recognisable in any more direct way. \( D_{96} \) is an event that has not been recognised elsewhere in the Yeneco Supergroup but at Nifty \( D_{6} \) is an upright folding and faulting event that folds \( S_{96} \). Associated with \( D_{97} \) is a slaty cleavage that is less developed than \( D_{96} \) and strikes north-north-east. \( D_{97} \) is a complex folding event with axial planes generally horizontal and folds coaxial with \( D_{96} \). It is interpreted that these folds resulted from stress release. A brittle deformation event, \( D_{98} \) has also been recognised. The structural synthesis presented in this chapter shows that there is significant complexity in the Nifty syncline area but most of the complexity is due to small scale, local, possibly fault related events. The gross, large-scale structure in the Nifty Cu deposit area is dominated by \( D_{98} \) folds.
Chapter Five – Alteration

5.0 Introduction

This chapter presents descriptions of alteration textures observed in Nifty diamond drill core and open pit. Alteration is a process of change, where the original host rock lithology is modified during the introduction of a fluid. The characterisation of alteration patterns, and the spatial distribution of those patterns, provides important information that may assist in the identification of possible fluid conduits. From the identification of alteration textures, mineralogy, and chemistry insights can be gained concerning the thermo- and physio-chemical nature of ore fluids (Franklin et al., 1981). Both of the proceeding features provide an important component in the understanding of the formation of the Nifty Cu deposit and for the development of an exploration model for use in the search for other Nifty-style deposits.

Two alteration phases were determined from logging of Nifty diamond drill core. Based on paragenetic relationships these alteration stages are defined as 1) early, pre-mineralisation textures, and 2) sym-mineralisation textures that occur in a zoned sequence about the main concentration of mineralisation. No post-mineralisation alteration textures have been observed in the primary sulphide ore body, however surificial processes have acted to form the secondary mineralisation. It is beyond the scope of this study to examine or describe the secondary enrichment-processes. This chapter follows on from Chapter Three where the host rock lithologies are described, and relates to Chapters Six and Seven where vein stages and mineralisation textures are described and discussed. The relationships between alteration, mineralisation and veining are discussed in Chapter Seven.

5.1 Previous Workers

Norris (1987) reported that the alteration of host rocks occurred in the form of silicification, dolomitisation and chloritisation, and that these alteration processes accompanied mineralisation. He identified two main phases of silicification, earlier equant quartz representing the silicification of various carbonate rocks and a later coarse-grained quartz. The formation of this later quartz was considered to have occurred over a long period of time and was spatially associated with chalcopyrite and chalcedony pyrite.

The dolomitisation and the relationships between carbonate phases and hydrothermal silica, chalcopyrite, and pyrite were examined by Norris (1987) using carbonate-staining techniques, thin section petrology and microprobe analysis. Norris (1987) grouped carbonate minerals on the basis of textures and paragenetic relationships. The earliest form of carbonate observed by Norris (1987) was diagenetic microsparry siderite which was followed by later sideritic and dolomitic carbonate related to hydrothermal fluids responsible for silicification and mineralisation. Norris (1987) noted the following siderite forms 1) recrystallised diagenetic siderite carbonate at quartz-carbonate interface, 2) very fine-
grained carbonate rhombs in microcrystalline quartz, 3) as relict carbonate inclusions in quartz grain interfaces, 4) as rare cores to zoned dolomite grains in veins, and 5) as rare blebs in blocky dolomite (Norris, 1987). Dolomite was recorded as 1) crosscutting veins and and bedding parallel veinlets generally with quartz, 2) replacement of bladed evaporite minerals, 3) irregular and cubed/2d grains in microcrystalline quartz, 4) blocky zones sub-parallel to bedding, and 5) open space fill within coarse quartz grained crystals (Norris, 1987).

To examine the chloritic alteration of shales in the footwall beds, Nifty member, and hanging wall beds, Norris (1987) used drill core descriptions, XRD analyses, and whole rock geochemical data. He noted that chloritic shales were most common in the footwall beds and lower parts of the Nifty member, and that their abundance decreased up stratigraphy. Two groups of chlorites from the Nifty member were identified as i) radiating sheaves of pyrochlore within or at the margin of chalcopyrite, pyrrhotite, galena, and sphalerite and ii) chlorites associated with detrital micas. Norris (1987) concluded that alteration accompanied copper (1) lead, zinc) mineralisation and that the alteration was most intense in the Nifty member where it is represented by a hydrothermal quartz-dolomite body. No other studies have examined altered rocks at the Nifty Cu deposit.

5.2 Methods
Alteration textures described in this chapter were defined during logging of diamond drill core. Working descriptions of alteration textures and their relationships to host rocks, other alteration textures, veining, and mineralisation were developed during logging of diamond drill core. Thin-section petrology and micro-probe analysis of samples from each of the alteration classes, defined using hand specimens, supplemented the descriptions and were used to clarify relationships between alteration types.

5.3 Alteration Definitions
Two broad phases of alteration have been defined on the basis of their relationship to mineralisation. Pre- and syn-mineralisation alteration phases have been designated as E, or S standing for early and syn-mineralisation respectively. Descriptive names are also provided but in general the E or S designation is used. Note that the designations for alteration are in italics whereas cleavage, for example S3Q, is in normal text and the number is as a sub-script.

Pre mineralisation

| E1 | Fe-Mg Carbonate |
| E2 | Green Quartz |

Syn-mineralisation

| S1 | Chloritic Shale |
| S2 | Silicified Pyritic Shale |
| S3 | Hydrothermal Quartz-Dolomite |
| S4 | Silicified Dolomitic Shale |
| S5 | Black Silica |
5.4 Pre-mineralisation

Two pre-mineralisation alteration stages overprint shale and dolomitic shale lithologies and are overprinted by slaty cleavage, later alteration textures, and vein stages. The age of pre-mineralisation alteration textures cannot be clearly defined because no age dating has been conducted on early alteration minerals. However, their formation can be constrained as occurring between deposition and D6. The depositional age of the Broadhurst Formation is poorly constrained as between 1132±21 and 816±5Ma (see section 2.4.1). Peak metamorphic and deformational conditions occurred during D6 which has been dated at 717Ma (Reed, 1996).

5.4.1 E1-Fe Mg Carbonate

E1-Fe Mg Carbonate (Fig. 5.1A-D) is a laterally extensive alteration texture found in inter-bedded carbonaceous shale immediately above the contact of the PMB and overlying hanging wall beds (Fig. 5.1A-B). Host rock for E1-alteration is blue-black, fine grained, laminated, carbonaceous shale with traces of very fine-grained, disseminated frambooidal pyrite. When fresh, Fe-Mg carbonate is light grey and when weathered becomes increasingly brown. E1 can appear as bedding parallel bands or as isolated rounded nodules in black shale (Figs. 3.11 and 5.1C). E1 is deformed by D6g giving it a nodular appearance. Internally, the nodules and bands of Fe-Mg carbonate have remnant bedding and rare pyrite trails that extend into unaltered host rock. Nodule and band margins vary from sharp to diffuse over several millimetres.

In thin section (Fig. 5.1D) E1 is a very fine-grained, crypto-crystalline groundmass of sideropelitic with inclusion-rich quartz crystals and rare euhedral pyrite grains. Quartz grains are 5-20µm in diameter, rhombic shaped, and have thin (<10µm) Fe-rich carbonate overgrowths. Nodule and band margins are gradational into sheared carbonaceous shale.

Whole rock geochemical results and microprobe analyses (Appendix Three) indicate that E1-Fe Mg Carbonate consists of Fe-Mg rich and Ca poor carbonates (eg sample 1281 major oxides in percentage, SiO2:14.4, Al2O3:3.25, Fe2O3:31.5, MgO:15.7, CaO:0.5, LOI:30). These data indicate that the E1-Fe Mg Carbonate is dominated by sideropelites (i.eMgCO3). E1 has been crosscut by 1) a series of parallel dolomite-pyrite veins that crosscut at high angles and that do not extend beyond the nodules or band margins, 2) S2 cleavage and 3) S30 parallel stylolites that crosscut both E1-altered rocks and the dolomite-pyrite veins.

5.4.2 E2-Green Quartz

E2-Green Quartz (Fig. 5.2A-G) has a restricted distribution and is found in the principal carbonate bed, in areas of high-grade mineralisation (Fig. 5.2A) and is not observed in distal diamond drill holes such as TND8 and TND27. Although spatially restricted to areas of high-grade mineralisation, the host rocks altered by E2 are replaced by later syn-mineralisation alteration phases. Fresh samples of E2-Green
Figure 5.1A-D: A. E1 outcrops as a series of prominent bands above the PMB/hangingwall shale contact. B. A representative stratigraphic column showing the location of the E1-Fe-Mg carbonate and the relative location and magnitude of Cu mineralisation. C. Photograph of E1 alteration from DDH TNJ 9 (266.3m) showing laminated, black, carbonaceous shale with bands of light brown-grey, Fe-Mg rich Cu poor carbonate. Also in this photograph are thin pyrite-carbonate fracture veins of RC vein stage. Note that this vein stage does not extend beyond the edge of the brown-grey bands. D. Photomicrograph of E1 alteration from DDH THRD 781 (292.5m). The fine grained groundmass consists of Fe-Mg rich and Cu poor carbonate with isolated quartz grains.
Figure 5.2A-G: A. Representative stratigraphic columns showing the location of E2-Green Quartz altered rocks and the relationship between alteration and location and extent of mineralization. B. Photograph of the E2-Green Quartz alteration from THRD675 (324.5m) in a matrix of S1-Black Silica. C. E2-Green Quartz has a more red form, that is observed in the centre of green pseudomorphs, also note the fracture vein that has been infilled by S1-Black Silica and chalcopyrite (THRD636A, 288.6m). D. Photomicrograph of E2-Green Quartz with fine-grained quartz coated with very fine-grained sericite and chlorite. Also note the radiating laths of stilpnomelane (TN09, 397.7m). E. Photomicrograph of the red form of E2 alteration THRD636A (288.6m). Quartz grains are coated with very fine-grained sericite and hematite that gives the red colour. F and G. E2-Green Quartz altered rocks exposed in the open pit show evidence of layer parallel extension resulting in E2 fragments in bedding parallel trains.
Quartz consist of pale, cloudy, green or rarer red quartz with both forms having pale creamy white margins approximately 1-2mm thick (Fig. 5.2A-B). Weathered samples are exposed in the open pit and appear as cemented, white to pale green quartz without the red variety (Fig. 5.2E-F). In fresh samples the red colour occurs as small (0.5mm) coalescing spots in the centre of larger pale green areas (Fig. 5.2B).

Thin section petrography indicates that the pale-green or red quartz is due to fine chlorite, hematite, and sericite coatings of quartz grains (Fig. 5.2C-D). Other constituents of E2 are radiating laths of fibrous stilpnomelane, small black to brown flecks of carbonaceous material and <1mm pyrite ashebra (Fig. 5.2C-D). E2 alteration has a strong bedding parallel appearance and has preferentially replaced individual beds (Fig. 5.2E-F), however the protolith that formed those beds cannot be determined with any certainty as the replacement of the host rock has obliterated the original lithology and textures while preserving “bedding”. The likely protolith of E2-Green Quartz are carbonaceous and dolomitic shales. The E2 alteration stage forms two styles of isolated pseudo-clasts in a S5-Black Silica matrix. The first style of pseudo-clast is the result of layer parallel boudinning and fractured of competent E2 bedrocks with the gaps filled by S5-Black Silica. These pseudo-clasts are dominantly angular tabular (3-5cm) with 2-3mm wide pale creamy-white margins and with chalcopyrite in the black silica on the margins of green quartz. A second form of pseudo-clast is well rounded and shows evidence of emplacements suggestive of dissolution and replacement of E2 by S5-Black Silica. In thin section (Fig. 5.2C-D) E2 alteration is very fine-grained (<5μm), crystalline quartz with the main accessory minerals of sericite, hematite, chlorite and stilpnomelane. A single example of anhedral chalcopyrite in E2 was observed in thin-section (THRD752, 334.9m), Quartz crystals have irregular boundaries and exhibit undulose extinction. Sericite, hematite and chlorite occur as very fine crystals that coat quartz grains. Rare dolomite and euhedral grains of pyrite are also associated with this alteration texture. 

5.5 Syn-mineralisation

5.5.1 S1-Chloritic Shale

This texture has a restricted distribution and is found on the distal margins of the Fe-rich dolomite texture of the S3-hydrothermal Quartz-Dolomite. S1-Chloritic Shale occurs as beds ranging in thickness between 10-100cm (commonly 30cm thick) of soft, soapy to touch, black to blue-black, finely laminated, graphitic and chloritic shale. Sulphides of euhedral pyrite and anhedral chalcopyrite are rarely observed in S1 altered intervals. S1-Chloritic Shale is visually indistinguishable from unaltered carbonaceous shale and is identifiable by its hardness and soapy feel. Samples of S1-Chlorite Shale from THRD752 (390.2M) and TND12 (287.4m) were analysed by XRD at Mineral Resources Tasmania and results indicate that S1-Chlorite Shale consist of 10-40% chlorite. Chlorite in unaltered samples is below detection.

5.5.2 S2-Silicified Pyritic Shale

The alteration texture S2-Silicified Pyritic Shale (Fig. 5.3A-B) has a restricted distribution and is found at discrete zones in pyrite-rich sediments of the lowermost footwall beds, pyrite marker bed and in the footwall beds below the ore zone (Fig. 5.3A). S2 altered zones are thicker and are more extensive in the west seams of the primary ore body. To the east of cross-section 102240mSE S2 is restricted to thin, poorly
Figure S1A-D: A. The protolith of S2-Silicified Pyritic Shale is a fine-grained, laminar, frambooidal pyrite shale (THRD 635, 451.2m) and these beds are found predominantly in the uppermost footwall beds, pyrite marker bed, and lowermost hangingwall beds. B. During mineralisation, bedding parallel alteration introduces quartz, coarse-grained euhedral to subhedral pyrite, chalcopyrite, galena and sphalerite (THRD 753, 460.9m). C. Bedding parallel quartz flooding introduces euhedral to subhedral pyrite, anhedral chalcopyrite, galena and sphalerite. D. Collage of reflected light of photomicrographs from THRD 645 (265.7m) showing a large galena clot rimmed with chalcopyrite that has replaced an earlier pyritic clot. Sphalerite and galena replace pyrite frambois in beds close to the bedding parallel alteration and the clot.
developed occurrences. Fresh samples of S2 Silicified Pyritic Shale occur as olive-green, thinly laminated beds of very fine-grained pyrite framboids in carbonaceous shale (Fig. 5.3B and D), overprinted by quartz + coarse-grained, euhedral to subhedral pyrite ± anhedral chalcopyrite ± galena ± sphalerite (Fig. 5.3C and E). Pyrite, in both forms, may comprise greater than 70% of an interval. Bedding parallel replacement of pyritic and carbonaceous shale occurs firstly with the pseudomorphing of pyrite framboids with sphalerite and galena while preserving the framboidal texture. The concentration of pseudomorphs increases near bedding parallel silicous replacement where pseudomorphed framboids are overprinted by quartz + euhedral pyrite + galena + sphalerite + chalcopyrite. Associated with bedding parallel silicous replacement are galena clots up to 10mm in diameter that are typically rimmed with fine-grained chalcopyrite, quartz and carbonaceous material. The galena is interpreted to have replaced pre-deformational, pyrite clots and blobs (Fig. 5.3D).

5.5.3 S3-Hydrothermal Quartz-Dolomite
S3-Hydrothermal Quartz-Dolomite (Fig. 5.4A-D) has progressively altered shale host rocks into bands of S3 and unaltered shale. The progressive alteration can be separated into three textures that are defined here as 1) isolated quartz-dolomite spots, 2) coalesced spots that form in a recrystallized quartz-dolomite, or in areas of pyrite, a Fe-rich quartz-dolomite, and 3) a silicified, wavy laminated quartz.

The least intense alteration texture within the S3 classification is the development of isolated quartz-dolomite spots in carbonaceous shale intervals of the lower interbedded carbonate and footwall beds adjacent to zones of high-grade mineralization. The texture occurs as circular to oval spots up to 8mm in diameter, with a finer-grained inner core surrounded by a coarser-grained, outward radiating zone. Spots are composed of very fine-grained, crystalline, quartz + dolomite ± frond-apatite and a very fine-grained, sub-microscopic dusting of chlorite which imparts a slight green tinge to specimens (Fig. 5.3C-E). The mineralogy of the spot is heavily dependent on the composition of the host rock, in shale intervals the major constituent is quartz whereas in dolomite intervals the spots are dolomite. The majority of spots transgress sediment laminations and trails of pyrite grains suggesting replacement of the shale host by quartz and dolomite alteration. Rare examples of bedding laminae displaced by spot growth are also observed. The intensity of spotting increases preferentially along favourable horizons and in proximity to vein stage UB Alteration margin quartz-dolomite veins (see Chapter Six).

As the intensity of the alteration increases, spots form bands along bedding and gives the appearance of a progressively silicified recrystallized dolomite (Fig. 5.4D). Coarsely crystalline quartz and dolomite replacement occurs along bedding planes and results in the concentration of carbonaceous material into thin wavy laminae (Fig. 5.4 F-H). In protoliths with high concentrations of pyrite, an Fe-rich recrystallised quartz-dolomite occurs. Fe-rich quartz-dolomite is found on the margin of zones of intense silicification within the Nifty member and, where fresh, appears as black to dark grey, finely crystalline, wavy laminated rock (Fig. 5.4I). When core weathers it takes on a distinctive dark brown colour (Fig.
Figure 5.4A-J: A. In the deposit footwall, lower unit, and peripheral to vein stage III veins, S3-Hydrothermal Quartz dolomite alteration consisting of quartz + dolomite spots occur in carbonaceous shale (THRD781, 359.8m). Note that the spots preferentially form along favorable beds and increase in intensity toward mineralization. B. As the intensity of alteration increases the spots coalesce to form the S3-recrystalline dolomitic shale texture (THRD753, 351.5m). C. S4 spots in a fine grained carbonaceous shale matrix from THRD753 (351.5m). Remnant bedding trails can be seen in the lower portion of the central spot. D. Spots coalesce with increased alteration to form recrystalline dolomitic shale as in this photomicrograph from THRD753 (351.5m). E. Quartz or chalcopyrite-quartz associated with S4 alteration (top of photograph) replace S3 spots (THRD753, 351.5m). F. The replacement of carbonate and proalith by S4-Hydrothermal Quartz-Dolomite, and the development of stylolites concentrates carbonaceous and graphitic material into wavy laminated horizons (WR202510), giving hand specimen the appearance of the "cryptalgal laminated carbonates" of Norris (1987). G. In areas of more intense, progressive alteration where well developed S3-recrystalline dolomitic shale has formed, fluid flow along remnant bedding, spot boundaries or stylolites results in the dissolution of the carbonate component and the replacement by quartz or quartz-chalcopyrite. H. As the intensity of alteration increases the dolomitic component is replaced by a microcrystalline quartz (THRD781, 337.3m). I. Sample of finely cut surface of S4-rich variant of the S3 alteration texture from TN99 (332.4). Note the laminations with wavy boundaries and the replacement of E2 downhole side (right of photograph). J. Sample of S2 alteration from VN99 (332.4m) showing the distinctive brown staining of diamond drill core as it weathered in core trays. Photomicrographs have a 100xum scale and an indicator showing bedding (S2) or the best estimate of proto-bedding (S3).
5.41. Small flecks of disseminated euhedral pyrite occur within Fe-rich dolomite. Fe-rich silicified dolomite replaces shale and green quartz on the distal margin of alteration zones.

SJ-Hydrothermal Quartz-Dolomite is the main carbonate-bearing alteration phase and Table 5.2 lists summary electron microprobe data from dolomitic mudstone host rock, SJ alteration and BA vein stage. The main alteration carbonate phase at Nifty is dolomite with minor ankerite.

<table>
<thead>
<tr>
<th>Label</th>
<th>Dolomitic mudstone</th>
<th>( \text{SJ-Hydrothermal Quartz-Dolomite} )</th>
<th>( \text{HA-Chalcopyrite-dolomite vein} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lost rock</td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>FeCO(_3)</td>
<td>8.98</td>
<td>10.81</td>
<td>10.81</td>
</tr>
<tr>
<td>MgCO(_3)</td>
<td>1.91</td>
<td>2.46</td>
<td>2.46</td>
</tr>
<tr>
<td>CaCO(_3)</td>
<td>35.77</td>
<td>37.68</td>
<td>37.68</td>
</tr>
<tr>
<td>ZnCO(_3)</td>
<td>51.17</td>
<td>51.17</td>
<td>51.17</td>
</tr>
<tr>
<td>Sum Ox%</td>
<td>99.29</td>
<td>101.36</td>
<td>101.36</td>
</tr>
</tbody>
</table>

Table 5.1: Comparison of summary electron microprobe analyses of carbonates observed at Nifty, Ba, Sr, Pb, and Ni are below detection in all three carbonate phases.

As alteration increases early quartz-dolomite spots are crossed by later quartz + chalcopyrite + pyrite (Fig. 5.4E). The sulphides have thin pressure shadows less than 1 mm wide of quartz, chlorite or phlogopite. The next phase of progressive SJ alteration consists of the dissolution of quartz-dolomite spots and recrystallised quartz-dolomite and the precipitation of fine-grained silica, initially along spot boundaries (Fig. 5.4G). Carbonaceous material is also removed from the wavy laminites. As the intensity of alteration increases recrystallised quartz-dolomite is replaced by fine-grained quartz + apatite while leaving remnant, irregular patches of dolomite (Fig. 5.4H). The silicic replacement of SJ-Hydrothermal Quartz-Dolomite results in SJ-Black Silica. When the SJ-Hydrothermal Quartz-Dolomite alteration is exported in the open pit it appears as a coarse-grained, granular quartz with a very fine-grained powdery white matrix cement (Fig. 5.2F). The less intense textures of SJ have not been observed in the open pit.

Norris (1987) recorded the presence of displacive nodular evaporitic pseudomorphs coalescing up section to dense evaporitic bands. This "evaporite pseudomorph" form of light grey "spot" texture was recognised during this study of Nifty alteration and the texture is similar in appearance to the least intense SJ spot texture. However, these quartz-dolomite pseudomorphs of birdseye evaporites that occur in the intermediate shale can be differentiated from the SJ alteration texture because the pseudomorphs are smaller (<1 mm), have bedding wrap around them, no chalcopyrite or fluorapatite is associated with them, and they have single grain cores. Norris (1987) did not recognise the two forms of spots and it is likely that the two groups may have been confused and at times combined. Norris (1987) also did not record the presence or association of spots and veins with alteration margins.
5.5.4  S4-Silicified Dolomitic Shale

S4-Silicified Dolomitic Shale (Fig. 5.5A-D) is a progressive alteration texture that is observed on the periphery, and within, intensely silicified zones within the Nifty member. S4 is concentrated in the Nifty member and has preferentially altered dolomitic shale beds. This alteration texture does not occur, or is poorly developed, in distal diamond drill holes. This alteration phase occurs as the progressive replacement of dolomitic shales with quartz replacement of dolomitic shale that occurs along bedding planes and concentrates carbonaceous material into wavy laminated bands. At the maximum S4 occurs as 3-5mm thick siliceous laminae with wavy margins of carbonaceous material (Figs. 5.17 and 5.19). The host lithology is a dolomitic mudstone (with lesser shale) that has been subject to variable siliceous replacement along bedding planes. The siliceous replacement has concentrated carbonaceous material into thin wavy bands and it is this concentration that gives S4 the wavy laminated appearance. Alteration mineralogy consists of dominantly fine-grained quartz with patches and remnant dolomite, anhedral chalcopyrite and fine needles of fluorapatite.

Both S3 and S4 are progressive alteration textures and at their maximum intensity have similarities; they both include wavy laminated concentrations of carbonaceous material in a highly silicious groundmass. The difference in the two alteration classifications is that the protolith of S3 is shale dominated while the S4 protolith had a higher dolomite composition. With continued siliceous alteration both the S3 and S4 textures are replaced by S5-Black Silica.

5.5.5  S5-Black Silica

The occurrence of S5-Black Silica (Fig. 5.6A-F) is restricted to zones of intense mineralisation in the core and northern limb of a macroscopic fold in the Nifty member. S5-Black Silica is a pervasive alteration texture that is progressive between two end members of black silica and moulded black and white quartz.

The black silica texture consists of microcrystalline quartz with abundant black carbonaceous material between quartz grains. Associated with S5 silicification are euhedral pyrite, irregular shaped chalcopyrite blebs and occasional, coarsest crystalline dolomite inclusions (Figs. 5.6B-F and 5.7B). S5 alteration often surrounds and infills fractures of E2 alteration (Figs. 5.4 and 5.5). S5 alteration stage is associated with chalcopyrite mineralisation. Thin-sections of the black silica texture show (Fig. 5.6B) quartz grains as either a circular to sub-circular or as tabular grains with pointed ends. Both forms of quartz are coarser grained than E2-Quartz. The margins of both forms of quartz grains are irregular. A defining feature of the S5 texture is the appearance of abundant, randomly oriented apatite needles approximately 10-20μm long and a length to width ratio of 10:1 (Fig. 5.6C). Representative electron microprobe analyses of fluorapatite crystals are presented in Table 5.3. Electron microprobe results (Table 5.3) indicate that apatite in S5-Black Silica is a fluor-apatite of the general form Ca\(_{5.61}\)F\(_{0.35}\)(PO\(_4\))\(_{3.97}\)(OH\(_{0.69}\),

\(e_{219} F_{0.23} O_{0.78}\).
Figure 5.5A-D: A. Generalized stratigraphic column showing the location of S4 Silicified Dolomitic Shale on the outer edge of the zone of the most intensely altered rocks and mineralization. B. The protolith for the S4 alteration texture is a laminated, fine-grained, dolomitic shale with randomly distributed dolomite rhombs. Progressive silicification replaces the dolomite and concentrates carbonaceous material into bedding parallel bands as seen in this photograph. C. Increased replacement of dolomite with the precipitation of quartz and chalcedony occurring preferentially along bedding planes (WR202531). D. The most intensely altered rocks have undergone the total replacement of the dolomitic component by quartz and the concentration of carbonaceous material into wavy laminated bands (TND13, 363m). This texture was defined by Norris (1987) as a silicified cryptogal laminated carbonate, an interpretation that is not supported here (see text for explanation).
Figure 5.6A-G: A. Representative stratigraphic column showing the location of SS-Black Silica and the relationship to Cu mineralisation. B. Photograph of the SS-Black Silica with E2-Green Quartz pseudomorphs from THR0752 (324.5m). C. Photomicrograph of SS-Black Silica showing quartz grains with a black carbonaceous/graphitic material filling the grain interstices and bedding parallel stylolites. Apatite occurs as thin, randomly oriented needles. D. Photomicrograph of contact between SS and E2 alteration textures THR0636A (288.6m). E-G. Progressive alteration along bedding during SS-Black Silica alteration initially results in the development of a halved appearance as in E. (TN017, 178.4m) & F. (THR0753, 399.1m) and then finally in the obliteration of all banding resulting in a mottled black and white texture as show in G. (THR0752, 359.5m). The best estimate of bedding is marked at (5.7).
### Table 5.2: Representative electron microprobe analyses of fiam-apatite crystals in SS alteration (THRD647, 351.5m and THRD636A, 288.6m).

Black, carbonaceous material occurs between quartz grains and it is this material that gives SS-Black Silica its dark colour (Fig. 5.6C-D). Within the carbonaceous material are very fine-grained inclusions of unaltered and pitchblende (WMC Resources Ltd. written comm., 1989, 1991).

At the maximum intensity of alteration, found in the core of the enteralized zone, a texture with a mottled black and white appearance occurs as bands of irregular margined black silicified shale and white quartz (Fig. 5.6E-G). This alteration texture completely obliterates previous textures and lithologies. Anhedral chloritepyrite and lesser echidna pyrite occurs within the irregularly margined bands. At the alteration stage maximum development, the texture appears as dominantly white-grey quartz with isolated, small approximately 1mm remnants of irregularly shaped silicified shale. The progression from black silica texture to mottled black and white texture is best seen in the margins of quartz-carbonate veins where the degree of silicification decreases with distance from the vein.
5.6 Footwall and Hangingwall Alteration

Footwall and hangingwall alteration is restricted to areas above and below the zones of intense alteration. No paragenetic relationships where observed that placed constraints on the timing of alteration.

5.6.1 Footwall

Unaltered footwall beds (Fig. 3.3) consist of grey to blue-black chlorite, micaceous, and pyritic shale and siltstone with abundant frambooidal pyrite interbeds. XRD results of laminated, black carbonaceous shale with minor pyrite (TND5, 35.3 km, for location see Fig. 3.2) indicate that the sample consists of chlorite 56%, quartz 36%, K-feldspar 11%, and pyrite 7% (WMC Resources Ltd., written comm., 1982). Footwall beds in TND8 of similar lithology to the previous sample consist of phlogopite and muscovite 51%, quartz 31%, chlorite 8% and siderite 5% (WMC Resources Ltd., written comm., 1982). In thin-section, footwall chlorite consists of very fine-grained, felted masses. The timing of chloritic alteration cannot be constrained.

5.6.2 Hangingwall

The hangingwall beds consist of 20-60% of very fine-grained, light-grey to black, carbonaceous shale with interbeds of dolomitic mudstone (Fig. 3.6). In hand specimen no alteration was observed however whole rock geochemical data shows a broad zone of elevated K in the hangingwall shale. XRD analysis conducted by Mineral Resources of Tasmania on finely laminated, black carbonaceous shale with minor dolomitic shale interbeds and laminae of frambooidal pyrite (THRD647, 288.1 m) indicate the concentration of the following mineral occurrences; mica (two unspecified forms) 40-60%, quartz 25-40%, K-feldspar 5-10%, and pyrite 5-19%.

5.7 Post mineralisation

No post-mineralisation alteration was observed in the primary ore deposit. The secondary oxide ore body has been subjected to surficial alteration processes and these processes were not examined as part of this study.

5.8 Distribution of Alteration Textures

This section describes the distribution of alteration texture associated with Cu mineralisation. The distribution of alteration textures provides information on the extent of a hydrothermal mineralising system and of the possible orientation of fluid conduits.

Figure 5.7 presents a summary of XRD results of samples from cross-section 102080 mE. As a generalisation the footwall beds are dominated by chlorite, the ore zone of the Nifty member by quartz, and the outer halo by high concentration of phlogopite, muscovite and quartz (Fig. 5.7). Figure 5.8 compares three columns, column A is the generalised stratigraphy as erected by WMC Resources Ltd.
Figure 5.7: Most lithologies are often very fine-grained and this has hindered the identification of mineral phases. XRD results (WMC Resources Ltd written comm., and this study) from cross-section 10280mE. Abbreviations: FWB = footwall beds, NM = Nifty member, PMB = pyrite marker bed, HW Sh = hangingwall shale, UC = upper carbonate, E3-Green Quartz, S2-Silicified Pyritic Shale, S3-Hydrothermal Quartz-Dolomite, S4-Silicified Dolomitic Mudstone, S5-Black Silica, sh-cc = carbonaceous shale, py = pyrite, phi = phlogopite, musc = muscovite, qtz = quartz, sid = siderite, dol = dolomite, K-fld = K-feldspar, chl = chlorite, mg = medium grained, fg = fine grained.
A-Generalised WMC Resources Ltd Stratigraphic Column
(Revised 1984, 1987a, 1987b)

- Carbonaceous shale
- Upper carbonate bed
- Limestone and dolomite beds
- Lower sulphur beds
- Lower carbonate bed

B-Extended Stratigraphic Column

- Carbonaceous pyrite shale
- Upper sulphur beds
- Lower carbonate bed
- Limestone and dolomite beds
- Upper sulphur beds

C-Hydrothermal Alteration Overprint

- Silicified Pyrite Shale
- Silicified Carbonate Bed
- Silicified Limestone
- Silicified Dolomite

Figure 5.8: A comparison between the stratigraphy established by WMC Resources Ltd, geologists (A), that interpreted from this study (B) and the distribution of overprinting alteration textures (C). Column A has been derived using a combination of stratigraphy and localised alteration textures that are related to chalcopyrite mineralisation. The pyrite-texture described in column A is redefined as an alteration texture that is the result of the concentration of carbonaceous material into wavy laminae during quartz replacement of a dolomitic shale protolith.
(Norris, 1985, 1987a, 1987b; Carmichael, 1990, 1992, 1993; Haynes et al., 1995; Dare, 1994), column B is the revised stratigraphy developed as part of this study (Chapter Three), and column C shows the distribution of alteration textures that overprint stratigraphy in column B. The footwall beds, upper shale, hangingwall beds and upper carbonate were generally not altered during the quartz-dolomite alteration event. The upper and lower units (column B) have zoned alteration about a central core of S5-Black Silic. Outward S5 altered rocks are silicified dolostones of S4 that pass outwards into banded S3-Hydrothermal Quartz-Dolomites and finally into unaltered host rock. The S1-Chloritic shale is a minor alteration phase and is generally located on the distal margin of Fe-rich S3-Quartz-Dolomite altered rocks and in the intermediate shale. There is a high degree of similarity in columns A and C, because WMC Resources Ltd. geologists have used localised alteration to define stratigraphic boundaries in column A. The stratigraphy shown in column B occurs in unaltered and unmineralised diamond drill holes and this reflects the original stratigraphy.

The distribution of alteration textures in the western wall of the open pit (1997) is shown in Figure 5.9. Footwall beds are located to mine north (N of Fig. 5.9) and the pyrite marker bed and hangingwall beds to mine south (S of Fig. 5.9). Above the photographs is listed the stratigraphic succession and the distribution of alteration textures. The lower unit contains banded S3-Hydrothermal Quartz-Dolomite and unaltered carbonaceous shale and dolomitic mudstone. The concentration of S3 bands increases toward the south. Further south again, S3 grades into S4-Silicified Dolomitic Shale and forms a zone about 10m thick with a banded appearance. With increased silicification S4 passes into S5 and this is seen in Figure 5.9 as a dark, high relief zone. The intermediate shale occurs as a discrete zone 1-4m thick and is shown north of centre in Figure 5.8. Within this interval there are high concentrations of S3-Chlorite Shale. Continuing southwards, the distribution of alteration textures observed in the lower unit is repeated in reverse order in the upper unit (S3-S4-banded S3 and host rock). Note that in Figure 5.9 the S5 texture has obliterated bedding and other sedimentary features and at outcrop scale S4 appears to have preserved bedding. The zone containing S3 altered rocks is interlayered with unaltered shales and the thickness and frequency of shale beds increase away from the mineralised and altered central core. The S2-Silicified Pyritic Shale overprints framboidal pyrite of the pyrite marker bed.

Cross-sections from 102000mE, 102090mE, 102160mE, 102240mE and 102300mE (Fig. 5.10A-E) show the distribution of alteration textures and stratigraphy. S1 altered rocks are irregularly distributed and generally form bands less than 10cm thick and because of this limited extent and thickness this texture does not show up on the following cross-sections. Figure 5.10A illustrates alteration textures on cross-section 102000mE where S4-Silicified Dolomitic Shale surrounds a central core of S5-Black Silica. Further out from the S4-Silicified Dolomitic Shale in a laterally continuous zone of S3-Hydrothermal Quartz-Dolomite altered rocks. A thin isolated zone of S5 altered rocks with a S4 halo are observed in the lowermost part of THRD634. S2-Silicified Pyritic Shales are observed in the pyrite marker bed area and in footwall beds below the Nifty member/footwall contact. A thin zone of S4-Silicified Dolomitic Shale is observed in TND24 at approximately 150m below the ground surface.
Figure S.9: Photo-collage of the western wall of the Nifty open pit (1997) showing the full deposit mine sequence. The view is looking west and with the younging direction to mine south. 200RL and 260RL (left of photograph) refer to the reduced level of the open pit benches. Ground surface is at ~300RL. Above the photograph are the stratigraphic successions as defined by this study and the distribution of alteration textures with respect to that stratigraphy.
Figure 5.10A-E: The distribution of alteration textures is shown in five cross-sections (102000mE, 102600mE, 102160mE, 102240mE, 102320mE). The distribution within individual cross-sections are discussed in the text however a similar distribution pattern occurs in all sections. The most distal alteration classification is a siliceous overprinting (S2) of framoidal pyrite beds in the pyrite marker bed and immediate deposit footwall. Inward of the S2 Siliceous Pyritic Shales is a progressive sequence of interbedded/banded S3 Hydrothermal Quartz-Dolomite altered rocks and unaltered shale beds. Proximal to the highest ore grade, S4 Silicified Dolostone grades into the S5 Black Silica altered rocks in the centre of the ore body. The S4 Chloritic Shale occurs as thin bands (~10cm thick) and therefore these bands do not show up on the sections.
The distribution of alteration textures in cross-section 102960mE (Fig. 5.10B) is similar to that of 102000mE (Fig. 5.10A). The maximum alteration is observed in the Nifty member in diamond drill holes of THRD753, THRD647, and THRD752 where an extensive S3 alteration zone is surrounded by an S3 halo. Thin zones of S3 altered rocks occur within S5-Black Silica and these zones consist of the Fe-rich form of S3-Hydrothermal Quartz-Dolomite. A reduction of the intensity of alteration occurs to the north and south of the main ore body as shown in TND5, TND1, and TND8, TND5 is dominated by S3-Hydrothermal Quartz-Dolomite altered rocks and a minor zone of S2-Silicified Pyritic Shale in the base of the diamond drill hole. Alteration patterns in THRD781 have been offset by a fault at 369m. To the south of THRD781 the intensity of quartz-dolomite replacement decreases so that in TND8 only minor S2-Silicified Pyritic Shale alteration occurs in the vicinity of the pyrite marker bed and several small Nifty member beds.

Cross-section 102160mE (Fig. 5.10C) shows a thick zone of S5 altered rocks surrounded by the halo of S4 and then S3 altered rocks. The intensity of alteration decreases to the south of this cross-section while to the north the thick S3 alteration in THRD648A has not been closed off to the north. The distribution of S2-Silicified Pyritic Shale is restricted in thickness and extent in the pyrite marker bed area and in the footwall is only present in THRD755. S2 is absent from THRD755, however this is likely to be the result of faulting. A thin zone of S3 altered rock is observed below the pyrite marker bed in the southern-most diamond drill hole (THRD779).

A striking feature of alteration distribution on cross-section 102240mE (Fig. 5.10D) is the limited extent of S2-Silicified Pyritic Shale. S2 occurs as intervals approximately 10m thick in TND12 and THRD636A and in the footwall of THRD780 and THRD635. In other diamond drill holes S2 is either very thin or absent. Compared to the previous sections there is also a reduction in the distribution of S5-Hydrothermal Quartz-Dolomite and this classification appears to be restricted to the lower intervals of the diamond drill holes. The distribution of S5-Black Silica and the enveloping S4-Silicified Dolomite Shale are similar to that observed in the previous cross-sections (Fig. 5.10A-C).

The trend observed in Figure 5.10D of reduced concentrations of S3-Hydrothermal Quartz-Dolomite altered rocks is continued in cross-section 102320mE (Fig. 5.10E). Cross-section 102320 has a thick (~75m) zone of S5-Black Silica in diamond drill hole THRD639 which is the result of a fault repetition of the altered rocks. No S3 alteration is observed in THRD637 but S4-Silicified Dolomite Shale and minor S3-Hydrothermal Quartz-Dolomite are the dominant alteration. In the southern diamond drill holes (THRD646 and THRD757) thin zones of S3 are surrounded by S4. S2-Silicified Pyritic Shale distribution is restricted to the pyrite marker bed in the two northern-most diamond drill core (THRD37 and THRD639) and the footwall contact in THRD637. The distribution patterns of alteration textures in cross-section 102320mE suggests that these drill holes are located on the edge of the alteration and mineralisation zones.
5.9 Deposit Comparison

5.9.1 Marooydore

No alteration is recorded as occurring during Cu mineralisation at Marooydore (McKnight, 1992; Reid, 1996). Earlier studies of McKnight (1992) and Reid (1996) concentrated on the structural, stratigraphic and temporal setting of Marooydore and therefore did not examine the alteration of host rocks during mineralisation.

5.9.2 Warrabarty

Smith (1996) defined three host-rock textures, dark dolostone, massive dolostone A, and massive dolostone B. The dark dolostone is a dark grey to black, thick, monotonous bedded lithology that Smith (1996) interpreted to be the epigenetic replacement of limestone. Massive dolostone A was defined as light grey interbeds within dark dolostone. Massive dolostone B occurred as a thick zone in the southern region of the Warrabarty prospect and is observed as a light grey, massive dolostone. Smith (1996) interpreted that this host-rock immediately predated and was synchronous with mineralisation, and that it formed due to the alteration of earlier dolostones.

<table>
<thead>
<tr>
<th>Term</th>
<th>Mode of occurrence</th>
<th>Hand specimen texture</th>
<th>Thin section texture</th>
<th>Grain-size</th>
<th>Relationship to mineralisation</th>
<th>Interpreted mode of formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Dolostone</td>
<td>Thick, monotonous, bedded</td>
<td>Rock grey to black, bedded, parallel to bedding</td>
<td>Uniaxial, non-planar, bound inclusion-rich, organic-rich</td>
<td>Fine to medium</td>
<td>Pre-date all mineralisation.</td>
<td>Epigenetic replacement of limestone</td>
</tr>
<tr>
<td>Massive Dolostone A</td>
<td>Interbeds within dark dolostone, discontinuous sequence</td>
<td>Light grey, massive, minor S, parallel to bedding, solution alteration</td>
<td>Uniaxial, non-planar, bound inclusion-rich, organic-rich</td>
<td>Medium</td>
<td>Pre-date all mineralisation.</td>
<td>Epigenetic replacement of limestone</td>
</tr>
<tr>
<td>Massive Dolostone B</td>
<td>Thick zone at south of prospect. Thinner associated with Zn mineralisation</td>
<td>Light grey, massive, S, parallel to bedding, solution alteration</td>
<td>Uniaxial, non-planar, bound inclusion-rich, organic-rich</td>
<td>Medium to coarse</td>
<td>Immediately pre-date &amp; synchronous with mineralisation</td>
<td>Abnormality of earlier dolostones during mineralisation</td>
</tr>
<tr>
<td>Dolomite (i)</td>
<td>Thin cement rim on breccia fragments &amp; vein walls</td>
<td>Not visible in b.s.</td>
<td>Lamell, non-planar to plane</td>
<td>Medium to coarse</td>
<td>Commonly associated with vein grey stage sph.</td>
<td>Formed immediately prior to &amp; coincident with sph</td>
</tr>
<tr>
<td>Dolomite (ii)</td>
<td>Most abundant breccia &amp; vein cement, may include matrix</td>
<td>Grey, often zoned cement</td>
<td>Fluid inclusion-rich, rounded nonplanar (dolomite)</td>
<td>Course</td>
<td>Intimately associated with mineralisation, but post main vein grey stage sph.</td>
<td>Cement formed after initial sph deposition</td>
</tr>
<tr>
<td>Dolomite (iii)</td>
<td>Breccia &amp; vein cement, often contained in veins, occasionally included in matrix</td>
<td>White, occasionally zoned, polygonal or fibrous cement</td>
<td>Lamell, nonplanar, saddle dolomite</td>
<td>Medium coarse</td>
<td>Post main grey stage sph. associated with green and later sph.</td>
<td>Cement formed during late stages of mineralisation</td>
</tr>
<tr>
<td>Dolomite (iv)</td>
<td>Breccia &amp; vein cement with qtz.</td>
<td>Pink polyhedral or fibrous cement</td>
<td>Chazy, inclusion-rich, saddle dolomite</td>
<td>Medium to coarse</td>
<td>Post main grey stage sph. and green, associated with latest sph.</td>
<td>Cement formed during late stages of mineralisation</td>
</tr>
</tbody>
</table>

Table 5.3: Summary of dolomite terminology used by Smith (1996). Note that letter suffixes (ie A & B) are used for replacement dolomites and Roman Numerals (i to iv) are used for cement generations (Table from Smith, 1996). Abbreviation: qtz-quartz, gsa-galaena; sph-sphalerite; hts-hematite; sbs-bedding.
Smith (1996) further defined a series of textures as dolomites (i)-(iv).

Dolomite (i) — thin cement rims on breccia fragments and vein walls that formed prior to, and coincident with sphalerite. Dolomite (i) occurs as coarse-grained, planar, and limpid [clear?] dolomite.

Dolomite (ii) — abundant breccia and vein cement that formed after initial sphalerite deposition. Well-banded, coarse-grained, light to mid grey dolomite cement.

Dolomite (iii) — breccia and vein cement that formed during late stages of mineralisation as coarse-grained, white dolomite.

Dolomite (iv) — breccia and vein cement often with quartz that formed during the late stages of mineralisation as a distinctive pink, medium to coarse-grained dolomite that overgrows dolomite (iii).

5.9.3 Teller

Host rock for mineralisation and alteration of the Teller Au-Cu deposit are carbonaceous silstone, sandstone and dolomitic rocks of the Teller Formation in the stratigraphically younger Lusail Group (Rowins et al., 1997). Rowins et al. (1997) stated that there is no distinct vertical or lateral alteration zoning and that alteration is most intensely developed in wall rocks adjacent to reefs and veins.

Alteration at Teller is described as a high degree of silicification, sericitation, and carbonatization, with sericite-carbonate alteration best developed in argillaceous sandstone and calcareous silstone, and silica alteration best developed in quartzose sandstone (Rowins et al., 1997).

5.9.4 Mount Isa

The Mount Isa ore bodies form the largest underground mine in Australia and one of the world’s largest. The combined ore bodies rank among the world’s leading producers of lead, silver, copper and zinc (MIM Holdings Ltd. fact book, 1998). The ore bodies are located in the Western Succession of the Mount Isa Inlier, Queensland, Australia. The Western Succession of the Mount Isa Inlier consists of several Palaeoproterozoic intracratonic rift-sag cover sequences (Blake et al., 1990). Cover sequences 2 and 3 respectively provide the source and host for Cu mineralisation at Mount Isa. The igneous dominated rift-phase 2 consists dominantly of the continental theologies of the Eastern Creek Volcanics and interleaved fluvial clastic. The associated sag-phase 2 consists of fine-grained clastic unconformably overlain by rift-phase clastics and acid volcanics of cover sequence 3. Sag-phase 3 consists of the Mount Isa Group which is composed of fine-grained clastics and carbonates (Neudert and Russell, 1981). Part of the Mount Isa Group is the carbonate-rich, dolomitic silstone, Uqebart Shale. In the area of the Mount Isa mine, the Uqebart Shale consists of carbonaceous and pyritic units overlain by stacked stratiform Pb-Zn ore bodies. Deformation has juxtaposed Uqebart Shale and Eastern Creek Volcanics along the Paroo fault. Alteration textures are well defined for the Mount Isa copper and lead-zinc ore bodies (Perkins, 1984; Swager, 1985; Waring, 1990). Carbonaceous and dolomitic shales of the Uqebart Shale host the Mount Isa Cu ore bodies. These host rock have been altered in a well recognised, zoned, silica dolomite
alteration scheme where outer textures are progressive replaced by younger alteration textures toward the inner siliceous Cu-rich core.

Swager (1985) described a four-fold division of silica dolomite alteration at Mount Isa as 1) recrystallised shale, 2) crystalline dolomite, 3) irregularly brecciated recrystallised shale, and 4) brecciated siliceous shale. Recrystallised dolomitic shale was defined as the development of coarse-grained dolomitic rhombs aggregates in black dolomitic shale (Waring, 1990) and the coarsening of original fine-grained dolomite plus the neornorphic growth of ferroan dolomite (Swager, 1985). Recrystallised shale is overprinted by coarse ferroan dolomite porphyroblasts and coarse veins of ferroan dolomite + quartz, chlorite, pyrite, chalcopyrite and pyrrhotite (Waring, 1990). Irregularly brecciated recrystallised shales form inward of recrystallised shales and consist of dolomitic and/or siliceous shale fragments in a matrix of medium- to coarse-grained dolomite and quartz (Swager, 1985). Brecciated siliceous shale consists of a very fine- grained, locally pyritic, siliceous shale in a matrix of quartz with some chalcopyrite and pyrrhotite (Swager, 1985).

In addition to the four classifications of Swager (1985), Waring (1990) described silicified recrystallised shale, partially silicified massive crystalline dolomite, altered dolomitic lithologies with strong quartz vein, siliceous shale, siliceous breccia, pyritic bearing rocks, pyritic rocks, and talc. Waring (1990) described the alteration sequence as dolomitic shale → recrystallised dolomitic shale → irregularly brecciated dolomite → partially silicified dolomitic breccia → siliceous breccia.

5.9.5 Ruby Creek

The Ruby Creek Cu deposit consists of in excess of 100Mt @ 1.2%Cu and is hosted hydrothermally altered, Middle to Upper Devonian carbonates located in the Cosmos Hills, Alaska (Rennells, 1965, 1969; Hitzman, 1983, 1986; Bernstein and Cox, 1986). Basement is pre-Devonian Kogolakukk schists that consist of pelitic schists, quartzites, metabasalts and marbles of green schist to epidote- amphibolite facies metamorphic grade (Hitzman et al., 1982, 1986). Unconformable overlying the basement is a 700m thickness of Devonian pelitic schists and quartzite of the Anirak schist. Overlying the Anirak schist, with a gradational contact, is a 1000m thickness of the Middle to Upper Devonian Borntie carbonate sequence (Hitzman et al., 1982, 1986). The Borntie carbonate sequence hosts the Ruby Creek Cu deposit and consists of a phyllitic marbles at the base grading upward into less argillaceous lithologies. Cu mineralisation is restricted to a complex sequence of dolostone breccia units within a regional-scale, symmetrical, doubly plunging anticline Hitzman (1983, 1986).

Hitzman (1983, 1986) and Bernstein and Cox (1986) describe two alteration stages at Ruby Creek resulting in a hydrothermal dolostone hosted one body. An early alteration resulted in the widespread, progressive dolomitisation of the host limestone and produced a zoned, and intergradational arrangement of low iron dolostone (A dolostone) around a ferroan dolostone (B dolostone) to sideritic core (Hitzman, 1986). Minor base-metal mineralisation occurred during this period of dolomitisation. The second and
later alteration stage produced C carbonates that form veins and crackle-breccia that cross cut the earlier hydrothermal alteration. The main phase of Cu mineralisation occurred during this second phase of alteration.

A dolostones consist of light to medium grey, homogeneous to mottled or brecciated texture. Hitzman (1986) noted that successive dolomitisation had remobilised carbonaceous matter and reprecipitated this as thin films between dolomite grains, as clots in intergranular voids and along stylolitic contacts. B dolostone consists of grey to dark grey irregular veins and breccias with a variety of clasts of A dolostone and B dolostone in a matrix of B dolostone. B dolostone consists of pyrite, minor sphalerite, and cryptocrystalline C veins are associated with a second phase of mineralisation and show a distinct zonation in both distribution and mineralogy. The density of C veins decreases toward the periphery of the system and are most abundant above massive iron sulphide layers separating ferroan dolostones from siderite-bearing assemblages (Hitzman, 1986). Deep in the system the mineralogy consists of dolomite and sparse quartz in the middle dolomite, chalcopyrite with minor calcite, and pyrite, and on the edge C veins contain dolomite and calcite with minor sphalerite, pyrite and fluorite.

5.9.6 Comparison to Nifty

The zoned alteration system described for Mount Isa has many similarities to the zonation, mineralogy, and texture observed at Nifty. The alteration sequence described by Worring et al. (1998) of recrystallized dolomitic shale → irregularly brecciated dolomite → partially silicified dolomitic breccia → siliceous breccia is similar to the sequence S3-Hydrothermal Quartz-Dolomite → S4-Dolomitic Shale → S5-Black Silica, observed at Nifty. The main difference between Mount Isa and Nifty, apart from size of the system, is that alteration at Nifty is dominated by higher concentration of siliceous alteration in the centre of the ore body. The other analogue suggested for Mount Isa and Nifty is the Ruby Creek deposit where a two stage alteration sequence is described (Hitzman, 1983, 1986). Ruby Creek alteration is a dolomite dominated alteration system with a different mineral zonation to that of Nifty and Mount Isa. Alteration at Ruby Creek is similar to that described for Warrabury where Smith (1996) suggested that alteration and mineralisation were akin to dolostone associated with the Ruby Creek Zn-rich phase. Descriptions of Telfer alteration textures lack detail and this hinders meaningful comparisons. Cursory observations of Telfer diamond drill core and the M10-M12 reefs suggest that the style of dolomitic alteration is similar to that observed at Nifty and the intense silicification, common at Nifty, was not observed.

5.10 Summary of Alteration Sequence

In this section a summary of the alteration textures and zonation observed at Nifty is presented. The relationships between alteration, vein stages and mineralisation are discussed at the end of Chapter Seven. Mineralisation at the Nifty Cu deposit is associated with a zoned alteration halo that surrounds the ore body. The alteration halo consists of a central core of intensely siliceous replacement (S5) that has obliterated primary sedimentary textures and lithologies. The siliceous replacement consists of quartz, chalcopyrite, pyrite, fluorapatite and minor dolomite. Outward of the central core is a zone of silicified
dolostones that consist of quartz with minor remnant dolomitic shale. Quartz replacement has concentrated carbonaceous material into very thin (<1mm) layer parallel, wavy laminated bands and these bands give this alteration texture the appearance of the cryptagal laminated carbonates described by Norris (1987a). Outward of the S4-Silicified Dolomitic Shale are banded S3-Hydrothermal Quartz-Dolomite altered rocks and unaltered shales. The concentration and intensity of S3 alteration decreases outward and at its least intense appears as isolated quartz-dolomite spots associated with quartz-dolomite veins with distinctive alteration margins.

Figure 5.11 is a summary diagram showing the progressive alteration sequence that occurs over tens of metres and is associated with Cu mineralisation.

1) In shale dominated intervals the progressive alteration sequence is carbonaceous shale → interbedded S3-Hydrothermal Quartz-Dolomite alteration spots and unaltered carbonaceous shale → S3-Recrystalline dolomitic shale → S5-Black Silica → S5-mottled black and white quartz.

2) In carbonate-rich intervals the alteration sequence is, dolomitic mudstone S3-Hydrothermal Quartz-Dolomite → S4-Silicified Dolomitic Shale → S5-Black Silica → S5-mottled black and white quartz.

As an overall distribution S3 occurs on the outer edge of the alteration halo and is often banded with unaltered carbonaceous shale. The concentration of S3 progressively increases inward and gives way to S4-Dolomitic Shales and S4 in turn grades into S5-Black Silica.

![Diagram](image)

Figure 5.11: Progressive syn-mineralisation alteration of carbonaceous and dolomitic shale host rocks at Nifty results in the sequence of alteration textures and classifications shown above. The alteration pathway is strongly dependent on the host lithology. The mottled black and white quartz texture is part of S5 and occurs over a limited distribution in areas of maximum alteration.

Note that in Figure 5.11 the mottled black & white quartz texture of S5-Black Silica is the end member of both host rock alteration sequences. The S2-S5 alteration textures formed during the same event and from similar fluids but variations in host rock composition, water rock ratios and proximity to mineralisation have caused the zoned pattern. The boundaries between alteration textures and classifications are gradational and are heavily controlled by the host lithology.
EI-Fe Mg carbonate and E2-Green Quartz are not included in the alteration sequence shown in Figure 5.11 as they pre-date mineralisation. EI-Fe Mg carbonate is considered to have occurred very early, possibly during diagenesis, because the Fe-Mg carbonate is crosscut by cleavage parallel stylolites, and EC-Fracture carbonate veins (Chapter Six) contained within Fe-Mg carbonate are crosscut by syn-mineralised veins. The timing of E2-Green Quartz is less clear. E2 has a distribution restricted to the upper and lower units and although E2 is not mineralised, it is common in areas of highest concentration of chalcopyrite. As E2 is replaced and crosscut by quartz-dolomite alteration and syn-mineralisation veins, a pre-mineralisation timing is evident.

Descriptions of alteration at Telfer and Maroochydore lack detail on which to base meaningful comparisons. The dolostone A and B alteration at the Ruby Creek Cu deposit has similarities to the grey stage dolostone alteration at the Warrabarty Pb-Zn prospect. Of the comparative deposits, the zoned silica-dolomite alteration at the Mount Isa Cu deposit is similar to quartz-dolomite alteration observed at Nifty. The main differences between Mount Isa and Nifty are that at Nifty the size of the alteration system is smaller and alteration has a higher concentration of quartz replacement.
Chapter Six - Vein Stages

6.0 Introduction

The characterisation the vein styles, and their paragenetic relationships and relative timing with respect to mineralisation, provide information on the geochemical and physio-chemical conditions at the time of vein formation. During logging of Nifty diamond drill core numerous vein stages were identified and the paragenetic relationships between them determined. The relative timing of each vein stage has been made with reference to mineralisation and alteration, as these features provide datum on which to relate timing. Veins act as conduits for hydrothermal fluids and therefore this chapter follows on from the previous chapter on alteration textures and leads into the upcoming chapter on mineralisation styles.

The previous work on the Nifty Cu deposit (Norusis, 1987) does not describe or discuss vein stages and there are no other company-based descriptions of the vein paragenesis. Descriptions of vein stages from Maroochydore (Reed, 1990), Warrabury (Smith, 1990), Goosewacker (Proost, 1997) and Telfer (Goelnisch, 1988) are presented and compared to the vein stages identified and described at Nifty.

6.1 Vein Stage Definitions

Pre-mineralisation

- IA Bedding parallel dolomite veins
- IB Folded bedding-parallel pyrite-quartz-dolomite veins
- IC Fracture dolomite-quartz veins

Syn-mineralisation

- IA Chalcopyrite-dolomite veins
- IB Alteration margin quartz-dolomite veins
- IC Cleavage parallel dolomite-quartz veins

Post-mineralisation

- IIIA Coarse quartz veins
- IIIB Bladed carbonate veins

6.2 Pre-mineralisation Vein Stage

6.2.1 IA-Bedding parallel dolomite vein

IA-Bedding parallel dolomite veins (Fig. 6.1A, D) range in thickness from 3mm to 2 cm and typically occur in shale and dolomitic mudstone of the hangingwall and upper carbonate bed. Vein margins are sharp but in isolated areas, irregular margins are observed (Fig. 6.1D). The major component of IA vein stage is a coarse to medium crystalline dolomite that exhibits subaxial growth (Cox, 1987, Ramsey and Huber, 1987) with thin traces of quartz grains in the vein centre (Fig. 6.1A, D and vein IA on Fig. 6.4). At the vein-host rock interface there is a thin zone (20-50μm) of fine-grained quartz ± pyrite. Bedding parallel shortening has thrust veins as shown in Fig. 6.1A and this thrust ramping has the same shortening direction as P3 folds. Concentrations of pyrite occur at the sites of vein ramps where pyrite has
Figure 6.1A-F: A. Vein stage I4-bededding parallel dolomite veins (TIFD 635, 247.5m) are a series of folded and ramped dolomite-quartz veins hosted by carbonaceous shale of the hanging wall beds. B. Vein stage IB is bounded in the footwall beds and consists of crustiform growth of quartz, dolomite and pyrite (TND12, 355.7m). C. IC veins form as a series of thin planar to anastomosing quartz-dolomite fracture veins (TND10, 255.5m). D. I4 vein (TIOKO 635, 237.5m) showing fine-grained quartz growth along the vein margin, antitaxial dolomite growth and a meridional quartz trail. E. IIb vein showing the crustiform banding of quartz, dolomite and pyrite. F. IC veins from TND10 (255.3m) show composite vein development with synitaxial growth of dolomite and antitaxial, quartz dominated vein centre with numerous fine dolomite inclusion trails.
been introduced along the vein margins during D2 deformation to form a thin band at the vein/wallrock interface.

6.2.2 IB-Folded bedding parallel pyrite-quartz-dolomite veins
IB-folded, bedding parallel pyrite-quartz-dolomite (Fig. 6.1B, E) veins are typically found in dolomite and chloritic shales of the footwall beds and as the name suggests IB veins and the surrounding host rock have been subject to folding which is interpreted as F3. The veins are 5-20mm thick, folded, with crustiform banded pyrite, quartz, and dolomite and with minor mica (Fig. 6.1B, E and vein IB on Fig. 6.4). Vein margins are sharp with a thin (<20μm), very fine grained, quartz selvage. Within the veins are angular inclusions of wall rock that are aligned parallel to the vein edge. Crustiform banding occurs in three zones parallel to the vein margin, a central zone consists of meridional pyrite intergrown with elongate quartz grains whose long axis is at right angles to the vein wall. The interstices between these elongate quartz grains are filled with very fine-grained quartz and minor coarse-grained dolomitic intergrowths. A prominent pyrite trail, parallel to the vein margin, separates the central zone from the outer areas. The outer-most zones consist of a fine-grained mosaic of quartz, higher concentrations of irregularly shaped pyrite bands, and rare chalcedite (Fig. 6.1E).

6.2.3 IC - Fracture dolomite-quartz veins
IC - fracture dolomite-quartz veins (Fig. 6.1C, F) have a distribution restricted to the hangingwall beds and occur as multiple sets of planar to anastomosing, coarse to medium, crystalline dolomite + quartz veins. Veins show composite growth patterns with syntaxial dolomitic margins (Cox, 1987; Ramsey and Huber, 1987) of similar composition to, and optically continuous with, the wall rock (Fig. 6.1F) and a quartz-rich antitaxial core (Cox, 1987; Ramsey and Huber, 1987). The antitaxial core is composed of quartz that has grown at right angles to the vein margin with numerous, regularly spaced, fine-grained dolomite inclusion trails parallel to the vein margin (Fig. 6.1F). Veins crosscut bedding at high angles (Fig. 6.1A and vein 7 on Fig. 6.4). Although similar to IC-Cleavage parallel veins, the vein fracture stage is crosscut by S2c cleavage, the H series of mineralised veins (TND10 at 352-353m) and cleavage parallel stylolites suggesting an early timing for this vein stage.

6.3 Syn-mineralisation Vein Stage

6.3.1 IIA-Chalcopyrite-dolomite veins
IIA-Chalcopyrite-dolomite veins (Fig. 6.2A, D) occur throughout the lower portion of the Nifty member, with the largest concentration in the lower massive carbonate and lower interbedded zone. There are rare occurrences in the upper shale and upper interbedded zone, and IIA veins are not observed in the PMB. IIA veins also occur in the footwall beds, close to the contact with the Nifty member. IIA veins crosscut stratigraphy and are generally several centimetres thick but have been recorded up to 70cm (Fig. 6.2A, D and vein IIA on Fig. 6.4). Veins consist of high concentrations of chalcopyrite with dolomite, quartz,
Figure 6.A-F: A. Vein stage IIe-Chalcopyrite-dolomite vein (THR9506A, 290.8m) with euhedral pyrite. B. IIIb-Alteration margin veins have distinctive dolomite alteration halo that extends along bedding (THR950752, 287.1m). C. IIIC-Cleavage parallel dolomite-quartz veins are a series of thin dolomite + quartz veins that are coincident with S, cleavage (THR96047, 310.2). D. Detail of a IIIC-Chalcopyrite-dolomite vein margin from THR7761 (357.4m) showing from left to right, silicified carbonaceous shale host rock, fine-grained quartz margin, fibrous chlorite, coarse-grained quartz crystals, and chalcopyrite. The vein centre (not shown) contains coarse dolomite + quartz + euhedral pyrite. Abbreviations: qtz-quartz, chl-chlorite, cpy-chalcopyrite. E. Photomicrograph of a IIb vein from THR7752 (287.15m) showing the bedding parallel alteration of carbonaceous shale at the vein margin. F. IIIC-Cleavage parallel dolomite-quartz veins have sharp margins and consist of intergrown dolomite and quartz (THR96047, 310.3m).
phlogopite, chlorite and pyrite in varying amounts. Chalcopyrite occurs as anhedral masses in the vein centre (Fig. 6.2C). Dolomite occurs as well defined dog-tooth crystals commonly in the centre of veins with subbedal to euhedral pyrite grains up to 1 cm in size. Fine, fibrous chlorite occurs on the margin of chalcopyrite clots and as rare inclusions with these clots. Table 6.1 presents representative micro-probe analyses of vein chlorites from THRD635, THRD636A, and THRD752. Nifty vein chlorite is classified as chlideschlore with a Fe/(Fe+Mg) number between 0.21-0.36 (Table 6.1). Vein margins are irregular and include fragments of wallrock. Figure 6.2D shows a typical vein margin sequence of silicified carbonaceous shale host rock, fine-grained quartz, fibrous chlorite, coarse-grained quartz, chalcopyrite and in the vein centre subbedal to euhedral pyrite (Fig. 6.2A). In host rock with high dolomite component the vein selvage shows a zone of altered and reprecipitated dolomite instead of the fine quartz margin. Summary data from vein carbonates is presented in Table 5.1 and these results indicate that I/A are composed of approximately 2% MnCO₃, 10% FeCO₃, 35% MgCO₃ and 51% CaCO₃. I/A veins are associated with the main phase of mineralisation and S5-Black Silica alteration and as shown in Figure 5.2C I/A-Chalcopyrite-dolomite veins crosscut the pre-mineralisation E2-Green Quartz.

<table>
<thead>
<tr>
<th></th>
<th>THRD636A</th>
<th>THRD635</th>
<th>THRD752</th>
<th>THRD752</th>
<th>THRD752</th>
<th>THRD752</th>
<th>THRD752</th>
<th>THRD752</th>
<th>THRD752</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeO</td>
<td>26.92</td>
<td>28.83</td>
<td>29.20</td>
<td>28.44</td>
<td>28.84</td>
<td>29.71</td>
<td>28.53</td>
<td>28.45</td>
<td>29.53</td>
</tr>
<tr>
<td>FeO</td>
<td>18.10</td>
<td>20.20</td>
<td>12.22</td>
<td>11.89</td>
<td>12.28</td>
<td>12.23</td>
<td>13.17</td>
<td>11.95</td>
<td>12.11</td>
</tr>
<tr>
<td>MnO</td>
<td>0.12</td>
<td>0.43</td>
<td>0.18</td>
<td>0.13</td>
<td>0.12</td>
<td>0.12</td>
<td>0.15</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td>CaO</td>
<td>0.07</td>
<td>0.07</td>
<td>0.04</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.06</td>
<td>0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>nd</td>
<td>0.01</td>
<td>nd</td>
<td>0.03</td>
<td>nd</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.02</td>
<td>nd</td>
<td>0.02</td>
<td>0.01</td>
<td>nd</td>
<td>0.02</td>
<td>nd</td>
<td>0.10</td>
<td>nd</td>
</tr>
<tr>
<td>H₂O(C)</td>
<td>11.58</td>
<td>11.67</td>
<td>12.12</td>
<td>11.91</td>
<td>12.11</td>
<td>12.27</td>
<td>12.11</td>
<td>12.10</td>
<td>12.31</td>
</tr>
</tbody>
</table>
| TOTAL| 97.26    | 99.02   | 98.74   | 97.62   | 98.82   | 100.09  | 99.17   | 98.67   | 100.17  | 98.46

Table 6.1: Electron microprobe analyses of vein chlorites from THRD636A (288.1m), THRD635 (247.5m), THRD752 (357.4m).

6.3.2 IIB-Alteration margin quartz-dolomite veins

Carbonaceous and dolomitic shales of the lower unit and chloritic shales of the footwall beds host IIB-Alteration margin quartz-dolomite veins (Figs. 5.4A, 6.2B, E). This vein type has been recorded in
THRD789 approximately 275m below the lower unit/footwall contact (contact at 450m, vein at 725m).  

IVB occurs as thin, <2mm quartz-dolomite veins with a distinctive light grey, dolomitic, chloritic and white mica-rich, alteration halo that extends several millimetres into the host wallrock (Figs. 5.4A, 6.2B, E and vein IIb on Fig. 6.4). Vein mineralogy consists of dolomite, quartz, chloroppyrite, pyrite, muscovite, and chlorite. A simple sulphide mineralogy occurs in this vein stage of subhedral to subhedral chloropyrite and 2 subhedral to euhedral pyrite + quartz in the vein centre. Within veins, isolated chloropyrite and pyrite grains have thin, quartz and chlorite infilling pressure shadows. Fine fibrous brucite and muscovite have formed in both the wallrock-altered margin and within the vein. Vein margins are highly irregular as wall rock alteration creates a distinctive diffuse vein margin due to invasion along bedding laminations (Fig. 6.2C and D).

Where IVB veins crosscut bedding, alteration has occurred preferentially along beds of higher dolomite content (Fig. 6.2E). This alteration of the host rock creates a leaf-like pattern where the vein is the stem and the laminae parallel alteration of wall rock is the branch, and the leaves are the alteration that extends outward from the branch. IVB veins are associated with mineralisation and S3 Hot-water hydrothermal Quartz-Dolomite alteration. The composition of the alteration halo is strongly influenced by the wallrock lithology, so that the alteration mineralogy in dolomite-rich intervals is dolomite dominant and in shale intervals is quartz-rich. This vein stage has been folded with the fold axial plane discordant to S3, suggesting that the folding occurred post-D3 at (Fig. 6.2B).

6.3.2 IIIc-Cleavage parallel dolomite-quartz veins

IIIc-Cleavage parallel dolomite-quartz veins (Fig. 6.2C, F and vein IIIc on Fig. 6.4) occur in shale dominated intervals of the Nifty member. IIIc veins are a series of thin (<1mm), planar dolomite-quartz veins that have formed parallel to S2 cleavage (Fig. 6.2F). Vein mineralogy consists of intergrown dolomite and minor quartz with trace amounts of chloropyrite and fibrous brucite aligned along the vein margin. Quartz growth is preferentially concentrated adjacent to quartz-rich shale beds and in smaller veins less than 100 μm thick. IIIc veins are crosscut by late IIIA-Chalcopyrite dolomite veins (Fig. 6.2C) suggesting their formation during S3 cleavage development and prior to peak mineralisation. This vein stage is similar in appearance to IC-Fracture dolomite-quartz veins, however IIIc veins have a greater distribution and are coincident with cleavage whereas IC veins are found predominantly in shales of the hanging wall beds and are crosscut by S2 cleavage.

6.4 Post-mineralisation Vein Stage

6.4.1 IIIA-Coarse quartz veins

Coarsely crystalline, quartz-dolomite veins (Fig. 6.3A-B, and IIIA on Fig. 6.4) have a wide distribution both texturally and stratigraphically. Vein margins are irregular and numerous wall rock inclusions are contained in the vein (Fig. 6.3B). The main component of IIIA veins is a cloudy, inclusion free-quartz, with minor intergrown bright white dolomites. Rare pyrite and chloropyrite are observed in this vein stage.
Figure 6.3A-C: A. Vein stage IIIA with coarse-grained quartz with isolated intergrowths of dolomite (THRD752, 332.1m). B. Hand specimen of IIIIB-bladed carbonate vein (THRD781, 382.7m) showing a series of randomly oriented calcite blades with open void spaces between blades. IIIIB veins have a wide distribution in both lateral extent and stratigraphic level. C. IIIIB-bladed carbonate vein (THRD781, 505.9m) showing host rock fragments within the vein, and the undeformed calcite blades with open space voids between the blades.
as isolated euhedral crystals to anhedral blebs and spots suggesting remobilisation or entrainment during the post-mineralisation IllA veining.

6.4.2 IllB - Bladed carbonate veins

IllB-bladed carbonate veins (Fig. 6.3C-D, and IllB on Fig. 6.4) have a wide distribution and have been found in most diamond drill core, and at varying stratigraphic levels. These veins occur as a series of thick 2-20cm, irregular margined veins with randomly oriented bladed calcite (Fig. 6.3 and vein 5 on Fig. 6.4). As shown in the hand specimen and thin-section photographs (Fig. 6.3C) open voids occur between the randomly oriented blades. Fine to very fine-grained euhedral pyrite and chalcopyrite grains have formed as inclusions on, and within, the blades and it is interpreted that these sulphides have been remobilised. Fragments of transported and rotated host rock are included in the veins and the edges of these fragments have a thin, 5cm, very fine grained quartz growth zone at the interface. Many fragments have a well-developed S_{0c} cleavage and the orientation of cleavage in fragments is different to that of the surrounding host rock, suggesting a post-D_{3a} timing for this vein stage. A second feature suggesting a late timing, is the undeformed nature of delicate calcite blades.

6.5 Vein Paragenesis

The relative timing of vein stages is based on the paragenetic relationships and also the relationship of the veins to deformation events. A summary diagram showing the paragenetic relationships between vein stages is shown in Figure 6.6.

6.5.1 Pre-mineralisation

The earliest vein stages are the IA and IB (Fig. 6.1). The syntaxial growth of fibrous dolomite in IA veins indicates progressive vein growth that occurred from the wall to the vein centre. Crustiform banding of IB veins indicates crack seal vein development (Cox, 1987). IC veins record a change from syntaxial to antixial vein growth and the numerous trails of dolomite inclusions in centre of IC veins suggest repeated opens of the vein and therefore a crack seal vein growth. Both vein stages have been subjected to D_{3b} and possibly D_{3a} deformation. The ductile and brittle deformation style of IA and IB veins reflects rheological differences between host rock lithologies in the hangingwall and footwall beds and composition of veins. (Suppe, 1985). The other early vein stage is the IC veins which are restricted to the hangingwall beds and the E1-Fe Mg rich carbonate alteration stage. Presence of cleavage parallel stalojolites and IllA mineralised, veins crosscutting IC veins suggest formation of IC veins before mineralisation but after the formation of the E1-Fe Mg Carbonate altered rocks.

6.5.2 Syn-mineralisation

IIA, IB and IIC veins are directly related to mineralisation as all three vein stages are chalcopyrite-bearing and have associated syn-mineralisation alteration textures. A change in the style of veining is
Figure 6.4 Summary diagram showing the paragenetic relationships between vein stages observed in diamond drill holes from the Nifty Co deposit. Early, pre-mineralisation vein stages are named IA, IB, and IC. These early vein stages have been overprinted by syn-mineralisation vein stages of IIA, IIB, and IIC. The last phase of vein development (IIB and IIC) occurred after mineralisation. The orientations of bedding (S1) and cleavage (S2) are indicated in red. Individual descriptions of the vein stages are contained in the text.
evident from pre- to syn-mineralisation vein stages as the pre-mineralisation crack seal types are not observed in this later stage. **IIA** veins are the main chalcopyrite-bearing veins and are also associated with siliceous alteration of host rock. Euhedral pyrite, dolomite and quartz are typically observed in the vein centre suggesting that these mineral phases formed late in the paragenetic sequence after the main influx of chalcopyrite. The **IIIb** veins are the feeders for the fluid responsible for the SJ alteration sequence, where quartz-dolomite spots form in unaltered carbonaceous shale and then develop into a recrystallised dolomite and hydrothermal quartz dolomite textures. **IIC** veins are included as syn-mineralisation based on the presence of chalcopyrite mineralisation in the veins and their timing relative to D2 deformation, however as these veins are crosscut by **IIA** veins it is likely that **IIC** veins formed early in the mineralisation sequence.

6.5.3 Post-mineralisation

**IIA** veins are assigned as post mineralisation because they crosscut I and II vein stages. The presence of isolated pyrite and chalcopyrite clots within these veins suggests that the chalcopyrite was remobilised during the formation of this vein stage. **IIIb** veins also crosscut all stages I and II veins and have rotated sulphide-bearing wall rock fragments that suggest this is the last vein stage to form. In epithermal environments bladed carbonate veins are considered indicative of phase separation (White & Helensquist, 1990; Simmons and Christenson, 1994).

6.6 Comparison of Other Vein Stage Descriptions

This comparison with other mineralised occurrences within the Throssell Group of the Paterson Orogen is based on descriptions of the mode of occurrence, mineralogy, and paragenetic relationships for veins from Maroochydore (Reed, 1996); Warrabury (Smith, 1996), Goosewacker (Pivov, 1997), and Telfer (Götzpicht et al., 1988).

6.6.1 Maroochydore

Reed (1996) subdivided veins at Maroochydore on the basis of their timing of formation, and orientation with respect to the major fold structures. The vein stages defined are 1) veins associated with shear and opening along bedding planes, 2) veins discordant to bedding and oriented parallel to the axial planes of D2 folds, 3) discordant veins oriented orthogonal to the main D2 cleavage and D2 fold axes, and 4) veins crosscutting D3 structures and oriented orthogonal to D3 cleavage.

The earliest formed vein sets recorded by Reed (1996) were defined as discordant dolomite veinlets less than 2mm wide with diffused margins and composed of euhedral to normally anhedral, medium grained dolomite. Reed (1996) interpreted this vein stage to have formed early in the diagenetic sequence. A second style of this early vein stage is restricted to Maroochydore hangingwall rocks and occurs as bedding parallel veins up to 7mm wide and composed of elongate and fibrous white dolomite. Veins belonging to this classification have been folded and sheared and therefore their formation predates
deformation and metamorphism. Reed (1996) interpreted that this vein stage formed during late
diagenesis when the sediments were semi-lithified. The second group of veins recorded by Reed (1996)
were defined as veins oriented axial planar to D2 folds and these veins are found predominantly in a
brittle dolostone unit that contains the Maricohydrite mineralisation. Veins with straight margins range in
width from a few millimetres to 5cm and can reach up to 20cm. Vein consist of medium to coarse-
grained, pink to white, vuggy euhedral dolomite grains to 5mm intergrown with subhedral to subhedral
clear quartz. Pyrite is the most common sulphide and is accompanied by varying amounts of chalcopyrite,
galena and rarely sphalerite and fine-grained euhedral to subhedral fluorapatite. The third group of veins
(Reed, 1996) are oriented orthogonal to the axes of D2 folds and found commonly in dolomitic shales of the
hanging wall to the Maricohydrite mineralised horizon. The veins are no more than 5mm wide and
composed of medium- to coarse-grained dolomite, quartz, and with sulphides of galena and chalcopyrite.
The last classification proposed by Reed (1996) was of syn-D2 veins and these veins are defined as rarely
exceed a few millimetres in width and comprised of white anhedral calcite and rare quartz.

6.6.2 Warrabarty

Smith (1996) detailed the micro- and micro-scale characteristics of two vein types (grey and white vein
stages) observed at the Warrabarty carbonate replacement prospect. Grey stage veins describe those veins
composed of predominantly the grey stage minerals of dolomite (iii) with lesser quartz, dolomite (iv), and
minor sphalerite and pyrite (dolomite textures are described in paragraph 5.9.2). Two styles of grey stage
vein were identified (Smith, 1996) as 1) a relatively planar form with sharp margins, and 2) wispy,
irregular veins with diffused margins produced by wallrock replacement. White stage post-dates grey
stage are characterised by fibrous crystal morphology and branched, tawny, symbaloidal shapes. White
stage veins consist of dolomites (iii) and (iv), quartz, pyrite, minor sphalerite, and galena with rare
chalcopyrite, arsenopyrite, bornite, chalcocite, and chalcopyrite.

6.6.3 Goosewacker

Freud (1997) defined four vein stages from logging of Goosewacker diamond drill holes. These vein
stages are 1) layer parallel, sulphide vein, 2) quartz carbonate ± sulphide vein, 3) sulphide quartz ±
carbonate vein, and 4) sulphide carbonate ± quartz vein. Freud (1997) records that the stage 4 veins are
the main mineralising and host-rock altering stage at Goosewacker.

Layer parallel, sulphide vein (stage 1) occur as stratabound, 2-20mm thick veins consisting predominantly
of pyrite, with lesser quartz and minor carbonate. Quartz carbonate ± sulphide vein (stage 2) contain
quartz with lesser siderite, pyrite and rare hematite. Freud (1997) noted that this vein stage crosscut stage
1 veins. Sulphide - quartz ± carbonate vein (stage 3) are 0.5-5cm thick and consist of mainly quartz,
pyrite, galena, and chalcopyrite. Also present are siderite, rare sphalerite, bornite, covellite, and marronite.
Crustiform and vuggy sulphide, carbonate ± quartz veins (stage 4) are 1-20cm wide and consist of
siderite, galena, pyrite, chalcopyrite, with lesser quartz, sphalerite, bornite, covellite and minor
bismuthinite and wittichenite. Froud (1997) suggested that pervasive sericite and pyrite alteration is associated with this vein stage. The final vein stage identified by Froud (1997) was a pyrite inversion vein that occurred in conjunction with minor galena and chalcopyrite precipitation.

6.6.4 Teller

Gooch et al. (1988) described eight vein classifications at Main Dome, Teller, and further divided these vein classifications into early hydrothermal veins, main stage veins, and late hydrothermal veining. During early hydrothermal alteration, thin, irregular quartz veins up to 3 cm thick, with a characteristic lime-green, silicified alteration halo occur. Main stage veining consists of four classifications: SQ-1, SQ-2, CcO/DeO, and concordant quartz veins. SQ-1 veins are west-southwest to east-north-east trending, quartz, massive sulphide and oxide, vuggy, <30 cm thick, planar to irregular; SQ-2 veins are similar to SQ-1 veins, however SQ-2 are oriented north-south and are described as massive quartz sulphide and oxide, vuggy, <10 cm thick, planar to irregular. CcO/DeO veins are thin, planar, massive oxides. The last main stage vein classification is found generally within silstones at very continuous, concordant quartz veins, <5 cm thick, locally folded, quartz, albite ± pyrite vein.

Three late hydrothermal vein classifications are described as EQ, MO, and chert dikes. EQ veins are thin (<3 mm thick), planar stockwork-like veins of discordant to bedding and of variable orientation, MO veins are described as north-south trending, sub-vertical massive sulphide (pyrite/chalcopyrite) and oxide veins. Chert dikes are north-south trending, grey to cream, stockwork-like veins of cryptocrystalline silica.

6.6.5 Deposit Comparison

The comparison of vein paragenesis between Nifty and other Throssell and Laxoil Group mineralised occurrences (Fig. 6.5) is problematic because the timing of vein generations has been related to mineralisation. The timing of mineralisation ranges from after late diagenetic dolomitisation and bedding parallel pressure solution but before S_{cb}/D_{sh} cleavage at Warnaburty (Smith, 1996) to syn-D_{sh} deformation for Maroochydore (Reed, 1996), Goosewacker (Froud, 1997) and Nifty (Anderson et al., 1997). The interpreted timing of mineralisation may be different but the timing of D_{sh} deformation provides a framework to related vein stages. The timing of Laxoil Group D_{2} may be different from that of the D_{sh} in the Throssell Group. Figure 6.5 provides a comparison and suggests that Nifty syn-mineralisation veins formed at similar times to the straight margin veins at Maroochydore, while stage at Warnaburty, and vein stages 3 and 4 at Goosewacker.

79
<table>
<thead>
<tr>
<th></th>
<th>Pre-D(_{32})</th>
<th>Syn-D(_{32})</th>
<th>Post D(_{32})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nifty (This study)</td>
<td>IA</td>
<td>IB</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IB</td>
<td>IC</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\bar{IC})</td>
<td>(\bar{IB})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\bar{IA})</td>
<td>(\bar{IIA})</td>
</tr>
<tr>
<td></td>
<td>(\bar{IIB})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maroochydore (Reed, 1996)</td>
<td>Discordant Bedding parallel</td>
<td>Straight margin</td>
<td>vuggy</td>
</tr>
<tr>
<td>Warrabarty (Smith, 1996)</td>
<td>Grey</td>
<td>(\bar{White})</td>
<td>(\bar{White})</td>
</tr>
<tr>
<td>Goosewacker (Fred, 1997)</td>
<td>Stage 1</td>
<td>(\bar{Stage 2})</td>
<td>(\bar{Stage 3})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\bar{Stage 4})</td>
<td>(\bar{Stage 5})</td>
</tr>
<tr>
<td>Tefer (Goelnlacht et al., 1988)</td>
<td>Irregular</td>
<td>SQ-1</td>
<td>SQ-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Co/CDeO</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Concordant quartz</td>
<td>Eq</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MO</td>
<td>Chert dikes</td>
</tr>
</tbody>
</table>

Figure 6.5: A postulated comparison of vein stage development in mineralised occurrences from the Threebelle Group, Paterson Orogen. \(D_2\) deformation is a regional folding and cleavage dated at \(\sim 700\) Ma (Reed, 1996; Smith, 1996). See text for vein descriptions.

### 6.7. Summary of Vein Stages

Vein stages observed at Nifty are divided into pre-, syn-, and post-mineralisation groups based on paragenetic relationships. Pre-mineralisation veins consist of IA-Bedding parallel dolomite veins, IB-Folded bedding-parallel pyrite-quartz-dolomite veins, and IC-Fracture dolomite-quartz veins. Pre-mineralisation veins have a restricted distribution, with IA veins typically occurring in the deposit hangingwall, IB the deposit footwall, and IC in the hangingwall and \(E_1\) altered rocks. Syn-mineralisation veins consist of IIA-Chalcopyrite-dolomite veins, IIB-Alteration margin quartz-dolomite veins, IIC-Cleavage parallel dolomite-quartz veins. IIC veins formed early during mineralisation and are cross-cut by IIA and IIB veins. IIB veins typically occur in the outer alteration halo and it is interpreted that these veins are responsible for \(S_3\) alteration. IIA veins consist of high concentrations of chalcopyrite with varying amounts of dolomite, quartz, pyrite, and phlogopite. Two types of post mineralisation veins are defined as IIA-Bladed quartz veins, and IIB-Bladed carbonate veins. IIA and IIB veins have a wide distribution. The bladed calcite of IIB veins suggests that phase separation has occurred during vein formation and it is interpreted that this vein stage is associated with stress release during \(D_{31}\) deformation.