GEOLGY AND GENESIS OF THE
GEORGE FISHER Zn-Pb-Ag DEPOSIT,
MOUNT ISA, AUSTRALIA.

VOLUME 2

Thesis submitted by
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(b) Fe\(\text{CO}_3\)/Mn\(\text{CO}_3\) versus Mg\(\text{CO}_3\) (mol. %)

(c) Mn\(\text{CO}_3\) (mol. %) versus Fe\(\text{CO}_3\) (mol. %)

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(b) Fe\(\text{CO}_3\)/Mn\(\text{CO}_3\) versus Mg\(\text{CO}_3\) (mol. %)

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<table>
<thead>
<tr>
<th>REGIONAL DEFORMATION EVENT</th>
<th>MOUNT ISA MINE</th>
<th>LAKE MOONDARRA AREA</th>
<th>HILTON AND GEORGE FISHER AREA</th>
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<tr>
<td>$D_2$</td>
<td>Mesoscopic folds with subhorizontal axial planes. No foliation recorded.</td>
<td>?</td>
<td>Mesoscopic folds with subhorizontal axial planes. No foliation recorded.</td>
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<td>$D_{2,3}$</td>
<td>Upright NNW-SSE trending, steeply south-plunging folds and penetrative cleavage. Reactivation and rotation of $S_2$.</td>
<td>NWW-SSE trending folds, variable plunge, with penetrative cleavage.</td>
<td>Intensification of $S_2$. Spatially restricted NNW-SSE trending folds.</td>
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<td>post-$D_3$</td>
<td>Local folds and crenulation. Brittle faults.</td>
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<td>Local NW-SE trending folds. Brittle faulting including Transmitter and Gidyea Creek Faults. Reactivation along Mt Isa and Paroo Fault Zone.</td>
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<th><strong>CORRELATION WITH MACROSCOPIC STRUCTURAL EFFECTS</strong></th>
<th><strong>CORRELATION WITH REGIONAL DEFORMATION EVENTS (TABLE 1)</strong></th>
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</table>
| D<sub>1</sub>          | 1. Bedding parallel foliation.  
Syn- to post-foliation development? | Not evident. | Equivalent to pre-D<sub>1</sub> bedding parallel foliation at Hilton Mine recorded by Valenta (1994). |
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2. Fibrous Qtz-carbonate veins.  
3. NW-SE and NE-SW conjugate Gm±Sp±Carb vein set (i.e. discordant vein-hosted galena) spatially associated with fine grained Sp or Gm-rich breccia/shear zones (i.e. fine grained Sp- or Gm- or mixed sulphide breccias).  
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<th>SULPHIDE CONTENT AND RELATIVE ECONOMIC SIGNIFICANCE</th>
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<td>STRATABOUND GALENA-</td>
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<td>Major</td>
<td>Spatially associated with coarser-</td>
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Table 4. Metal budgets for the Mount Isa, Hilton and George Fisher deposits; <sup>1</sup>Forrestal (1990), <sup>2</sup> Perkins (1990), <sup>3</sup> Mullens (1993), <sup>4</sup> 1998 MIM report to shareholders.
Figure 1. Map of the Mount Isa-McArthur minerals province illustrating major tectonostratigraphic subdivisions and the location of significant mineral occurrences (modified after Plumb et al. 1990, and Blake and Stewart, 1992).
Figure 2. Stratigraphic framework of the Western Fold Belt, Mount Isa Inlier (compiled from Page and Sweet, 1998, O'Dea et al., 1997 and references therein). U-Pb SHRIMP results from Page and Sweet (1998) for 1Urquhart Shale (Upper Mount Isa Group) at Mount Isa, 2Urquhart Shale at Hilton, 3Paradise Creek Formation (underlies host rocks to Lady Loretta deposit), 4Upper McNamara Group of the Lawn Hill Formation which hosts the Century Deposit.
**Figure 3.** Geological map illustrating major structural and stratigraphic elements of the Mount Isa area (after Blake, 1987 and Valenta, 1994).
Figure 4. Geology map of George Fisher and surrounds (after Valenta, 1994).
Figure 5. Interpreted plan geology map of the main economic zone at 12 level (approximately 700m below surface) illustrating the extent of underground development prior to the commencement of mining, major structural features and stylized outlines of Zn-Pb-rich zones. Collar positions of drill holes that were logged for this study are also illustrated (adapted from unpublished MIM Ltd data).
Figure 6. Interpreted geological cross-section at 7020mN illustrating major stratigraphic and structural elements at George Fisher. Fault interpretation has been adapted from MIM Ltd data and inset is adapted from Mullens (1990).
Figure 7. Simplified stratigraphic column with metal distribution patterns and dominant gangue at the George Fisher deposit. Relationships illustrated for Zn±Pb-bearing intervals based on relationships in the southern end of the deposit (this study). Tuff marker bed characterization was undertaken by MIM geologists and stratigraphy above the A interval, and below the I interval is adapted from Mullens (1990).
Key to Figure 8.

LEGEND FOR DRILL HOLE LOGS

Left hand side
- Shaly banded mudstone
- Banded mudstone
- Stylolitic, medium-bedded mudstone

Fault (Flt)

Right hand side
- Distribution and relative abundance of rhythmically laminated carbonaceous siltstone
- Distribution and relative abundance of rhythmically laminated pyritic siltstone
- Distribution and relative abundance of rhythmically laminated pyritic siltstone with interlayered nodular carbonate

Massive sulphide
- Denotes presence of layer-parallel white carbonate bands

Tuffaceous marker bed (TMB)

LEGEND FOR CORRELATED ZONES

- Medium-bedded, stylolitic mudstone
- Intercalated shaly banded mudstone and rhythmically laminated carbonaceous and pyritic siltstones
- Banded mudstone
- Intercalated banded mudstone and rhythmically laminated carbonaceous siltstone
- Rhythmically laminated pyritic siltstone ± Zn-Pb bands
- Rhythmically laminated pyritic siltstone with nodular carbonate ± Zn-Pb bands
- Intercalated banded mudstone and rhythmically laminated carbonaceous and pyritic siltstones ± Zn-Pb bands
- Intercalated banded mudstone and nodular carbonate-bearing rhythmically laminated pyritic siltstone ± Zn-Pb bands
- Layer-parallel white carbonate bands
Figure 8a. Stratigraphic sections, drawn to true thickness, for the H stratigraphic interval from 7020 mN to 7820 mN. Intercalated shaly banded mudstones and rhythmically laminated carbonaceous and pyritic siltstones, nodular carbonate-rich rhythmically laminated pyritic siltstones and packages of layer-parallel white bands are correlated on this section.
Figure 8b. Stratigraphic sections for the F and E intervals from 7020 mN to 7820 mN and drawn to true thickness. The distribution of major rock types and nodular carbonate-bearing intervals are highlighted.
Figure 8c. Stratigraphic sections drawn to true thickness for the D, C and B intervals illustrating the distribution of mudstones, irregular distribution of some nodular carbonate-bearing intervals and rhythmically laminated carbonaceous and pyritic siltstone-rich zone in the B stratigraphic interval.
(a) Planar laminated to massive and stylolitic, medium-bedded mudstone (MM) forms a sharp contact (arrow) with overlying intercalated banded mudstone and pyritic siltstone interval that contains abundant white calcite bands (WB) at its base. Way up is from top left to bottom right. (J702 WI#5, 56.5 - 64.7m).

(b) Planar laminated to massive, banded mudstones (BM) display distinctive light grey calcitic and dark grey dolomitic banding. The lower mudstone (top) forms a gradational contact over 10 cm characterized by abundant white calcite bands (WB) with the overlying rhythmically laminated pyritic siltstone (PS). This siltstone contains abundant layer-parallel nodular carbonate (Nod). The pyritic siltstone is juxtaposed against the upper mudstone (BM) by a L70-type late fault (arrow). The fault zone is approximately 20cm thick and is characterized by pink and white calcite-fill, and some carbonaceous gouge. Way up is from top left to bottom right. (J702 WI#5, 40.6-48.6m).

(c) Graded bedding intervals (way up to right) within a banded mudstone (BM) interval that contains abundant white calcite bands (WB). The white calcite bands have planar and stylolitic contacts along which pyrite and pyrrhotite (Po) are developed (HS# 24, J702WI#2, 38.6m).

(d) Thin shaly banded mudstone (SM) characterized by several cm-thick, pyritic black shale and cross-beded shaly siltstone bedding intervals and bounded by intercalated rhythmically laminated pyritic siltstones (PS) and banded mudstones (BM). The start and end of the shaly banded mudstone interval is indicated with arrows. Fibrous calcite veins are developed near the base whereas white calcite bands (WB) are prevalent to the top. White bands occur in a triplet association. Way up is from top left to bottom right (HS# 29, J702WI#2, 48.5 - 50.2m).

(e) Rhythmically laminated carbonaceous siltstone characterized by sub-mm to mm-thick alternating wavy dark grey carbonaceous and light grey carbonate-rich laminations with intermittent mm-thick light grey planar laminations. Lens-like pyrrhotite aggregates with long axes oriented parallel to bedding are prominent central to the sample. Core is 4cm wide. (HS# 129, J702WI#6, 75.7m).
Figure 9.

(f) Photomicrograph of a rhythmically laminated siltstone interval illustrating the discontinuous nature of wavy laminations compared with planar laminations (arrow) distinguished by an increase in proportion of relatively coarse-grained detrital quartz (Qtz) (HS# DC838, H766ED#1, 561m).

(g) Intercalated banded mudstone (BM) and rhythmically laminated pyritic siltstone with abundant white planar calcite bands (WB) and syndeformational, irregular calcite fibre veins (Cal). Way up is from top left to bottom right. (J702WI#5, 48.6-56.5m).

(h) Nodular carbonate (Nod) occurs as bedding parallel and displacive, wavy layers in thin pyritic siltstone beds (PS). The majority of bedding contacts in this section are stylolitic. White calcite bands occur as pyritic siltstone (PS) -banded mudstone (BM) -white band (WB) triplets in this specimen. Width of rock wafer is 2cm and way up is to the right (HS# DC845, H766ED#1, 554m).

(i) Photomicrograph illustrating the textural similarity between white band calcite (WB) and nodular calcite. The discontinuous nodular calcite layer is superimposed on a thin laminated pyritic siltstone bed (PS) and is discordant to and cross-cuts bedding at this scale. Note the relative abundance of detrital quartz within the pyritic bed and stylolitic nature of contacts (HS# DC845, H766ED#1, 554m).

(j) Banded, calcitic (Cal) and dolomitic (Dol) banded mudstone contains solitary and stacked white band couplets. White bands (WB) have sharp planar and stylolitic contacts and are spatially associated with elongate, smooth calcite nodules (N) (HS# 47, J702WI#5, 73.9m).
Figure 10. Interpretative cross-sections at 7020mN, 7180mN, 7300mN and 7820mN, illustrating major stratigraphic subdivisions and late-stage faults, core axis to bedding angles, and the distribution of small-scale fold zones (based on MIM Ltd data).
Figure 11. Mapped sections illustrating mesoscale structural features in the southern and northern walls of the Core zone, 7200mN underground cross-cut.
(a) Photomicrograph illustrating the pervasive development of a D$_1$ bedding-parallel foliation in variably carbonaceous banded mudstones (BM) and local development of an upright D$_2$ foliation. A sub-mm thick sphalerite-bearing vein is boudinaged and pods have long-axes parallel to S$_2$. The S$_2$ fabric is locally intensified around these pods. Thin section is vertically oriented, west is to the left and photograph was taken looking north (HS# UG8, Core zone, 7200mN cross-cut).

(b) Bedding-parallel and symmetrically infilled quartz (Qtz)-K-feldspar (Kfs)-sphalerite (Sp)-hydrophlogopite (Hphl) vein. Note that the orientation of hydrophlogopite laths within the vein mimics the orientation of S$_1$. West to east orientation runs from the top left to bottom right corners and photograph was taken looking north (HS# UG8, Core zone, 7200mN cross-cut).

(c) Photomicrograph illustrating crenulate sphalerite-bearing vein margins. Note the abundance of euhedral pyrite (Py) crystals with quartz pressure shadows that have long axes oriented along probable S$_2$ reactivation planes. Vertically oriented thin section looking north (see Fig. 12d) (HS# UG8, Core zone, 7200mN cross-cut).

(d) Vertically oriented thin section photomicrograph (looking north) illustrating the microstructural effects of D$_2$. Major features are illustrated by the inset (HS# UG8, Core zone, 7200mN cross-cut):

- a. $S_0$ parallel to $S_1$
- b. $S_1$ is crenulated by $S_2$
- c. $S_1$ hinges
- d. $S_2$ differentiated cleavage
Figure 13. Photomicrograph mosaic and line diagram illustrating the microstructural effects of $D_3$ and $D_4$. Vertically oriented thin section looking south. The curved nature of fibres in carbonate-quartz veining to the top left indicate that these veins were emplaced synchronous with $D_3$ and/or $D_4$. Discordant veins with blocky carbonate infill (Carb, bottom centre) are interpreted to have been emplaced syn- to post-$D_4$ (HS# UG1, C ore zone, 7200mN cross-cut).
(a) Rhythmically laminated pyritic siltstone folded around D$_2$ folds that have been variably rotated into inclined to subhorizontal orientations. A coarse-grained galena breccia is irregularly distributed in the lower part of the sample and spatially associated with the development a discordant coarse-grained galena vein set that cross-cuts the fold zone and is oriented NNE-SSW. Fine-grained sphalerite (Sp) breccias envelope the fold zone and contain sub-mm to mm-thick refolded mudstone layers (arrow). Sample is vertically oriented, west is to the right and south is into the page. (HS# UG2, Core zone, 7200mN cross-cut).

(b) Flat-lying fold developed in intercalated rhythmically laminated pyritic siltstones and banded mudstones. Quartz fibre veins (Qtz) are developed in the hinge regions of these folds. Fibres have a subhorizontal elongation direction but are also bent into inclined orientations. This is probably associated with the development of the NNE-SSW oriented galena+sphalerite vein set (Gn) that cross-cuts the flat-lying fold. Vertically oriented sample looking south, with west to the right (HS# UG, Core zone, 7200mN cross-cut).

(c) Complex refold patterns produced by the superposition of D$_4$ folds on D$_2$ folds rotated by D$_3$ are prevalent in the upper part of this sample (see inset). The central portion of the sample is carbonate-rich and irregularly brecciated by fine-grained sphalerite (Sp). Fine-grained sphalerite also occurs with galena in discordant NNW-SSE vein sets that cross-cut pyritic siltstones (PS) (HS# UG1, Core zone, 7200mN cross-cut).

(d) An inclined D$_2$ fold in a pyritic siltstone (PS) is bounded to the west and east by fine-grained sphalerite (Sp) and galena (Gn) breccias, the former of which contains abundant mm-thick mudstone layers that have been refolded (arrow) (HS# UG5, Core zone, 7200mN cross-cut).
(a) Rhythmically laminated carbonaceous siltstone (CS) -hosted sphalerite style characterized by alternating pale brown sphalerite-rich (Sp) and dark grey carbonaceous laminations (in this sample) and is spatially associated with mudstone-hosted orange sphalerite mineralization (arrow). Very fine galena veinlets (Gn) are developed perpendicular to bedding in this sample and occur as part of a vein array that includes layer-parallel pyrite-rich (Py) veins. Core is 4cm wide (HS# 131, J702 WI#6, 54.9m).

(b) Rhythmically laminated pyritic siltstone-hosted honey-coloured sphalerite is characterized by the preferential development of sphalerite in dolomite-rich rather than pyrite-rich (Py) laminations. Sphalerite (Sp) typically occurs in fleck-like patches in carbonate laminations oriented parallel to bedding, though sphalerite-rich zones also fringe pyrite laminations. Also note the irregular development of honey-coloured sphalerite in a mm-thick planar lamination near the centre of the sample. Cross-cutting carbonate veins contain variable proportions of honey-coloured sphalerite. Core is 4cm wide (HS# 137, J702 WD#4, 183.5m).

(c) Nodular (Nod) calcite-hosted sphalerite. Sphalerite (Sp) is light honey-brown in colour whilst pyrite (Py) has a brassy appearance. Core is 4cm wide (HS#123, J702 WD#4, 183.5m).

(d) Photomicrograph illustrating preferential development of sphalerite (Sp) in coarser-grained nodular calcite layers (Nod) rather than rhythmically laminated pyritic siltstone beds (PS) (HS#123, J702 WD#4, 183.5m).
(e) Very fine-grained spheroidal pyrite (Py) and sphalerite (Sp) distributed along layers in a black shale. Pyrite-rich layers are brassy in appearance whilst sphalerite-rich layers are dull brown. A fibrous calcite vein is developed in the middle of the sample and localizes a vein network infilled by sphalerite-galena-pyrrhotite-pyrite-chalcopyrite. Core is 4cm wide (HS# 131, J702WI#6, 54.9m).

(f) Thin section photomicrograph of shale-hosted sphalerite which occurs with relatively coarse-grained calcite in pod-like zones. A significant proportion of the black material in this sample is cryptocrystalline bitumen (HS# 033d, J702WI#2, 55.4m).

(g) Fine-grained honey coloured sphalerite (Sp) is irregularly distributed along planar beds in a medium-bedded mudstone (MM). Its distribution also mimics bedforms in this sample. Mineralized layers are cross-cut and displaced by discordant dolomite veins. Core is 4cm wide (HS# 299, J718WI#4, 209.8m).

(h) Steel grey, fine-grained galena hosted by buff-coloured feldspathic mudstone layers from the D ore zone and spatially associated with galena-rich veins (Gn), orange mudstone-hosted sphalerite (Sp) and semi-massive orange and red-brown sphalerite bands. White calcite bands (Cal) and a large calcite nodule are also prominent features of this sample. Core is 4.5cm wide (HS# 254, J718 WI#5, 167.3m).
(a) A range of mineralization styles are represented in this sample. Sphalerite breccia-veins are prominent and typically a few mm thick. Veins to the far right contain semi-massive red-brown sphalerite bounded by folded sedimentary layers and are cross-cut by a cm-thick coarse-grained galena breccia and associated galena veins (Gn-arrow). A fine-grained galena breccia (Gn) is prominent to the left hand edge of the sample. Stratiform nodular carbonate (Nod) and rhythmically laminated pyritic siltstone-hosted honey-coloured sphalerite (PS) is also represented in this sample. Core is 4cm wide (HS# 63, J702WI#5, 199.8m).

(c) Fine-grained sphalerite breccia (Sp) developed in the central portion of the sample which contains abundant nodular carbonate-hosted sphalerite. Attenuation of bedding, and brecciation of white carbonate veins is associated with the development of small-scale folds (arrow) and less regular distribution of sphalerite. (HS# 166, J718WD#5, 336.2m).

(e) Coarse-grained galena occurs as breccia matrix in this sample. Large clasts are composed of sphalerite and galena-bearing feldspathic mudstones, white calcite and semi-massive sphalerite mineralization. Note that abundant mm-sized sphalerite clasts (e.g. Sp) are dispersed throughout the galena matrix. (HS# 143, J702WI#6, 234.7m).

(b) Thin section photomicrograph of a sphalerite breccia-vein (Sp) developed at the contact between a banded mudstone (BM) and laminated pyritic siltstone (PS). Carbonate and quartz occur as infill and as clasts (along with pyritic siltstone fragments) enveloped by sphalerite. Layer-parallel and tapered discordant galena veinlets (Gn) are developed adjacent to the sphalerite breccia-vein (HS# 255, J718WI#5, 171.7m).

(d) Stratabound fine-grained sphalerite breccias (e.g. Sp) developed in a banded mudstone. Core is 4.5cm wide. (HS# 278, K782WI#1, 93.7m).
(f) Fine-grained galena breccia characterized by rounded clasts that exhibit a wide range of compositions including fine-grained sphalerite breccia (Sp), stratiform sphalerite (arrow) and carbonate (Carb). Note presence of coarse-grained sphalerite rims on some shale and carbonate fragments (e.g. Sp, left of centre) (HS# 181, J718WI#3, 175.4m).

(g) Mixed sulphide breccia containing flame-like pyrite (Py), galena (Gn) and sphalerite (Sp)-rich domains. Large, rounded clasts are composed predominantly of fine-grained red-brown sphalerite and pyrite whereas mudstone clasts in the galena-rich domain are sub-mm to a few mm in size and well rounded (HS# 169, J718 WD#5, 345.7m).

(h) Feldspathic rock with relict fine pyritic laminations reminiscent of rhythmically laminated siltstones cross-cut by discordant chalcopyrite-pyrrhotite-galena veins with irregular pyrrhotite-rich selvages. Several thin pyrrhotite breccias (Po) are developed parallel to bedding within the pyritic interval in the middle of the sample (HS# 268, J718 WI#5, 248.9m).

(i) Very coarse-grained sphalerite (Sp) - galena - pyrite (Py) - pyrrhotite (Po) - calcite (Cal) - dolomite (Dol) vein infill probably related to a J70-type fault (HS# 272, I698WI#3A, 78.9m).

(j) Coarse-grained honey-coloured sphalerite (Sp-arrow)-galena (Gn)-calcite occurs as infill in a tension gash vein array that displaces banded sphalerite (Sp) and is typical of L70-type fault-fill where these faults intersect orebody intervals (HS# 152, J702WI#6, 250.7m).
## Key to Stratigraphic Column

**Left hand side**
- **Stylolitic, medium-bedded mudstone**
- **Banded mudstone**

**Right hand side**
- Relative abundance of rhythmically laminated carbonaceous siltstone
- Relative abundance of rhythmically laminated pyritic siltstone
- Relative abundance of nodular carbonate-bearing rhythmically laminated pyritic siltstone

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### Key to Correlated Intervals

- Intercalated banded mudstone and rhythmically laminated pyritic siltstones. Layer-parallel, planar and nodular carbonate layers generally abundant.
- Rhythmically laminated carbonaceous and pyritic siltstones.
- Medium-bedded or banded mudstone.

**Legend to accompany Figures 17a and b.**

- **Massive sulphide, mainly pyrite**
- Host rock unidentifiable

### Distribution and relative abundance of mineralization styles

- Fine-grained Gn breccia
- Coarse-grained Gn breccia
- Discordant vein-hosted Gn
- Fine-grained Sp breccia
- Breccia-vein-hosted Sp
- NOD and PS-hosted Sp

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### Plot of Zn and Pb % with depth

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<td>3 - 15-30%</td>
<td>7 - 60-75%</td>
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<td>4 - 30-45%</td>
<td>8 - 75-95%</td>
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<td>5 - &gt;95%</td>
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</table>

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### Relative abundance of texture for designated depth interval.

- Fine-grained Gn breccia
- Coarse-grained Gn breccia
- Discordant vein-hosted Gn
- Fine-grained Sp breccia
- Breccia-vein-hosted Sp
- NOD and PS-hosted Sp
Figure 17a. Distribution of sphalerite and galena-dominant mineralization styles compared with Zn and Pb assay data and superimposed on stratigraphic columns, for the F and E stratigraphic intervals at George Fisher.

---

Vertical Scale

10 metres

NORTH
Figure 17b. Distribution of sphalerite and galena-dominant mineralization styles compared with Zn and Pb assay data and superimposed on stratigraphic columns, for the D, C and B stratigraphic intervals at George Fisher.
Figure 18. Simplified stratigraphic columns for Mount Isa, Hilton and George Fisher. Mount Isa stratigraphic column adapted from unpub. MIM Ltd. data, Perkins (1997) and Neudert (1983). Hilton and George Fisher columns adapted from unpub. MIM Ltd. data. Stratigraphic correlations between Hilton and George Fisher were established by A. Shaw (MIM geologist).

LEGEND

- **Spear Siltstone**
- **Urquhart Shale**
  - Interbedded rhythmically laminated pyritic siltstones and shales with minor banded mudstone.
  - Rhythmically laminated pyritic siltstones with moderate to abundant nodular carbonate and layer-parallel carbonate bands, interbedded with shales and minor banded mudstone.
  - Interbedded rhythmically laminated pyritic siltstones and banded mudstone with minor shale.
  - Interbedded banded mudstones and rhythmically laminated pyritic siltstones with moderate to abundant nodular carbonate and layer-parallel carbonate banding.

- **Native Bee Siltstone**
  - Stratigraphic interval bearing economic Zn-Pb-Ag mineralization
  - Tuffaceous Marker Bed (TMB)
  - Line of stratigraphic correlation

- Massive and laminated, stylolitic mudstone.
- Banded mudstone.
PART B
<table>
<thead>
<tr>
<th>STAGE</th>
<th>HR</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV a</th>
<th>IV b</th>
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<th>VII</th>
<th>VIII</th>
<th>IX a</th>
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</tbody>
</table>

HR = Host rock constituents

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I - Calcitization and nodule development

---

STYLOLITIZATION

---

II - Spherosoid pyrite alteration

---

PRE- TO SYN- LOCAL D1 / PRE- REGIONAL D1

---

III - Celsian-hyalophane-K-feldspar/calcite-quartz vein development

---

IV - Sphalerite mineralization

---

REGIONAL DEFORMATION

LOCAL D2 - D2'/ REGIONAL D2 - D2', D3' )

---

V - Sugary ferroan dolomite veining

---

VI - Fine-grained sphalerite breccia formation

---

VII - Galena mineralization

---

VIII - Copper mineralization

---

IX - Late-stage faulting

---

a - syn-post local D1 (regional D1)

---

b - post local D1 (regional D1),

---

possibly unrelated to Isan Orogeny?

---

Table 1. Alteration and mineralization paragenesis at the George Fisher deposit.
<table>
<thead>
<tr>
<th>STAGE</th>
<th>INFILL ASSEMBLAGES</th>
<th>ALTERATION ASSEMBLAGES</th>
<th>KEY TIMING CRITERIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>III - Celsian-hyalophane-K-feldspar alteration</td>
<td>Cs-Hyl-Kfs-Ca±Qtz±FeDol</td>
<td>Veins cross-cut pyritized carbonaceous stylolites.</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>a- Migribitumen stage</td>
<td>Bit±Py±Sp±Gn,</td>
<td>Migrabitumen occurs interstitial to calcite</td>
</tr>
<tr>
<td></td>
<td>b- Brassy pyrite alteration</td>
<td>Bit±Py±Sp±Po±Calc±Qtz±Gn</td>
<td>Brassy pyrite occurs as replacements and overgrowths on spheroidal pyrite &amp; alteration of celsian-hyalophane-K-feldspar.</td>
</tr>
<tr>
<td></td>
<td>c - Hydrophlogopite stage</td>
<td>Stage III Cal-Qtz±FeDol-Stage IV Sp±Py±Hphl</td>
<td>Celsian-hyalophane-K-feldspar, minor calcite.</td>
</tr>
<tr>
<td>V - Sugary ferroan dolomite veining</td>
<td>FeDol±Sp±Gn</td>
<td>Cross-cuts banded and stratiform sphalerite mineralization.</td>
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<tr>
<td>VI - Fine-grained Sp breccia formation</td>
<td>Sp</td>
<td>Contains clasts of sugary ferroan dolomite veins.</td>
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<tr>
<td>VII - Galena mineralization</td>
<td>Gnt±Py±Sp±Po±carb</td>
<td>Galena, yellow pyrite, pyrrhotite</td>
<td>Galena-pyrite-pyrrhotite brecciates all sphalerite-dominant mineralization styles and occurs as replacements of sphalerite.</td>
</tr>
<tr>
<td>VIII - Copper mineralization</td>
<td>Cal-Py±Po±Cpy±Sp±Gn</td>
<td>Po±Sp±Calc±Cpy</td>
<td>Po replaces fine and coarse-grained galena breccias and all textural varieties of sphalerite. Po-Cpy infill in discordant veins with late-stage sphalerite and galena.</td>
</tr>
<tr>
<td></td>
<td>Sld±FeAnk-Ank±FeDol±Cpy±Po±Sp±Gn</td>
<td>Sld±FeDol±Ank±FeAnk±Mt±Po±Gn±Sp±Chl</td>
<td>Phyllisilicates occur as replacements of carbonates and feldspar and infill in veins with Po-Cpy. Late-stage galena and sphalerite occur as replacements of these phyllisilicates.</td>
</tr>
<tr>
<td>IX - Late-stage fault-hosted mineralization</td>
<td>Dol±Gnt±Tet±Ag</td>
<td>Late faults cross-cut and displace stratigraphy.</td>
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<tr>
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<td>a - 175-type fault matrix</td>
<td>Dol±Sp±Gn</td>
<td>Mineralization typically developed as fault matrix where faults intersect on ore lenses.</td>
</tr>
<tr>
<td></td>
<td>b - L.70-type fault matrix</td>
<td>Cal±Qtz±FeDol±Sp±Gn±Py±Po±Cpy</td>
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</tbody>
</table>

Table 2. Summary of major features of each paragenetic stage and key timing criteria (refer to List of Mineral Abbreviations).
<table>
<thead>
<tr>
<th>MODEL</th>
<th>CONCEPT</th>
<th>PRECIPITATION MECHANISM</th>
<th>REFERENCE</th>
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<tbody>
<tr>
<td>MIXING MODEL</td>
<td>Metals transported as chloride complexes in slightly oxidized, weak acid to neutral, basin-derived brines and encounter reduced sulphur-bearing fluids at the site of ore deposition. Fluid-derived ( \text{H}_2\text{S} ) was either transported to the site or locally derived.</td>
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<td>Mixing ( ^{35}\text{Cl} ) with ( \text{H}_2\text{S} ) derived from; 1. ( \text{H}_2\text{S} )-rich pore fluids in carbonate host rocks. 2. Bacterial sulphate reduction of in situ or proximal sulphate evaporites. 3. Thermochemical sulphate reduction of in situ or proximal sulphate evaporites. 4. Degraded hydrocarbons (oil-field brines). 5. Preexisting sulphides.</td>
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<td>E.g. Beales (1975) \hspace{1em} E.g. Beales and Jackson (1966) \hspace{1em} E.g. Anderson and Garven (1987) \hspace{1em} Kesler et al. (1994) \hspace{1em} E.g. Lovering (1961)</td>
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<tr>
<td>( \text{H}_2\text{S} ) BASINAL DEGASSING MODEL</td>
<td>Metals transported to site of deposition as chloride complexes in basin-derived brines. ( \text{H}_2\text{S} ) gas generated as a result of hydrocarbon maturation during deep burial.</td>
<td>Precipitation occurs when either metal-bearing fluids encounter trapped gas pockets or when buoyant, ascending gas percolates through metal-bearing fluid.</td>
<td>Hill (1993)</td>
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<tr>
<td>METAL+SULPHATE-BEARING FLUID</td>
<td>Metals as chloride complexes and sulphate are transported to site of ore deposition in a fluid.</td>
<td>Precipitation occurs as a result of thermochemical sulphate reduction at site of metal deposition (increase reduced sulphur availability) by; 1. encounter with hydrocarbons or organic detritus. 2. addition of ( \text{CH}_4 ) gas generated from thermal maturation of organic material.</td>
<td>E.g. Hinman (1996) \hspace{1em} Broadbent et al. (1998) \hspace{1em} E.g. Anderson (1991)</td>
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<tr>
<td>METAL+HYDROCARBON-BEARING FLUID</td>
<td>Metal chloride complexes and hydrocarbons are transported to site of ore deposition in a strongly reduced basinal brine.</td>
<td>Precipitation occurs when fluid encounters evaporitic sulphate source.</td>
<td>Thompkins et al. (1994)</td>
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</table>

Table 3. Common metal transport and precipitation models proposed for the formation of sediment-hosted Zn-Pb deposits.

1. Favoured model for the formation of the HYC deposit at McArthur River and 2. the Century deposit, both of which are situated in the Northern Australian Proterozoic.
<table>
<thead>
<tr>
<th><strong>TEXTURAL AND MINERALOGICAL SETTING</strong></th>
<th><strong>REACTION</strong></th>
<th><strong>METAL PRECIPITATION MECHANISM AND SULPHUR SOURCE</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphalerite precipitates in voids in veins and nodular calcite layers unaccompanied by carbonate dissolution (Figs. 4e and 5a).</td>
<td>(a) $\text{Zn}^{2+}(aq) + \text{H}_2\text{S}(aq) \rightarrow \text{ZnS} + 2\text{H}^+$</td>
<td>Mixing Model; $\text{H}_2\text{S}(aq)$ or $\text{H}_2\text{S}(g)$ trapped in pore fluids or introduced via a separate fluid. Reaction (a).</td>
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<td>(b) $2\text{CH}_2\text{O} + \text{SO}_4^{2-}(aq) \rightarrow 2\text{HCO}_3^- + \text{H}_2\text{S}(aq)$ (Machel, 1987) coupled with reaction (a)</td>
<td>Metal+ Sulphate Model; sulphate reduction by contact with organic material (sourced from adjacent pyritic siltstones?) Reaction (b) + (a).</td>
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<td>(c) $\text{CH}_4 + 2\text{H}^+(aq) + \text{SO}_4^{2-}(aq) \rightarrow \text{H}_2\text{S} + 2\text{HCO}_3^-$ (aq) (Machel, 1987) coupled with reaction (a)</td>
<td>Metal+Sulphate Model; mixing with a reductant such as $\text{CH}_4(g)$ trapped in pores. Reaction (c), (d) or (e) + (a).</td>
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<td>Alternatively, decarboxylation of acetate produces $\text{CH}_4$</td>
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<td>(d) $\text{CH}_3\text{COOH} + \text{SO}_4^{2-} + 2\text{H}^+ \rightarrow \text{H}_2\text{S} + \text{CH}_4 + \text{CO}_2(aq) + 2\text{O}_2(g)$</td>
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<td>(e) $\text{CH}_3\text{COO}^- + \text{SO}_4^{2-} + 2\text{H}^+ + \text{H}_2\text{O} \rightarrow \text{H}_2\text{S} + \text{CH}_4 + \text{HCO}_3^-(aq) + 2\text{O}_2(g)$</td>
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<tr>
<td>Sphalerite replaces carbonate (e.g. Fig. 12d).</td>
<td>(f) $\text{Zn}^{2+}(aq) + \text{H}_2\text{S}(aq) \rightarrow \text{ZnS}(s) + 2\text{H}^+$ drives the reaction</td>
<td>Mixing Model or Metal+Sulphate Model; Potential sulphur sources as above. Precipitation driven by availability of space.</td>
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<td>(g) $2\text{H}^+(aq) + \text{CaCO}_3(s) \rightarrow \text{Ca}^{2+}(aq) + \text{H}_2\text{CO}_3(aq)$ which creates space for further metal precipitation (cf. Barnes, 1997) and additionally drives the reaction</td>
<td>Metal+Sulphate Model; addition of reduced sulphur by sulphate reduction. Reaction (h).</td>
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<td>(h) $\text{SO}_4^{2-}(aq) + 2\text{H}^+(aq) \rightarrow \text{H}_2\text{S} + 2\text{O}_2$</td>
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<tr>
<td>Sphalerite replaces spheroidal pyrite (e.g. Fig. 12b).</td>
<td>(i) $2\text{Zn}^{2+}(aq) + \text{FeS}_2 + \text{H}_2\text{O} \rightarrow 2\text{ZnS} + \text{Fe}^{3+}(aq) + 2\text{H}^+ + \frac{1}{2}\text{O}_2$</td>
<td>Mixing Model; sulphur derived from preexisting sulphide mineral. Reaction (i).</td>
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<tr>
<td>Sphalerite and galena occur as intergrowths with migrabitumen (e.g. Fig 10b).</td>
<td>(b) $2\text{CH}_2\text{O} + \text{SO}_4^{2-}(aq) \rightarrow 2\text{HCO}_3^- + \text{H}_2\text{S}(aq)$ (Machel, 1987) induces metal precipitation</td>
<td>Metal+Sulphate Model; reduced sulphur derived by insitu thermochemical sulphate reduction by organic material. Reaction (b) + (a) and (j).</td>
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<td>(j) $\text{Pb}^{2+}(aq) + \text{H}_2\text{S}(aq) \rightarrow \text{PbS}(s) + 2\text{H}^+$ and is also coupled with reaction (a)</td>
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**Table 4.** Metal precipitation reactions derived to account for common textural associations at George Fisher. Precipitation mechanisms and sulphur source relate to fluid mixing and metal+sulphate models described in Table 3.
Banded mudstone

Shaly banded mudstone intercalated with rhythmically laminated pyritic and carbonaceous siltstones.

Rhythmically laminated pyritic and carbonaceous siltstones intercalated with banded mudstones and white bands ± Zn-Pb bands.

Rhythmically laminated nodular carbonate-bearing pyritic siltstones intercalated with banded mudstones and white bands ± Zn-Pb bands.

Nodular carbonate-bearing rhythmically laminated pyritic siltstones ± Zn-Pb bands.

Tuffaceous marker bed

Fault

Estimated percentage of Stage VIII ferroan dolomite-ankerite-ferroan ankerite siderite alteration in nodular carbonate layers and layer-parallel white bands. Estimated percentage of Stage I calcite alteration in mudstones and siltstones.

Figure 1. Carbonate distribution logs superimposed on a stratigraphic plan map of the H stratigraphic interval and illustrating the distribution of Stage I calcite developed in mudstones and siltstones and Stage VIII ferroan dolomite-ankerite-ferroan ankerite-siderite alteration in nodular carbonate layers and layer-parallel white bands. Refer to Part A, Fig. 5 for drill hole localities.
Rhythmically laminated pyritic and carbonaceous siltstones intercalated with banded mudstones and white bands ± Zn-Pb bands.

Nodular carbonate-bearing rhythmically laminated pyritic siltstones intercalated with banded mudstones and white bands ± Zn-Pb bands.

Stylolitic, medium-bedded mudstone

Banded mudstone

Figure 2. Carbonate distribution logs superimposed on simplified stratigraphic plan maps of the F and E stratigraphic intervals and illustrating the estimated percentage of Stage I calcite in mudstones and siltstones. Stage VIII ferroan dolomite-ankerite-ferroan ankerite-siderite alteration in nodular layers and layer-parallel white carbonate bands and intensity of Stage V sugary ferroan dolomite veins. Refer to Part A, Fig. 5 for drill hole localities.
Legend to Figure 3.

D-C-B STRATIGRAPHIC INTERVAL

- Rhythmically laminated nodular carbonate-bearing or plain pyritic and carbonaceous siltstones intercalated with banded mudstones and white bands ± Zn-Pb bands.
- Rhythmically laminated nodular carbonate-bearing pyritic siltstones intercalated with banded mudstones and white bands ± Zn-Pb bands.
- Rhythmically laminated pyritic and carbonaceous siltstones ± Zn-Pb bands.
- Nodular carbonate-bearing rhythmically laminated pyritic siltstones ± Zn-Pb bands.
- Stylolitic, medium-bedded mudstone
- Banded mudstone

Figure 3a

Estimated percentage of Stage VIII ferroan dolomite-ankerite-bearing alteration in nodular carbonate and layer-parallel white bands.
Estimated percentage of Stage I calcite alteration in mudstones and siltstones.

0 50 100%

1 3 5 >5

# veins/ specified interval (m)

Figure 3b

Distribution of Stage VIII pyrrhotite breccias
Distribution of Stage VIII phyllosilicate alteration
Distribution of Stage III Hyalophane-K-feldspar alteration

Stage VIII Chalcopyrite-bearing veins

# veins/ specified interval (m)
Figure 3a. Carbonate distribution logs superimposed on a simplified stratigraphic plan map of the D, C and B intervals and illustrating the distribution and relative abundance of Stage I calcite in mudstones and siltstones, Stage VIII ferroan dolomite-ankerite-ferroan ankerite ± siderite alteration in nodular carbonate layers and layer-parallel white bands and distribution and intensity of Stage V sugary ferroan dolomite veins. Refer to Part A, Fig. 5 for drillhole localities.
Figure 3b. Silicate-sulphide distribution logs superimposed on a simplified stratigraphic plan map of the D, C and B intervals and illustrating the distribution of Stage III hyalophane-K-feldspar alteration in mudstones and siltstones. Stage VIII phyllosilicate alteration, distribution of Stage VIII pyrrhotite breccias and distribution and intensity of Stage VIII chalcopyrite-bearing veins. The distribution of Stage VIII ferroan dolomite-ankerite-ferroan ankerite siderite alteration is superimposed to illustrate the spatial association between this alteration style and phyllosilicate alteration. Refer to Part A, Fig. 5 for drillhole localities.
Figure 4

a. Light grey Stage I calcite alteration (Cal) irregularly developed in a dark grey planar to discontinuously laminated ferroan dolomite-bearing medium-bedded mudstone (Dol). Carbonaceous stylolites cross-cut and juxtapose calcite alteration zones (core width=4cm, HS# 078b, J710WI#1, 74m).

b. Stage I calcite alteration selectively developed in a ferroan dolomite-bearing banded mudstone (Dol). Calcite alteration has a bleached appearance, is spatially associated with white calcite nodules and include irregular bands of ferroan dolomite-bearing mudstones (dark grey) within otherwise pervasive alteration zones (core width=4cm, HS# 044i, J702WI#5, 45m).

c. Photomicrograph illustrating extensive Stage I calcite alteration in a medium-bedded mudstone interval. Calcite (Cal) is coarser grained than quartz and ferroan dolomite (Dol) that occur together in irregular clots. A stylolite is developed in the middle of the sample and bedding-parallel foliation is developed throughout. Note the sutured nature of calcite (Cal) grain boundaries (HS# 078b, J710WI#1, 71.1m, XPL).

d. Bedding-parallel to discordant nodular calcite developed in a rhythmically laminated pyritic siltstone (PS). Calcite (Cal) in nodular layers (Nod) is colourless and contains irregular ferroan dolomite±detrital quartz aggregates (e.g. Dol). Dark laminations consist predominantly of spheroidal pyrite and irregular stringers of spheroidal pyrite (Py,) locally cross-cut a nodular calcite layer (HS# 050g, J702WI#5, 105.9m, PPL).

e. Microcrystalline subhedral to rhombohedral calcite crystals in a nodular calcite layer line microscopic vughs which are infilled by sphalerite (Sp) (HS# 050g, J702WI#5, 105.9m, PPL).
Figure 5.

(a) Backscattered electron image illustrating abundant Stage I rhombohedral calcite (Cal) and Stage IV sphalerite (Sp) infill in a microscopic nodular layer. Rhombohedral calcite crystals abut Stage I calcite-altered quartz (Qtz)±ferroan dolomite (FeDol) bearing wall rock that contains irregularly distributed Stage II spheroidal pyrite (Py₁) and Stage IV brassy pyrite (Py₂) (HS# UG 9, C ore zone, 7200mN cross-cut).

(b) Backscattered electron image of two nodular calcite layers separated by a very fine ferroan dolomite-quartz lamination with spheroidal pyrite. Calcite is intergrown with K-feldspar in nodular layers and contains irregular clots of ferroan dolomite-quartz (HS# DC840b, H766ED#1, 558.6m).
c. BSE image illustrating diffuse nature of layer-parallel white band contacts with dolomitic banded mudstones (FeDol+Qtz), defined by the distribution of Stage I white calcite (Cal). A lens-shaped calcite nodule occurs adjacent to a white band central to the sample (HS# 051a, J702WI#5, 111.6m).

d. Quartz (Qtz) concentrated around a carbonaceous stylolite. The stylolite juxtaposes two Stage I calcite-altered mudstone beds. The upper layer is calcite-rich (Cal) whilst the lower bed contains less calcite and more ferroan dolomite and quartz (FeDol+Qtz). Stage II spheroidal pyrite (Py) preferentially replaces carbonaceous material along the stylolite (HS# 078b, J710WI#1, 71.1m).
Figure 6. (a) Plot illustrating whole rock abundances of quartz versus ferroan dolomite+ Stage II calcite or representative samples of major rock types and carbonate banding. (b) Plot illustrating whole rock abundances of quartz versus Stage I calcite. The bulk of the quartz is assumed to be detrital based on thin section examination. Relative abundances were derived from XRD traces (see Appendix IX).

* Values for rhythmically laminated pyritic siltstones normalized to 100% quartz+whole rock carbonate.
Figure 7.

a. Celsian-hyalophane-K-feldspar alteration (Cs-Hyl-Kfs) is buff-white and preferentially developed along mudstone layers in this sample. Relict laminations and grey clots of ferroan dolomite-bearing host rock are preserved within altered beds. Banded sphalerite (Sp) in this sample is spatially associated with abundant orange sphalerite alteration in mudstones and semi-massive brassy pyrite (Pyb) that is commonly developed in rhythmically laminated pyritic siltstones but also occurs along a bedding contact in the middle of the sample (HS# 251, J718WI#5, 164.9m).

b. Intense buff-coloured hyalophane-K-feldspar Stage III alteration (Cs-Hyl-Kfs) developed in a medium-bedded mudstone. No internal bedding structures are preserved. However, Stage IX pyrrhotite alteration is preferentially developed along stylolitic planes and in discordant vein sets that are associated with lensoidal and spotted pyrrhotite-sphalerite alteration (HS# 213, J718WD#5, 380.6m).
Figure 8.

a. Discordant vein sequentially infilled by Stage III celsian (Cs), hyalophane (Hyl), K-feldspar (Kfs) and calcite (Cal). Feldspars in this vein exhibit at least three growth zones distinguished by progressively decreasing Ba. The vein is developed in a ferroan dolomite-quartz-bearing banded mudstone (FeDol+Qtz) and is associated with diffuse hyalophane-K-feldspar alteration (Cs-Hyl-Kfs) within the wall rock (BSE image, HS# 253, J718WI#5, 166.9m).

b. BSE image illustrating paragenetic associations within a sphalerite breccia-vein. Earliest infill in the vein is Stage III hyalophane-K-feldspar zoned from a blocky K-feldspar core (black-Kfs) that is consecutively rimmed by relatively Ba-rich (light grey), Ba-poor (medium grey) hyalophane (Hyl). Feldspars are irregularly intergrown with calcite (Cal) and both are microbrecciated and/or replaced by Stage IV sphalerite (Sp). Stage IV hydrophlogopite laths infill within the sphalerite microbreccia zone (HS#251, J718 WI#5, 164.9m).
c. Hyalophane-K-feldspar alteration concentrated in a dolomitic banded mudstone (BM) rather than a rhythmically laminated pyritic siltstone (PS). Stage IV sphalerite (Sp) is superimposed on Stage III Ba-K-feldspar alteration at the base of the BSE image (Cs-Hyl-Kfs) (HS# 254b, J718 WI#5, 167.3m).

d. Ultrafine-grained celsian-hyalophane-K-feldspar (Cs-Hyl-Kfs) developed along spheroidal pyrite (Py), quartz (Qtz) and ferroan dolomite (FeDol) grain contacts (BSE image, HS# 251, J718 WI#5, 164.9m).
Figure 9.

a. Ultrafine-grained celsian-hyalophane-K-feldspar (Stage III, Cs-Hyl-Kfs) is developed in a calcite-altered (Stage I, Cal) banded mudstone as preferential alteration of a coarse, elongate precursor. Brassy pyrite (Stage IVc) and sphalerite (Stage IVd) occur as preferential replacements of feldspars whilst minor spheroidal pyrite (PyS) is disseminated throughout calcite (HS# 251, J718WI#5, 164.9m, XPL).

b. Calcite-celsian-hyalophane-K-feldspar-calcite vein (Cs-Hyl-Kfs, Cal) cross-cuts a stylolite bearing abundant spheroidal pyrite (PyS). Brassy pyrite (Pyb) and sphalerite alteration is superimposed on the vein in the vicinity of the stylolite. The vein is developed in a ferroan dolomite-bearing banded mudstone (FeDol) (HS# 254b, J718WI#5, 167.3m, XPL).
a. Bitumen (Bit) and sphalerite (Sp) are intergrown and occur interstitial to carbonate and quartz in a banded mudstone bed (HS# 305, J730WI#1, 189.8m, refl.).

b. Stringers of brown migrabitumen (epi-impsonite, Bit) contain sphalerite, pyrite and galena inclusions in a shaly banded mudstone layer at the base of the photo. Sphalerite (Sp), galena (Gn), migrabitumen (Bit) and calcite appear to infill a vugh in the upper part of the photo (HS# 033d, J702WI#2, 55.4m, refl.).

c. Edge of a migrabitumen (epi-impsonite, Bit) - sphalerite (Sp) - brassy pyrite (Py) alteration zone (Stage IV) in a Stage I calcite-altered (Cal) mudstone bed (HS# 033d, J702WI#2, 55.4m, PPL).

d. Calcite - quartz - sphalerite (Sp) - brassy pyrite (Pyb) infill after fragmented solid migrabitumen (cata-impsonite, Bit). The latter is distinguished by the presence of devolatization pores. Stage II spheroidal pyrite (Py.) is present in mudstone wall rock (HS# 117, J702WD#4, 141.1m, refl.).

e. Photomicrograph of textural zonation exhibited by meso-impsonite (second migrabitumen population, Bit). Cores (C) of fragmented grains are isotropic. Grain rims can be subdivided into three texturally distinct zones. The inner zone is defined by a fine pin-point anisotropy (1), that grades outwards into a coarse pin-point anisotropy (2). The outer rim forms sharp contacts with the latter and displays a coarse anisotropy and fibrous texture. The photograph was taken by P. Crosdale (HS# 0861, J710WI#1, 42.6m, refl-in oil).
Figure 11. Plot of Maximum versus minimum bitumen reflectance (in oil) for migrabitumen populations 1 and 2.
Figure 12.

a. A brassy pyrite alteration band (Pyb) is irregularly bounded by hydrophlogopite (Hphl) and contained within a sphalerite-rich band (Sp). The band is complexly folded. Note that spheroidal pyrite grains can not be distinguished in the band (HS# 260b, J718WI#5, 202.9m, PPL).

b. Semi-massive sphalerite (light grey) breccia contains coarse grained celsian-hyalophane-K-feldspar-calcite clasts (b) and microbrecciates adjacent pyritic wall rock (a). Euhedral brassy pyrite (Pyb) occurs as infill along clast margins and spheroidal pyrite is disseminated within wall rock (a). However, the bulk of the spheroidal and brassy pyrite in this field of view has been replaced by sphalerite to form atoll textures (HS# 063a, J702WI#5, 199.8m, refl.).

c. Photomicrograph illustrating paragenetic associations from an economic intersection containing breccia-vein hosted sphalerite. Semi-massive sphalerite (Sp) microbrecciates coarse-grained Stage III celsian-hyalophane-K-feldspar and calcite (Cal) and envelopes euhedral hydrophlogopite laths (Hphl). The majority of opaque inclusions within the main sphalerite band are pyrrhotite. Sphalerite-hydrophlogopite alteration is preferentially developed within a celsian-hyalophane-K-feldspar-celsian altered mudstone layer (BM) central to the sample (HS# 251, J718WI#5, 164.9m, refl.).

d. Sphalerite (Sp) occurs as extensive alteration of fine- to coarse-grained carbonate and celsian-hyalophane-K-feldspar in breccia-veins, and adjacent wall rock. The only indication of a precursor host rock in this sample is spheroidal pyrite (Py). Brassy pyrite (Pyb) is abundant to the left of the sample, hydrophlogopite (Hphl) occurs with sphalerite in breccia-veins and pyrrhotite inclusions are abundant in sphalerite (HS# 251, J718WI#5, 164.9m, refl.).

e. Photomicrograph of a sphalerite breccia-vein. Sphalerite microbrecciates and replaces Stage III celsian-hyalophane-K-feldspar (Kfs) and calcite (Cal). The majority of inclusions in sphalerite are pyrrhotite (Po) (HS# 251, J718 WI#5, 164.9m, refl.).
Figure 13. Proposed model for the paragenetic and structural evolution of Stage IV breccia-vein-hosted sphalerite (banded sphalerite) at George Fisher. The model depicts the formation of Stage III Cal-Qtz±Kfs±Hyl veins and the fundamental association between the two paragenetic stages. The 'protolith' to stage III and IV alteration has been subjected to stage I calcitization which has preferentially developed in mudstone bands, stylolitization and Stage II spheroidal pyritization which is preferentially developed along carbonaceous horizons including styloitic surfaces and laminations in rhythmically laminated siltstones.
Figure 14.

a. Warped Stage VI sugary ferroan dolomite vein set cross-cuts Stage IV stratiform sphalerite whilst clasts of the same material are included in a Stage V fine-grained sphalerite breccia (right). Coarse-grained sphalerite irregularly rims these clasts (HS# 248, J718WI#5, 158.4m, core width = 4.5cm).

b. Preferential development of folds, and irregular brecciation of a sugary ferroan dolomite vein in sphalerite bands. Sugary dolomite veins (FeDol) also cross-cut fine-grained sphalerite breccias in this sample (HS# 282, K782WI#1, 127.3m, core width = 4.5cm).
Figure 15.

a. Coarse-grained galena breccia containing large clasts of banded and stratiform sphalerite (e.g. arrow). Discordant galena veins (Gn) brecciate celsian-hyalophane-K-feldspar altered mudstone clasts and wall rock (BM) and are structurally continuous with the main galena breccia (HS# 060g, J702WI#5, 183.4m).

b. Medium-grained galena breccia (Gn) is selectively developed in banded sphalerite and structurally continuous with discordant galena-sphalerite veins (Gn,Sp) in celsian-hyalophane-K-feldspar altered mudstone layers (e.g. BM). Galena breccia margins are irregular in this sample. Note the disharmonic folding exhibited by mudstone layers of different thicknesses (HS# 254a, J718WI#5, 167.1m).

c. Photomicrograph illustrating abundance of sphalerite clasts (Sp) in a medium-grained galena breccia. (HS# 143, J702 WI#6, 234.7m, refl.).
Figure 15.

d. Galena microbreccia contains fragments of sphalerite with ragged contacts. The large sphalerite fragment (Sp) appears to have been once continuous with adjacent clasts illustrating that at least a component of the galena occurs as infill. However, the imperfect fit of clasts and ragged nature of sphalerite fragments illustrates that galena also occurs as a replacement of sphalerite (HS# 143, J702WI#6, 234.7m, PPL).

e. Medium- to coarse-grained galena microbrecciates banded sphalerite (Sp). This microbreccia zone constitutes diffuse breccia margins seen in hand specimen (cf. Fig. 15b, HS# 143, J702 WI#6, 234.7m, refl.).

f. Photomicrograph illustrating interconnectivity of galena textural varieties. A medium-grained galena breccia (a) is preferentially developed in a sphalerite band. Mudstone-hosted galena (b) occurs as an alteration selvage to the breccia and discordant galena veins (c) developed in the mudstone layer are structurally continuous with the breccia (HS# 143, J702 WI#6, 234.7m, refl.).
Figure 15.
g. Fine-grained galena breccia contains elongate clasts of fine-grained sphalerite breccia (Sp, pale brown), angular carbonaceous mudstone fragments (black) and minor coarse-grained sphalerite clasts (Sp, red-brown). Thin discordant galena veins locally cross-cut clasts (e.g. Gn). Note that fine-grained sphalerite breccia and thin carbonaceous mudstones are major constituents of adjacent wall rock visible to the top right (HS# 150, J702WI#6, 244.5m).

h. Photomicrograph of a fine-grained galena breccia with abundant ultrafine sphalerite clasts (medium grey). Larger clasts are composed predominantly of carbonate (dark grey). However, the large rounded clast (left of centre) consists of sphalerite (Sp), celsian-hyalophane-K-feldspar, calcite and brassy pyrite. The composition of these clasts is equivalent to breccia-vein-hosted sphalerite illustrating that this galena breccia preferentially developed in a sphalerite-rich band (HS# 063a, J702 WI#5, 199.8m, refl.).

i. Galena (Gn)-yellow pyrite (Pyy)-pyrrhotite (Po) vein preferentially developed in a sphalerite band. The vein microbrecciates sphalerite and preexisting carbonate fragments. Galena, pyrite and pyrrhotite also occur as replacements of sphalerite (HS# 267a, J718WI#5, 248.2m, refl.).
a. Chalcopyrite veinlets (Cpy) superimposed on a deformed sugary ferroan dolomite vein and host rock. The sugary ferroan dolomite vein cross-cuts rhythmically laminated siltstone-hosted sphalerite. Pyrrhotite occurs predominantly as alteration preferentially developed along layering (e.g. Po) and is abundant throughout (HS# 276a, K766 WI#2, 241.2m).

b. Stage VIII Magnetite (Mt), chlorite, biotite and ankerite-siderite (Ank-Sid) alteration cross-cuts stratiform sphalerite. Stage VIII Fe-rich carbonate alteration zones are typically yellow/rust-coloured compared with buff-white celsian-hyalophane-K-feldspar alteration zones (HS# 310, J722 WI#2, 199.8m).

c. Pyrrhotite microbreccias (Po) developed along clast margins and bedding planes and cross-cut fine-grained sphalerite and coarse-grained galena breccias. Pale green chlorite-rich alteration (Chi) is pervasive in a mudstone interval left of the breccia zone (HS# 173b, J718 WD#5, 351.9m).

d. Biotite (Bt) and zoned celsian-hyalophane-K-feldspar (Cs-Hyl-Kfs) infill developed along alternate vein walls with pyrrhotite infill (Po) in the core of the vein. Pyrrhotite also microbrecciates zoned celsian-hyalophane-K-feldspar infill and wall rock. The wall rock to the left consists of ultrafine-grained celsian-hyalophane-K-feldspar and carbonate. Chlorite microbrecciates (Chi) celsian-hyalophane-K-feldspar-carbonate wall rock to the right of the vein (HS# 173a, J718 WD#5, 351.9m, XPL).
e. Photomicrograph of a lenticular pyrrhotite alteration pod as commonly observed at a hand specimen scale in mudstones. Pyrrhotite (Po) replaced biotite (pale brown) and coarse-grained carbonate in this case. Relatively coarse-grained Stage VIII red-brown sphalerite (Sp) and biotite (pale brown) alteration is dispersed through celtsian-hyalophane-K-feldspar-carbonate wall rock (HS# 208, J718WI#3, 257.5m, PPL).

f. Stage VIII galena as selective replacement of Stage VIII biotite, both of which occur as an alteration selvage to a pyrrhotite vein (HS#173a, J718WD#5, 351.9m, refl.).

g. Ultrafine-grained carbonate-dominant (carb) and phengite+muscovite -dominant (Phg-Ms) alteration zones developed in a banded mudstone are spatially associated with a coarse grained pyrite-sphalerite-carbonate-chlorite vein set (e.g. Chl). The vein set has either displaced altered beds, or phyllosilicate alteration has preferentially developed in brecciated layers due to a preexisting chemical heterogeneity (HS# 256, J718WI#5, 174m, XPL).
Figure 16.

h. Pyrrhotite (Po) and rare chalcopyrite lenses are preferentially developed in Stage I calcite-rich mudstones and layer-parallel white bands or as an alteration of brassy pyrite (Py_s) (HS# 88, J710WI#1, 89.6m).

i. Dark-coloured sphalerite enveloped and microbrecciated by irregular orange-brown sphalerite. Coarse-grained Stage VIII calcite (VIII-Cal) rims sphalerite alteration zones in a layer-parallel white band that otherwise consists of finer-grained Stage I calcite (I-Cal) (HS# 107, J702WD#4, 90.4m, PPL).

j. Inclusion-free, relatively coarse-grained Stage VIII sphalerite is rimmed by inclusion-free calcite (VIII-Cal) and occurs as an overgrowth on Stage IV sphalerite riddled with galena inclusions. Calcite rims abut a sphalerite-rich calcite layer (Cal) (HS# 090a, J710WI#1, 197.8m, PPL).
Figure 17a. Plots illustrating metal grade associations for Zn vs Pb, Cu vs Zn and Cu vs Pb derived from unpublished MIM Ltd assay data for diamond drill holes that were graphically logged as part of this study. Total number of samples points for each plot is 1766.
Figure 17b. Metal grade plots illustrating Zn vs Pb for the H through to A stratigraphic intervals and derived from the same diamond drillholes as represented in figure 17a (Unpub. MIM Ltd data).
Figure 17c. Metal grade plots illustrating Cu vs Zn for the H through to A stratigraphic intervals and derived from the same diamond drillholes as represented in figure 17a (Unpub. MIM Ltd data).
Figure 17d. Metal grade plots illustrating Cu vs Pb for the H through to A stratigraphic intervals and derived from the same diamond drillholes as represented in figure 17a (Unpub. MIM Ltd data).
Figure 18a. Simplified longsections for A through to H stratigraphic ore-bearing intervals illustrating Zn/Zn+Pb. Zones with steep contour gradients are to fine to represent at this scale. Such zones are not outlined in black. Plots were derived by projecting ratio data for each respective interval from 6800mN to 7200mN (main economic zone) on to a vertical plane. Orebody outlines represent limit of assay data and are a true reflection of ore body shape. Areas with Zn=0 represent undifferentiated fault windows and zones in which Zn and Pb levels were lower than the limit of analytical detection. Original plots were produced by S. Versace from unpublished MIM Ltd data.
Figure 18b. Simplified longsections for A through to H stratigraphic ore-bearing intervals illustrating Cu/Cu+Pb. Zones with steep contour gradients are too fine to represent at this scale and are not outlined in black. Plots were derived by projecting ratio data for each respective interval from 6800mN to 7820mN (main economic zone) on to a vertical plane. Orebody outlines represent limit of assay data and are a true reflection of ore body shape. Areas with Cu=0 represent undifferentiated fault windows and zones in which Cu levels were lower than the limit of analytical detection. Original plots were produced by S. Versace from unpublished MIM Ltd data.
Figure 19. (a) Plot of $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for Stage VII and Stage IXa galena from a range of textural settings. (b) Plot of $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for the same samples. (c) Plot illustrated in (b.) superimposed on Pb-age model curve, and illustrating data for Mount Isa and HYC at McArthur River derived by Sun et al., (1994) for the Mount Isa Inlier and McArthur River area.
Figure 20. (a) Plot of $\delta^{34}$S for adjacent samples.
(b) Plot of $\delta^{34}$S and sample location with respect to northing.
Figure 21. Schematic stratigraphic column and mineral distribution logs illustrating spatial-temporal-temperature zonation patterns at George Fisher.
Ore-forming window shifts to left with decreasing concentrations of \( \Sigma \) dissolved sulphur at constant temperature

\[ \text{H}_2\text{S(aq)} - \text{HS}^- \] boundary shifts to right with increasing temperature

Neutrality shifts to left with increasing temperature

**Figure 22.** Cartoon Log/\( f_{O_2} \)-pH diagram illustrating approximate stability fields for aqueous sulphur species and iron mineral stability fields relative to metal solubility contours. The shaded area defines the window of fluid compositions that are considered capable of transporting ore-forming quantities of metals. Hatched zones approximate fluid compositions estimated for reduced acid brines carrying metal as chloride complexes (Sverjensky, 1984), slightly oxidized brines carrying metals as chloride or organic complexes (e.g. Anderson, 1975, Giordano, 1992, Cooke and Large, 1998) and oxidized alkaline brines (Cooke and Large, 1998). Arrows illustrate pathways of metal precipitation (cf. Table 3). Adapted from Anderson (1973), Anderson (1975), Giordano and Barnes (1981), Sverjensky (1984), Giordano (1992), Cooke and Large (1998).
<table>
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<td>Waring (1990a), Waring et al. (1998).</td>
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<td>Nodular carbonate</td>
<td>Hilton and George Fisher - Nodular dolomite and calcite</td>
<td>Sulphate evaporite layers pseudomorphed by carbonate.</td>
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Table 1. Summary of previous interpretations on the origin of Urquhart Shale host rock carbonate constituents.
Table 2. Modified paragenesis of the George Fisher deposit with emphasis on carbonate evolution. 1. Peak temperature estimates for metamorphism based on migrabitumen reflectance data (Part B). 2. Hydrothermal temperature of copper event based on phyllosilicate associations (Part B). Refer to Part A for explanation of age constraints. $\mathcal{N} = $ carbonate phase dissolution or replacement, $\times = $ carbonate recrystallization, $\leftarrow\rightarrow = $ deformation of Stage IV sphalerite and galena. Dolomite textural classification after Sibley and Gregg (1987). PL-S = subhedral grains with planar grain boundary contacts, PL-E=euhedral crystals, Npl=non-planar grain boundary contacts, Matrix-R=matrix is replacive in origin.
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<th>SEDIMENTATION</th>
<th>DIAGENESIS</th>
<th>REGIONAL DEFORMATION &amp; METAMORPHISM</th>
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<td>1654Ma -&gt; ?</td>
<td>1580 -&gt; 1530Ma</td>
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<td>D_3 -&gt; D_3</td>
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<td>increasing burial depth</td>
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<td>hydrocarbon maturation</td>
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Rocks and Minerals

- Detrital Quartz
- Organic Detritus
- Detrital Mica
- Detrital Feldspar
- Detrital Dolomite
- Dolomite - PL-S, MATRIX-R, CEMENT?
- Ankerite - PL-E & NPL, MATRIX-R
- Ferroan Dolomite - PL-E & NPL, MATRIX-R
- Calcite - NPL, MATRIX-R: PL-E VOID FILL
- Calcite Nodules in Mudstones
- Pyrite Alteration
- BAK-K-Feldspar S_p/VEIN INFILL & ALT.
- Ferroan Dolomite - S_p/VEIN INFILL
- Calcite - S_p/VEIN INFILL
- Migrabitumen Embalacement
- Hydrophlogopite
- Spalhiterite
- Galena
- Sugary Ferroan Dolomite - Vein Infill
- Pyrrhotite
- Chalcopyrite
- Magnetite
- Fe Dol - NPL to PL-E Matrix-R: Vein Infill
- Ankerite - NPL to PL-E Matrix-R: Vein Infill
- Fe Ankerite - NPL to PL-E Matrix-R: Vein Infill
- Siderite - Vein Infill
- Biotite-Chlorite-Muscovite-Phengite-Greenalite
Table 3. Summary table listing carbonate chemistry. Carbonate populations are subdivided according to paragenesis, textural characteristics, and setting. A selection of chemical analyses of Hilton Mine and Mount Cu Mine carbonates are taken from Valenta (1988), Tuesley (1993) and Waring (1990a). 1 Colour refers to the variation in electron density of the particular carbonate group as seen in BSE and referred to here relative to an arbitrary grey. 2 Setting of the carbonates for each population on the basis of sample location within the Mount Isa system (Isa=Mount Isa area, Hil=Hilton Mine, GF=George Fisher deposit), and the relative proximity of the sample to Zn-Pb-Ag or Cu ore bodies (economic=sample located in an ore body, proximal=mine environment near ore body, distal=peripheral to ore system), and development of other paragenetic stages within the same sample (e.g. Stage I calcite alteration, Stage III celsian-hyalophane-K-feldspar alteration, Stage VIII phyllosilicate alteration). 3 Paragenetic stage for George Fisher samples as for Table V including differentiation of early carbonates as Stage OI from clastic grains. Paragenetic associations for samples from Hilton and Mount Isa are correlated with George Fisher events (denoted equ. = equivalent) on the basis of comparisons of textural and/or mineralogical and/or structural timing comparisons.

<table>
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<tr>
<th>PARAGENETIC STAGE</th>
<th>TEXTURE AND COLOUR 1</th>
<th>SETTING 2</th>
<th>CARBONATE TYPE</th>
<th>HOST ROCK 4</th>
<th>CaCO3 (mol. %)</th>
<th>MgCO3 (mol. %)</th>
<th>MnCO3 (mol. %)</th>
<th>FeCO3 (mol. %)</th>
<th>(Fe,Mn)CO3 (mol. %)</th>
<th>Fe+Mn: Mg</th>
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<td>Early dolomite OI a</td>
<td>dark grey cores</td>
<td>GF proximal Zn-Pb-Ag proximal subeconomic Cu</td>
<td>dolomite &gt;&gt; ferroan dolomite</td>
<td>PS, CS, MM, BM, SM</td>
<td>49.34 - 56.22</td>
<td>41.78 - 49.54</td>
<td>0.02 - 0.43</td>
<td>0.31 - 3.48</td>
<td>0.55 - 3.88</td>
<td>11.74 - 86.84</td>
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<td>light grey inner rims</td>
<td>GF proximal Zn-Pb-Ag proximal subeconomic Cu</td>
<td>ankerite &gt;&gt; ferroan dolomite</td>
<td>CS, MM, SM</td>
<td>49.60 - 52.57</td>
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<td>7.85 - 17.23</td>
<td>8.26 - 14.09</td>
<td>1.85 - 5.08</td>
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<td>medium grey outer rims and matrix</td>
<td>GF proximal Zn-Pb-Ag proximal subeconomic Cu</td>
<td>ferroan dolomite &gt;&gt; ankerite</td>
<td>PS, CS, MM, BM, SM</td>
<td>48.43 - 52.81</td>
<td>36.84 - 45.21</td>
<td>0.25 - 2.60</td>
<td>4.14 - 9.32</td>
<td>4.61 - 10.62</td>
<td>3.22 - 9.76</td>
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<td>GF proximal Zn-Pb-Ag proximal subeconomic Cu</td>
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<td>49.22 - 51.51</td>
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<td>TEXTURE AND COLOUR</td>
<td>SETTING</td>
<td>CARBONATE TYPE</td>
<td>HOST ROCK</td>
<td>CaCO₃ (mol. %)</td>
<td>MgCO₃ (mol. %)</td>
<td>MnCO₃ (mol. %)</td>
<td>FeCO₃ (mol. %)</td>
<td>(Fe,Mn)CO₃ (mol. %)</td>
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<td>GF economic Zn-Pb-Ag proximal subeconomic Cu Stage III feldspar zone</td>
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<td>GF economic Zn-Pb-Ag proximal subeconomic Cu Stage III feldspar zone</td>
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<td>BM</td>
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<td>BM, MM</td>
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<td>matrix and infill</td>
<td>GF proximal Zn-Pb-Ag proximal subeconomic Cu</td>
<td>calcite</td>
<td>Nod</td>
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<td>0.44 - 1.76</td>
<td>0.45 - 1.52</td>
<td>0.49 - 1.29</td>
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<td>Syntectonic ferroan carbonates Stage VIII</td>
<td>light grey matrix and rhomb core</td>
<td>GF proximal Zn-Pb-Ag proximal subeconomic Cu</td>
<td>ankerite &gt;&gt; ferroan ankerite</td>
<td>MM, BM, PS</td>
<td>47.98 - 52.01</td>
<td>36.29 - 25.44</td>
<td>1.18 - 4.50</td>
<td>11.42 - 22.79</td>
<td>14.97 - 26.05</td>
<td>0.98 - 2.38</td>
<td>24</td>
</tr>
<tr>
<td>Syntectonic ferroan carbonates Stage VIII</td>
<td>grey matrix</td>
<td>GF proximal Zn-Pb-Ag subeconomic Cu Stage VIII phyllosilicate with Stage III feldspar zone</td>
<td>ferroan ankerite &gt;&gt; ankerite</td>
<td>MM</td>
<td>47.35 - 49.05</td>
<td>27.66 - 30.76</td>
<td>2.69 - 3.87</td>
<td>17.23 - 21.1</td>
<td>19.97 - 24.71</td>
<td>1.12 - 1.64</td>
<td>9</td>
</tr>
<tr>
<td>Syntectonic ferroan carbonates Stage VIII</td>
<td>Vein Infill</td>
<td>GF proximal Zn-Pb-Ag subeconomic Cu Stage VIII phyllosilicate with Stage III feldspar zone</td>
<td>ferroan ankerite &gt;&gt; ankerite</td>
<td>-</td>
<td>48.79 - 52.21</td>
<td>18.94 - 31.27</td>
<td>1.52 - 3.5</td>
<td>17.17 - 29.53</td>
<td>19.52 - 32.38</td>
<td>0.56 - 1.60</td>
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<td>PARAGENETIC STAGE</td>
<td>TEXTURE AND COLOUR</td>
<td>SETTING</td>
<td>CARBONATE TYPE</td>
<td>HOST ROCK</td>
<td>CaCO$_3$ (mol. %)</td>
<td>MgCO$_3$ (mol. %)</td>
<td>MnCO$_3$ (mol. %)</td>
<td>FeCO$_3$ (mol. %)</td>
<td>(Fe,Mn)CO$_3$ (mol. %)</td>
<td>Fe+Mn: Mg</td>
<td>n</td>
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<tr>
<td>Syntectonic</td>
<td>Vein Infill</td>
<td>GF proximal Zn-Pb-Ag subeconomic Cu Stage VIII phyllosilicate with Stage III feldspar zone</td>
<td>siderite</td>
<td>-</td>
<td>0.62 - 0.77</td>
<td>14.53 - 15.15</td>
<td>3.05 - 3.57</td>
<td>80.63 - 81.80</td>
<td>84.07 - 84.85</td>
<td>0.17 - 0.18</td>
<td>3</td>
</tr>
<tr>
<td>Syntectonic</td>
<td>Vein Infill</td>
<td>GF proximal Zn-Pb-Ag subeconomic Cu</td>
<td>ferroan ankerite</td>
<td>-</td>
<td>47.82 - 51.35</td>
<td>23.50 - 29.84</td>
<td>2.46 - 3.37</td>
<td>18.26 - 24.29</td>
<td>20.72 - 27.60</td>
<td>0.85 - 1.44</td>
<td>6</td>
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<tr>
<td>Syntectonic</td>
<td>Grey matrix</td>
<td>GF proximal Zn-Pb-Ag subeconomic Cu</td>
<td>ferroan dolomite &gt;&gt; ankerite</td>
<td>Nod</td>
<td>49.70 - 50.75</td>
<td>39.55 - 42.13</td>
<td>2.60 - 3.50</td>
<td>4.50 - 7.52</td>
<td>7.96 - 10.75</td>
<td>3.68 - 5.29</td>
<td>8</td>
</tr>
<tr>
<td>Syntectonic</td>
<td>Light grey matrix</td>
<td>GF proximal Zn-Pb-Ag subeconomic Cu</td>
<td>ferroan dolomite &gt;&gt; ankerite</td>
<td>Nod</td>
<td>51.77 - 54.99</td>
<td>24.23 - 27.33</td>
<td>1.81 - 2.87</td>
<td>17.20 - 21.11</td>
<td>19.09 - 23.78</td>
<td>1.05 - 1.39</td>
<td>15</td>
</tr>
<tr>
<td>Stage V sugary</td>
<td>Vein Infill</td>
<td>GF proximal Zn-Pb-Ag subeconomic Cu</td>
<td>ferroan dolomite ankerite</td>
<td>-</td>
<td>48.77 - 50.45</td>
<td>37.77 - 43.23</td>
<td>0.84 - 2.24</td>
<td>5.41 - 10.47</td>
<td>7.21 - 12.40</td>
<td>3.05 - 6.00</td>
<td>20</td>
</tr>
<tr>
<td>Wall rock to</td>
<td>Grey matrix</td>
<td>GF proximal Zn-Pb-Ag subeconomic Cu</td>
<td>ferroan dolomite</td>
<td>-</td>
<td>48.31 - 50</td>
<td>35.8 - 45.26</td>
<td>0.96 - 1.82</td>
<td>4.89 - 13.39</td>
<td>5.85 - 15.01</td>
<td>2.39 - 7.74</td>
<td>9</td>
</tr>
<tr>
<td>Stage III</td>
<td>Vein Infill</td>
<td>GF economic Zn-Pb-Ag subeconomic Cu</td>
<td>calcite</td>
<td>-</td>
<td>94.88 - 98.01</td>
<td>0.95 - 2.72</td>
<td>0 - 1.95</td>
<td>0 - 1.42</td>
<td>0.53 - 2.79</td>
<td>-</td>
<td>24</td>
</tr>
<tr>
<td>Stage III</td>
<td>Vein Infill</td>
<td>GF economic Zn-Pb-Ag subeconomic Cu</td>
<td>ferroan dolomite</td>
<td>-</td>
<td>47.28 - 48.24</td>
<td>44.84 - 47.55</td>
<td>1.09 - 3.52</td>
<td>3.41 - 5.19</td>
<td>4.75 - 6.93</td>
<td>6.47 - 10.01</td>
<td>7</td>
</tr>
<tr>
<td>Stage VIII equ.</td>
<td>Matrix and vein</td>
<td>Hi economic Zn-Pb-Ag subeconomic Cu Valenta (1988)</td>
<td>ferroan dolomite, ankerite, ferroan ankerite, siderite</td>
<td>NA</td>
<td>0.40 - 57.54</td>
<td>9.60 - 37.56</td>
<td>1.20 - 15.32</td>
<td>3.70 - 83.90</td>
<td>0.14 - 7.67</td>
<td>4.90 - 90.00</td>
<td>14</td>
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<tr>
<td>Stage VIII equ.</td>
<td>Matrix</td>
<td>Hi economic Zn-Pb-Ag subeconomic Cu Stage III equ. feldspar Stage VIII equ. phyllosilicate alteration. Tuesley (1993)</td>
<td>ferroan ankerite, siderite</td>
<td>NA</td>
<td>0.41 - 49.81</td>
<td>16.52 - 34.59</td>
<td>1.54 - 12.98</td>
<td>14.06 - 63.22</td>
<td>15.60 - 74.77</td>
<td>0.34 - 2.22</td>
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<tr>
<td>Stage VIII equ.</td>
<td>undifferentiated</td>
<td>Isa silica-dolomite, economic Ca, adjacent Zn-Pb-Ag zones. Waring, 1990</td>
<td>dolomite, ferroan dolomite, ankerite</td>
<td>NA</td>
<td>49.07 - 54.18</td>
<td>26.39 - 48.60</td>
<td>0 - 2.98</td>
<td>1.45 - 19.27</td>
<td>1.36 - 32.65</td>
<td>1.45 - 19.85</td>
<td>50</td>
</tr>
<tr>
<td>Stage VIII equ.</td>
<td>undifferentiated</td>
<td>Isa silica-dolomite, economic Ca, adjacent Zn-Pb-Ag zones. Waring, 1990</td>
<td>siderite-magnesite</td>
<td>-</td>
<td>0.10 - 0.22</td>
<td>78.86 - 80.27</td>
<td>0.89 - 1.38</td>
<td>18.72 - 19.95</td>
<td>19.61 - 21.00</td>
<td>-</td>
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<tr>
<td>Stage VIII equ.</td>
<td>undifferentiated</td>
<td>Isa silica-dolomite, economic Ca, adjacent Zn-Pb-Ag zones. Waring, 1990</td>
<td>Calcite</td>
<td>-</td>
<td>95.68 - 99.25</td>
<td>0.52 - 3.11</td>
<td>0 - 0.64</td>
<td>0 - 1.07</td>
<td>0.18 - 1.53</td>
<td>-</td>
<td>23</td>
</tr>
<tr>
<td>Carbonate Type</td>
<td>Location</td>
<td>Associations</td>
<td>Interpretation</td>
<td></td>
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<tr>
<td>Stage VIII, Dolomite-ankerite-ferroan ankerite-siderite micropar.</td>
<td>Mount Isa, Hilton and George Fisher Zn-Pb ore bodies in subeconomic zones of Cu mineralization</td>
<td>Stage VIII phyllosilicate, magnetite and minor chalcopyrite-pyrrhotite alteration and ferroan ankerite-siderite veining. Absence of Stage I calcite (i.e. nodular dolomite). Accompanied by abundant sugary ferroan dolomite veining.</td>
<td>Syntectonic hydrothermal alteration developed peripheral to economic zones of Cu mineralization i.e. outer alteration zone cf. silica-dolomite.</td>
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Table 4. Summary of carbonate constituents of the Urquhart Shale in the Mount Isa area including mineralogical and vein-associations and genetic interpretation based on this study.
Stage I calcite alteration in mudstones dominant

Stage VIII ferroan dolomite-ankerite-ferroan ankerite alteration dominant: Stage I calcite absent as major constituent of nodular carbonate or layer parallel white bands.

Mixed zones in which host rock ferroan dolomite with minor Stage I calcite is the dominant constituent of mudstones, and nodular carbonate and layer-parallel white carbonate bands consist of either Stage I calcite or Stage VIII ferroan dolomite-ankerite-ferroan ankerite

Interpreted boundary between mixed carbonate zones and zones of pervasive Stage VIII ferroan dolomite-ankerite-ferroan ankerite alteration.

Figure 1. Carbonate distribution patterns presented in Part B (Figs. 1 to 3) simplified and projected onto 12L plan map illustrating the distribution of Zn-Pb and Cu mineralization (unpub. MIM data).
Figure 2. Schematic cross sections at 7180mN illustrating (a) distribution of large-scale pervasive Stage VIII alteration zones and Stage VIII phyllosilicate alteration determined during this study or interpreted from MIM drill logs and compared with the distribution of Zn-Pb mineralization. Interpretation of alteration zone is in part inferred from the distribution of Stage VIII phyllosilicate alteration (cf. Part B). (b) Distribution of Cu mineralization compared with Zn-Pb mineralization (unpub. MIM data). Footwall stratigraphic intervals are characterized by small-scale Stage VIII ferroan carbonate alteration zones and abundant Stage I calcite (cf. fig. 1 and Part B).
Figure 3. Stylized cross-section of Hilton Mine illustrating large-scale distribution of Cu and Zn-Pb mineralization, and ankerite and siderite-rich portions of stratigraphy in otherwise ferroan dolomite-bearing Urquhart Shale. Modified after Suttill, 1990, Tuesley, 1993 and Valenta, 1988.
Figure 4. Simplified northern cross-section of Mount Isa Mine illustrating large-scale distribution of Cu and Zn-Pb mineralization, and nodular dolomite - rich portions of stratigraphy in otherwise ferroan dolomite-bearing Urquhart Shale (after Perkins, 1997).
Figure 5. Ternary diagrams illustrating carbonate compositions from George Fisher and distal Urquhart Shale (refer Table 3).
Figure 6.

a. Abundant Stage OI early dolomite alteration developed in a mudstone includes an array of grains which are zoned from dolomite cores to inner ankerite rims and outer ferroan dolomite rims. The unusually coarse dolomite core to the right itself has an inclusion-rich core which has a rounded shadow grain outline. Ferroan dolomite forms the dominant matrix component in this field of view (BSE image, PTS# 131, HS# DC838, H766ED#1, 564m).

b. Abundant zoned stage OI early dolomite grains exhibit irregular to rhombohedral outlines defined by the zonation of ferroan dolomite to ankerite in outer rims. One grain is characterized by an ankerite core (BSE image, PTS# 131, HS# DC838, H766ED#1, 564m).
Figure 6.

c. High magnification BSE image illustrating systematic zonation of ankerite and ferroan dolomite around an inclusion-rich dolomite core in a shaly banded mudstone. Ankerite and ferroan dolomite are matrix components (PTS# 8, HS#052g, J702WI#5, 113.8m).

d. BSE image illustrating abundance of Stage OI early dolomites in a rhythmically laminated pyritic siltstone. Stage I calcite and K-feldspar alteration and Stage II spheroidal pyrite are also present. Note grain truncation along microstylolitic seams at the base of the image (PTS# 130, HS# DC840a, H766ED#1, 558.0m).
a. BSE image illustrating abundant Stage I calcite alteration (Cal) in a layer-parallel white band and preservation of irregular clots of Stage OI dolomite-ferroan dolomite-ankerite and detrital quartz (Zoned Dol, Qtz) (PTS# 18, HS# 051a, J702WI#5, 111.65m).

b. BSE image illustrating abundant Stage I calcite alteration in a medium-bedded mudstone and preservation of irregular clots of Stage OI dolomite-ferroan dolomite-ankerite and detrital quartz. A bedding-parallel foliation is developed with a preferred orientation defined by elongation of grain aggregates (PTS# 103, HS# 044b, J702WI#5, 45m).
c. BSE image illustrating contact relationships between a nodular calcite layer and rhymically laminated pyritic siltstone. Calcite laths in the nodular band form radiating arrays around spheroidal pyrite grains but the majority of calcite in the band is blocky. The former textural association suggests that a component of nodular calcite formed after the spheroidal pyrite or that the nucleus of calcite growth was susceptible to later spheroidal pyrite alteration. Calcite microbreccias are continuous with nodular bands and microbrecciate core-rim-matrix zonation patterns defined by Stage OI early dolomites (PTS# 14, HS# 050g, J702WI#5, 105.9m).

d. BSE image from the same sample above illustrating ultrafine network of Stage I calcite developed along quartz-Stage OI dolomite grain contacts in a rhythmically laminated pyritic siltstone.
a. Dominant carbonate constituents in a mudstone sampled from the B stratigraphic interval include irregular, subhedral Stage VIII ferroan carbonate matrix which display a systematic zoning from ankerite to ferroan dolomite and rare Stage OI early dolomite grains (BSE image, PTS# 43, HS# 202b, J718W1#3, 237.8m).

b. High magnification BSE image from same sample above illustrating that Stage VIII zoned, ferroan ankerite-ankerite-ferroan dolomite rhombs are relatively coarse grained relative to Stage OI dolomite grains and are accompanied by Stage VIII quartz (Qtz) development.
c. BSE image of a nodular carbonate band which consists of an irregular array of Stage VIII ferroan dolomite and ferroan ankerite. The domain characterized by abundant quartz is interpreted to be relict of a Stage OI early dolomite clast that commonly are preserved in Stage I nodular calcite bands. However, no Stage OI early dolomite or Stage I calcite is preserved in this sample (PTS# 49, HS# 118, J702WD#4, 168.4m).

d. Stage VIII zoned ferroan dolomite-ankerite rhombs are the matrix component in this mudstone. Abundant quartz alteration post-dates the ferroan carbonates (BSE Image, PTS# 121, HS# 256, J718WI#5, 174m).
c. Irregular ferroan ankerite + ferroan dolomite matrix

Qtz
Po
Po
Po

Irregular ferroan ankerite + ferroan dolomite matrix

25μm

d. Ankerite to ferroan dolomite matrix

Qtz
Po
Qtz

Ankerite to ferroan dolomite matrix

Regular zoned rhombs

125μm
Figure 9. Geological map of the Mount Isa area illustrating major structural and stratigraphic elements and the general area from which samples of distal Urquhart Shale examined during this study were collected (after Blake, 1987, Valenta, 1988, Painter and Neudert, 1994).
Figure 10.

a. Dominant carbonate constituents in a mudstone (distal to mineralization) include ferroan dolomite matrix which envelopes very fine-grained carbonate grains which have subhombic dolomite cores and poorly defined ferroan dolomite rims. Abundant coarse calcite occurs as an alteration of ferroan dolomite matrix (BSE Image, PTS# MPC2a, HS# MPC, Zw295, 822.2m).

b. Zoned, subhedral and euhedral, dolomite-ferroan dolomite grains enveloped by ferroan dolomite matrix and replaced by calcite (BSE Image, PTS# MPC1a, HS# MPC, Zw295, 822.2m).
Figure 11. Plots illustrating variation in carbonate compositions of Stage I early dolomites from a number settings at George Fisher and examples of carbonate constituents of Urquhart Shale distal to Mount Isa Mine.
Figure 12. Plots illustrating variation in carbonate compositions of Stage I calcites at George Fisher and Urquhart Shale distal to Mount Isa Mine.
Figure 13. Plots illustrating variation in composition of Stage VIII ferroan carbonates at George Fisher.
Figure 14. Plots illustrating variation in carbonate compositions of Stage OI early dolomites, Stage I calcites (b. only), Stage VIII ferroan carbonates and Stage III and V carbonate vein infill. Refer to the legend on Figure 13 for the key to Stage VIII ferroan carbonate symbols.

SYNDIAGENTIC CARBONATES
- Stage OI dolomite - GF
- Stage I calcite - GF
- Stage OI dolomite - distal
- Stage I calcite - distal

VEIN INFILL
- Stage III dolomite vein infill
- Stage III calcite vein infill
- Stage V Sugary dolomite vein infill
- Dolomite in wall rock to Stage V veins

**a. George Fisher Carbonates**
- Stage I Early Dolomite
- Stage I Calcite alteration
- Stage VIII ferroan carbonate alteration
- Stage VIII ferroan carbonate vein infill

**b. Hilton and Mount Isa Carbonates**
- Hilton Stage VIII Ferroan Carbonate equ.: alteration and infill 1.
- Mount Isa Silica-dolomite: Dolomite alteration and infill 2.
- Mount Isa Silica-dolomite: Calcite vein infill and alteration 2.
- Mount Isa Silica-dolomite: Magnesite alteration 2.
- Mount Isa: Zn-Pb host rock carbonates 3.
Figure 16. Plots illustrating variation in carbonate compositions of Stage OI early dolomites, Stage III and V dolomite vein infill and Stage VIII ferroan carbonates from George Fisher with Stage VIIIequ. Hilton carbonates, and distal and Cu-related carbonates at Mount Isa.
Figure 17. δ¹⁸O and δ¹³C variation relative to stratigraphic position.
Figure 18. Plots of depth versus δ¹³C %oPDB and δ¹⁸O %oSMOW superimposed against a simplified stratigraphic column, for carbonates sampled from the I stratigraphic interval.
Figure 19. Plots of depth versus $\delta^{13}C\%_{PDB}$ and $\delta^{18}O\%_{SMOW}$ superimposed against a simplified stratigraphic column, for carbonates sampled from the C stratigraphic interval.
GF South - I stratigraphic sequence
- Mudstone-hosted, whole rock Stage OI ferroan dolomite
- Stage I calcite from nodular layers
- Mudstone-hosted Stage I calcite

GF North - C stratigraphic sequence
- Mudstone-hosted, whole rock Stage OI ferroan dolomite
- Stage I calcite from nodular layers

GF South - Ankerite alteration
+ Mudstone-hosted whole rock Stage VIII Ferroan carbonate
X Whole rock Stage VIII ferroan carbonate from nodular layers

GF South - Carbonate veins
X Stage V sugary dolomite veins
- Ferroan dolomite from Stage IXa vein, also containing Cpy-Sp-Gn-Po-Py infill.

Figure 20. Plot illustrating δ¹³C versus δ¹⁸O for carbonates from George Fisher.
Legend for Figure 21.

GF South - I stratigraphic sequence
- Mudstone-hosted Stage I whole rock ferroan dolomite
- Mudstone-hosted Stage I calcite
- Stage I calcite from nodular layers
- Stage I calcite from white bands

GF North - C stratigraphic sequence
- Mudstone-hosted Stage I whole rock ferroan dolomite
- Stage I calcite from nodular layers
- Stage I calcite from white bands

GF South - Stage VIII Ankerite alteration
- Mudstone-hosted Stage VIII whole rock ferroan carbonate
- Whole rock Stage VIII ferroan carbonate from nodular layers

GF South - carbonate vein infill
+ Stage V sugary ferroan dolomite vein infill
○ Ferroan dolomite from Stage IXa vein, also containing Sp-Gn-Po-Py-Cpy infill.

Hilton Mine and Lake Moondarra carbonates
- Whole rock shale-hosted dolomite from the Lake Moondarra area (Waring, 1990)
- Carbonate infill sampled from an early bedding parallel vein (Valenta, 1988)
- Hilton Mine Cu-related vein-filling and whole rock carbonates (Valenta, 1988)

Carbonate Populations
Field 1. Mount Isa; late-stage dolomite alteration associated with subecononic Cu drillhole intersections 2km south of the mine (Waring, 1990).
Field 2. Mount Isa; late-stage dolomite alteration from the 1100 Cu orebody at 4200mN (Waring, 1990).
Field 3. Mount Isa; late-stage dolomite alteration from the 1100 Cu orebody at 5030mN (Heinrich et al., 1989).
Field 4. Mount Isa; late-stage dolomite alteration from the 650 Cu orebody (Heinrich et al., 1989).
Field 5. Mount Isa; Urquhart Shale distal to 1100 Cu orebody at 4200mN (Waring, 1990).
Field 6. Mount Isa; Urquhart Shale proximal to 1100 Cu orebody at 5030mN (Heinrich et al., 1989).
Field 7. Mount Isa; Urquhart Shale proximal to 1100 Cu orebody at 4200mN (Waring, 1990).
Field 8. Mount Isa; Urquhart Shale adjacent to subeconomic Cu drillhole intersections 2km south of Mount Isa Mine (Waring, 1990).
Field 9. Mount Isa; Urquhart Shale samples located furthest away from Cu intersections south of Mine (Waring, 1990).
Field 11. George Fisher deposit; Stage V vein-filling ferroan dolomite, Stage VIII whole rock ferroan carbonate alteration and Stage IXa vein-filling ferroan dolomite.
Field 12. George Fisher deposit - north; Stage I whole rock ferroan dolomite and Stage I calcite.
Field 13. George Fisher deposit - south; Stage I whole rock ferroan dolomite and Stage I calcite.
Field 14. Lake Moondarra; Whole rock shale-hosted dolomite (Waring, 1990).
Figure 21. Plots illustrating carbon (PDB) versus oxygen (SMOW) isotope compositions for carbonates from the George Fisher deposit compared with data previously collected at Mount Isa Mine (Heinrich et al., 1989, Waring, 1990a), Hilton Mine (Valenta, 1988) and Lake Moondarra (Waring, 1990a). Data points for George Fisher, Hilton and Lake Moondarra samples are illustrated in (a), whilst fields defined by proposed carbonate populations for the Mount Isa mineralization system as a whole are presented in (b). Carbon and oxygen isotope compositions for carbonates at George Fisher overlap with Cu-related carbonate populations at Mount Isa Mine and Hilton Mine and define a new niche of values not previously identified in the Mount Isa mineralization system. Approximate fluid/rock isotope exchange lines for Cu-bearing fluids (after Waring, 1990a) and early carbonates associated with Zn-Pb-Ag mineralization at George Fisher are also illustrated.
Interbedded rhythmically laminated pyritic siltstones and banded mudstone, nodular carbonate bands common, rare shale.

- Banded mudstone
- Medium-bedded, stylolitic mudstone
- Stratigraphic interval

**Figure 22a.** Simplified stratigraphic column illustrating the distribution of major rock types, nodular carbonate banding, economic sulphides and alteration assemblages at George Fisher.
Interbedded rhythmically laminated pyritic siltstones, banded mudstone and shale, rare nodular carbonate.

Interbedded rhythmically laminated pyritic siltstones, banded mudstone and shale, nodular carbonate bands common.

Interbedded rhythmically laminated pyritic siltstones, and banded mudstone, nodular carbonate bands common, rare shale.

Banded mudstone

Medium-bedded, stylolitic mudstone

Figure 22b. Simplified stratigraphic column illustrating the distribution of major rock types and nodular carbonate banding, and distribution of economic sulphides and alteration assemblages at Hilton Mine. A generalized comparison with George Fisher is also included (adapted from unpub. MIM Ltd data, Tuesley (1993), Valenta (1988) and Perkins and Bell (1998)).
Figure 22c. Simplified metal and alteration distribution patterns at Mount Isa (adapted from Stanton, 1963, Waring, 1990, Swager, et al., 1987, and Perkins, 1997). Refer to Fig. 23b for legend.