Sponsors Meeting - Presentations

P544 - Proterozoic Sediment Hosted Copper Deposits

December 2002

Centre for Ore Deposit Research –
University of Tasmania
Colorado School of Mines
P544 – Proterozoic Sediment-hosted Copper Deposits

Progress Meeting

10 December 2002, CODES, University of Tasmania

This meeting repeats of presentations made at Colorado School of Mines, 1 November 2002, with addenda from Wallace Mackay and Mawson Croaker

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David Selley, Mawson Croaker, Robert Scott & Stuart Bull
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David Broughton
Murray Hitzman
Robert Scott
AMIRA P544 Meeting
Golden, CO
1 November 2002

Proterozoic sediment-hosted copper deposits

Project Aims

"to compare and contrast Proterozoic sediment-hosted copper deposits in Australia and Zambia"

- Study Areas: Zambian Copperbelt, South Australian Neoproterozoic sequences, Paterson Orogen in WA
- formal Research Collaboration CODES, CSIRO (AMIRA & ARC funding - SPIRT/Linkage Scheme)
- complementary UWA CGM geochronology (separate ARC Discovery grant funding)
**Personnel**

- David Selley, Peter McGoldrick, Stuart Bull, Rob Scott,
  David Cooke, Ross Large, Wallace Mackey, Nicky Pollington, Mawson Croaker
- Murray Hitzman, David Broughton
- (Galvin Dawson, Neal McNaughton)

**Timing & progress to date**

- July 2000 to December 2000 start-up with AMIRA funding only
- First progress meeting and report in Perth, December 2000
- 2001 first full year at full funding (ARC & AMIRA)
- Second progress meeting and field trip in Zambia, June 2001
- Major progress report dated December 2001 covering CODES work for 2001 was circulated to sponsors in March 2002
- Third progress meeting and field trip was held in South Australia in May 2002
Timing & progress to date (con)

- CSM did not attend May meeting, but two reports from David Broughton were presented on his behalf by Rob Scott, and circulated to sponsors in July
- Field guide and Powerpoint presentations from the May meeting circulated to sponsors in August
- Fourth progress meeting in Golden, November 2002
- Final sponsors meeting in Hobart in August 2003

NB: All reports and Powerpoint presentations are available from secure AMIRA web site

PhDs

David Broughton (CSM) commenced August 2000:
Regional stratigraphic architecture of the Katangan sequences, ZCB

- Wallace Mackey (CODES) commenced February 2001:
Sedimentology, structure and geochemistry of the Callanna Group, north Flinders Ranges, SA

- Nicky Pollington (CODES) commenced June 2001:
Sedimentology and geochemistry of the Konkoia North deposit

- Mawson Croaker PhD (CODES) commenced August 2001
Aspects of the geology of the Nkana ore system
**South Australia**

Focus on two key stratigraphic associations:

- Umberatana Group hosted Cu mineralisation e.g., Stuart Shelf deposits and widespread minor Cu elsewhere in the AFB
- Callanna Group (Curdimurka Subgroup) basal level of the AFB sequence and tectonostratigraphic equivalent of Roan sequences

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**Western Australia**

Paterson Orogen/ Yeneena Basin

**Aims**

- use potential field and EM data sets to develop a better structural/stratigraphic framework
- place recent deposit-related PhD studies into this context
Zambia

Copperbelt stratigraphy/basin architecture
- regional - Kalwe Anicline
- Chambishi Basin
  - basement topography
  - (growth faults)
  - ore sitting

Copperbelt deformation history
- structural history of Katangan of Muva & Lutuubu
- thrust at top of Mwasha

Katangan chemistry, isotopes & mineralogy
- orebody specific studies
- stratigraphic studies
- alteration
- fluid sources, fluid chemistry

Meeting Format

am
- Introduction
- Zambian geochemistry
- Zambian geochronology
- (Callanna Gp PhD; Patterson review)

- Chambishi basin deposits
- ZCB regional stratigraphy
- Review & synthesis
Principle Areas of Study

Aims of P544

To understand the processes responsible for transporting, concentrating and fixing Cu and other ore constituents during sedimentary basin evolution.

To document the various stages and paragenesis of copper deposition and remobilisation during basin evolution.

To develop a range of geological, geochemical and isotopic vectors that point toward ore, both on a district and a deposit scale.
Aims of P544 (con)

To determine what is different about the setting and geological evolution of the African Copperbelt, compared to Australian Proterozoic sedimentary basins, that may explain the difference in Cu (and Co) endowment in these areas.

To apply research results from both Africa and Australia to produce better empirical exploration models for Proterozoic sediment-hosted Cu deposits.

Some Key Questions

- Is there a spectrum of deposits related to basin history from early stratabound Cu (cpy-cc) formed during diagenesis (up to the earliest stages of basin inversion?), to late structurally controlled Cu (cpy only) formed during metamorphism – deformation?

- Are the different types of deposits geochemically distinct, and can their geochemical and isotopic signatures be used to design vectors to hidden deposits?

- What are the chemical and thermal characteristics of ore fluids related to each type of Cu deposit?
Some Key Questions (con)

- what are the regional and local factors that control deposit size and ore grade?
- can a basin host one style of deposit and not the others, and what are the conditions for this?
- at the basin scale, is there any metal zoning (Cu, Co, Ag, Au, Pb, Zn)?
- how do the sites favourable for Cu mineralisation change in terms of structural style and/or stratigraphic position and/or redox state, during basin evolution?

Key findings: this meeting

Argillite-hosted deposits:
- Cu, Co, Ag, Bi and Au (?Mo) are ‘ore-association’ elements
- As, Sb, Ni, Po, TI and Zn are at levels ≤ or ‘average shale’
- U possibly forms a broad halo
- only Co is present at anomalous levels in both unmineralised and barren-gap samples
- Cu, Co, U, Au (?and Bi & Mo) are an ‘oxidised’ fluid signature
- low organic C in some deposits (e.g., Konkola)
- variable Au tenor
**Key findings: this meeting (con)**

**Konkola North:**
- Many ‘Ore Shale’ samples are oxidised, i.e. high-Cu but low-S (supergene)
- Cu, Co, Bi, U, Mo, Ag and Au remain high in oxidised samples
- Secondary Mn oxides and phosphates host Cu and trace elements in some oxidised samples

**Roan Chemostratigraphy:**
- Upper Roan siliciclastics are K₂O-rich & K₂O/Al₂O₃ increases systematically toward ore in h/w rocks (vector?)
- (may be) a slight increase of Co & Zn towards Ore Shale in DDH RCB2
- C/O isotopes show a wide spread but both become lighter toward the Ore Shale position
- Carbonates from Ikana/Mindola ores have the lightest C & O isotope signature
- Hence C & O isotopes may be vectors to ore
Key findings: this meeting (con)

Geochronology
- All xenotime ages (so far) are consistent with all mineralisation being epigenetic.
- Ages record protracted or episodic synorogenic fluid flow between 615 Ma and 410 Ma.

Key findings: this meeting (con)

Chambishi basin deposit studies:
- Position of Cu mineralisation in Chambishi Basin is strongly influenced by “footwall succession” rift architecture.
- Fluid flow responsible for mineralisation was directed principally through permeable (coarse-grained) “footwall” strata.
- Transfer systems or fault intersections provide optimum sites for Cu mineralisation.
- Change in basin configuration at Ore Shale times provides transgressive seal to underlying basin compartments.
Key findings: this meeting (con)

ZCB regional stratigraphy:
- the Lower Roan sequences have a recognisable coherent stratigraphy
- master faults controlling LR sedimentation can be recognised (at a regional scale)
- for the Upper Roan stratigraphic thicknesses are highly variable and simple 'layer-cake' stratigraphy doesn't apply
- there is a structural break at the contact between the Upper Roan and the Mwashia, and a simpler stratigraphic architecture pertains for the Katangan above this break

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Diagram showing geological strata and ages.
Geological development and mineralisation
Yeneena Basin – Paterson Orogen, W.A.

Robert Scott
Centre for Ore Deposit Research

Paterson Orogen
- Paterson Orogen: 1200 km long SE-trending belt of Palaeo- to Neoproterozoic rocks at the eastern margin of the Pilbara Craton, central Western Australia
Paterson Orogen

- Paterson Orogen consists of three main elements:
  - Rudall Complex (Palaeo- to Mesoproterozoic, >2015–1765 Ma)
  - Yeneena Supergroup (Neoproterozoic, <1250–818 Ma)
  - Tarcunyah Group (Neoproterozoic, <700 Ma)

- As a whole, orogen is moderately to strongly deformed, poorly exposed, and — with the exception of several mineral deposits — poorly studied
  - as a result, age constraints and relationships between many of the between major lithostratigraphic units (particularly within the Yeneena Supergroup) are poor.

Background to Study

- Neoproterozoic sedimentary rocks of the Yeneena Basin, within the Paterson Orogen, host the giant Telfer Au-Ag deposit, stratabound copper deposits (e.g. Nifty) and carbonate-replacement Zn-Pb deposits (Warrabarty)

- The age, setting, structural evolution and mineral endowment of the Yeneena Basin all invite comparisons with the Zambian Copperbelt

- Apart from Geological Survey of Western Australia 1:100,000 mapping and reports and PhD, MSc and Honours studies of major mineral deposits, the region has received little study, and many aspects of the geological development are not well understood.
Aims

- Provide synthesis of geological development of Paterson Orogen based on:
  - review of previous (largely deposit-based) studies
  - recent 1:100,000 mapping by Geological Survey of Western Australia
  - interpretation of available potential field data (magnetics, gravity, EM)
- Develop model(s) for the formation and subsequent inversion of the Yeneena Basin
- Evaluate origin, timing and distribution known mineralisation in terms of geological development of the Yeneena Basin
- Compare with Zambian Copperbelt

This Presentation

- Synthesis and analysis of Paterson Orogen geophysical data is ongoing
- This report presents
  - overview of the geological development of the Paterson Orogen based on review of existing literature, and observations by the author during a 2 week field visit in October 2001
  - review of models for stratabound copper deposits in the Yeneena basin and comparisons with the Zambian Copperbelt
  - delineation of critical problems to be addressed by this study
Regional Geology

- Simplified geology of the Paterson Orogen showing location of major mineral deposits

Temporral Evolution of Paterson Orogen

- Diagram showing geological events and stratigraphic units
- Key events:
  - D1 (peak metam.) 2015 Ma
  - D2 (peak metam.) 1750 Ma
  - Late Yarragoochean Orogeny (955 Ma)
  - Early Yarragoochean Orogeny (1010 Ma)
  - Pan-African Orogen (900-490 Ma)
  - Tonian Orogen (1.8-1.6 Ga)
  - Pre-Ordovician Orogen (1.8-1.6 Ga)
  - Pan-African Orogen (900-490 Ma)
  - Tonian Orogen (1.8-1.6 Ga)
  - Pre-Ordovician Orogen (1.8-1.6 Ga)
Metal Endowment

- **Telfer (Au-Cu)** *Mulu Formation, Lamil Group*
  - >175 t (5.6 Moz) Au prior to closure in 2000
  - Recent reappraisal identified resource of 19 Moz Au (based on $A 500/oz) and 740,000 t Cu
- **Nifty (Cu)** *Broachurst Formation, Throssell Group*
  - Total resource 148 Mt @ 1.3% Cu
  - Includes chalcopyrite resource 110 Mt @ 1.4% Cu, leachable reserve 27.6 Mt @ 1.1% Cu
- **Maroochydore** *Broachurst Formation, Throssell Group*
  - 140 Mt @ 0.5% Cu, including 51.3 Mt @ 1.0% Cu, 0.04% Co
- **Warrabarty (Zn-Pb)** *Broachurst Formation, Throssell Group*
  - Sub-economic
- **Kintyre (U)** *Yandagooge Formation, Rudall Complex*
  - 35,000 t U₂O₈ @ 1.5–4.0 kg U₂O₈ per tonne

Rudall Complex

- The Palaeo- to Mesoproterozoic Rudall complex broad zone of imbricate thrust sheets (younger to east)
- Major thrusts separate three main tectono-stratigraphic elements:
  - Talbot, Connaughton and Tabletop Terranes
- Oldest rocks of the complex underwent two episodes of folding, faulting and fabric development (2000–1760 Ma Yapungku Orogeny), prior to deposition of unconformably overlying Yeneena Supergroup
- Peak amphibolite- (–granulite) facies metamorphic conditions during D₂ (1790–1760 Ma)
Tectono-stratigraphic elements of the Rudall Complex

- **Talbot Terrane**
  - siliciclastic sedimentary rocks (paragneiss) and granitoids (orthogneiss) metamorphosed to intermediate-pressure amphibolite facies

- **Connaughton Terrane**
  - mafic schist and gneiss, chert, carbonates, pelite and BIF metamorphosed to high-pressure amphibolite- (granulite) facies

- **Tabletop Terrane (potentially exotic)**
  - granitoids, diorite dykes and (?) felsic volcanic rocks dated at ~1300 Ma

Constraints on deformation and metamorphism in Rudall Complex

- Two generations of orthogneiss form ~50% of Rudall complex. Younger series 1787–1765 Ma (illustrated) contain S2 fabric but not S1. The gneisses were refolded and locally retrogressed during the post-Yeneena Supergroup Miles Orogeny.
Yeneena Supergroup

- Yeneena Basin interpreted as either pull-apart basin formed during strike-slip faulting or a failed rift
- The Yeneena Basin succession unconformably overlies the Rudall complex and is divided into two groups:
  - Throssell Group (exposed in the west and south) and
  - Lamil Group (exposed in the east)
- Contacts between the groups are not exposed and while the Lamil Group is considered younger, stratigraphic relations have not been reliably established. The successions may be, at least in part, temporally equivalent (Bagas, pers. comm. 2002).

Yeneena Supergroup (Throssell Group)

- Coolbro Sandstone
  - Basal unit of Throssell Group
  - Unconformably overlies Rudall Complex
  - Qtz-rich sandstone with lesser siltstone and shale; locally developed basal polymict conglomerate
  - Thins against basin edge in S and SE, N- to NE-directed palaeocurrents

Hickman & Clarke, 1994
Hickman & Bagas, 1998
Yeneena Supergroup (Throssell Group)

- Broadhurst Formation
  - conformably overlies Coolbro Sst.
  - main host to mineral deposits
  - carbonaceous, graphitic and sulfuric shale, minor sandstone and dolomite
  - records rapid subsidence of Yeneena Basin

View west along Nifty Pit. Steeply S-dipping dolomite and graphitic shales of the Broadhurst Formation

Yeneena Supergroup (Lamil Group)

- Contact with Throssell Group not exposed
  - stratigraphic relationship unresolved, potentially exotic
- Age constraints:
  - younger than 1070 Ma detrital zircons
  - older than post orogenic 678±12 Ma Mt Crofton Granite
- Sandstone–shale–carbonate succession

Main Dome at Teller, prior to commencement of mining in the mid 1970s. Photo Newcrest Mining.
Tarcunyah Group

- Initial deposition within the Savory Sub-basin of the Officer Basin
- Extensive development along western margin of the Paterson Orogen

Canning Basin (Permian)

- Permian fluvio-glacial strata (Paterson Formation) of the Canning Basin succession cover much of the Paterson Orogen
- Thickest sequences deposited in N-directed palaeovalleys
  - deep palaeovalley between regions of outcropping Throssell and Rama Groups, consistent with possible underlying crustal weakness (i.e., northern continuation of Canel–Tabletop fault zone)
Stratabound copper deposits within the Yeneena Basin

- Two major deposits known
  - Nifty (operating mine)
  - Maroochydore (140 Mt low grade resource)
- Recent PhD studies of Nifty (Anderson, 1999) and Maroochydore (Reed, 1996) indicate
  - deposits hosted by similar successions of interbedded carbonaceous, pyritic and dolomitic shale and dolostone within the upper Broadhurst Formation (~1500 m above Coolbro Sandstone)
  - copper mineralisation synchronous with second phase of deformation (D₂) affecting the Throssell Group (i.e. main phase of basin inversion during Miles Orogeny, regional D₄)
  - 717±5 Ma ⁴⁰Ar/³⁹Ar apparent age for phlogopite associated with chalcopyrite mineralisation at Maroochydore

Syn-deformational mineralisation

- chalcopyrite
  - partial replacement of individual beds, particularly those having undergone bedding-parallel shear
  - rims and replaces diagenetic frambooidal pyrite
  - occurs within the hinges of D₂ folds, along the associated cleavage and faults and within syn-D₂ pressure shadows and cleavage parallel veins

Maroochydore
YNC-82, 144 m

Nifty
THRD 790 W1
388–396 m
Mineralisation styles

- Marocchydore
  - chalcopyrite predominantly disseminated or precipitated in dilational sites

- Nifty
  - massive chalcopyrite replacive, associated with intense quartz-dolomite alteration
  - lesser disseminated and vein-hosted mineralisation

Mineralisation styles

- late-stage massive and breccia matrix chalcopyrite mineralisation at Nifty
Deposit comparisons

- Fluid inclusions
  - Inclusions from syn-mineralisation veins at Maroochydore and Nitty have similar salinities (8–27 eq. wt % NaCl), homogenisation temperatures (160°–450°C) and estimated trapping temperatures (median values: 360°–440°C), consistent with epigenetic mineralisation at greenschist facies metamorphic conditions.

- Sulfur isotopes
  - (i) diagenetic framboidal and (ii) pre- to syn-mineral euhedral pyrite:
    - (i) δ^{34}S +16 to −27 ‰, (ii) δ^{34}S +3.8 to −12 ‰ (Nitty)
    - (i) δ^{34}S −22 to −31 ‰, (ii) δ^{34}S −4.0 to −10 ‰ (Maroochydore)
  - Chalcopyrite:
    - δ^{34}S +6 to −9 ‰ (Nitty)
    - δ^{34}S −13 to −23 ‰ (e.g., Maroochydore)
    - δ^{34}S −25 to −31 ‰ (e.g., Maroochydore)

Mineralisation models

- At Maroochydore Reed (1996) argues
  - Cu transported as chloride complex
  - Local heterogeneous sulfur source (diagenetic pyrite and sulfate) for syn-D_{v2} epigenetic copper mineralisation
  - Syn-mineralising fluid infiltration by a combination of distributed structurally-enhanced permeability and intergranular flow, with no evidence for significant fluid focussing at the site of deposition
  - Cu deposition due to increased H_{2}S activity and decreased O_{2} due to interaction between Cu-bearing fluid and sulfide sediments

- At Nitty, Anderson (1999) argues
  - Homogeneous sulfur source for chalcopyrite and coeval (euhedral) pyrite
  - H_{2}S dominant in the fluid phase not sourced from host rocks
  - Syn-D_{v2} mineralisation with fluids ascending thrusts interpreted to intersect the hinge and north limb of the Nitty Syncline
Mineralisation models - Nifty

- Subsequent drilling at Nifty does not support existence of thrust faults postulated by Anderson (1996).
- Gross geometry of mineralisation and associated alteration halo (particularly Pb-Zn-enriched Pyrite Marker bed) suggests initial stages of deposit formation prior to, or during the earliest stages of D2 foliation.
- Lateral rather than vertical fluid flow implied.

Yeneena Basin vs. Copperbelt

- Although stratabound Cu mineralisation in both areas may be largely epigenetic (formed during the early(?)) stages of inversion in their respective basins), the Yeneena Basin deposits appear to have only the most superficial similarities to those in the Zambian Copperbelt.
- Strong silica-dolomite alteration and predominance breccia-fill, vein and replacement style mineralisation at Nifty suggests greater affinities with Mount Isa Cu ore bodies.
Critical Questions to be addressed

- Ongoing studies of the Yeneena Basin / Paterson Orogen will focus on a number of key issues:
  - Determining the original architecture of the Yeneena Basin and how this influenced structural geometry during subsequent basin inversion (Miles Orogeny);
  - Evaluate distribution, timing and character of deposits in terms of their regional stratigraphic and structural context. Implications for patterns of fluid flow during basin inversion.

Critical Questions

- A critical aspect to be addressed in reconstructing the Yeneena Basin is the relationship between the Lamil and Throssell groups:
  - Does Lamil overlie Throssell?
  - Correlative sequences deposited in different parts of Yeneena Basin?
  - Were these groups deposited in separate terranes juxtaposed in the Miles Orogeny across the northern continuation of Camel–Tabletop fault zone, i.e. the fault system separating the easternmost and potentially exotic Connaughton terrane from the rest of the Rudall complex (Bagas & Smithies, 1998)
Acknowledgments

- Bruce Hooper, Ivan Jerkovic, Phil Shields (Straits Resources)
- Rio Tinto Exploration
- Leon Bagas (Geological Survey of Western Australia)
- Alistair Reed (Mineral Resources Tasmania)
Structure of the Curdimurka Subgroup, northern Willouran Range, South Australia.

Wallace Mackay

Introduction

- There is a paucity of copper mineralisation within the Adelaide Fold Belt compared with the Copperbelt
- Project is examining the Curdimurka Subgroup
  - Part of the basal package of the Adelaide Fold Belt
  - Known copper mineralisation small and/or low-grade
- By understanding the sedimentology and structure of the Curdimurka Subgroup
  - Test the validity of the comparison
  - Identify areas for exploration
3.2

Location

The Wiluna Range

~ 50 km

Northern Hinders Ranges

Stratigraphy of the Adelaide Foldbelt

- ~ 26 km thick
- 4 basin phases
- ~ 840 Ma to ~ 500 Ma
- 8 basin elements
- Mineralisation
  - Cu
  - Pb/Zn
  - Magnesite
  - Au
Introduction

- Structure of the northern Willouran Range is a complex mixture of folding and faulting
- Evidence for three folding events
  - $F_1$, pre-Delamerian
  - $F_2$, has Delamerian NW-SE trends
  - $F_3$, late Delamerian?
- Evidence for extension at initiation of deposition of the Umberatana Group ($F_2$?)
- Cu mineralisation has a structural control

Geology of the northern Willouran Range
Boorloo Siltstone: Fold Hinge

Right $F_2$ fold in the fold hinge.

Recumbent $F_2$ fold on northwestern limb.
F₁ - Boorloo Siltstone

Fold interference patterns; variations of mushroom pattern
Superposition of non-coaxial upright folding on recumbent folds

F₁ Regionally - Norwest Fault
Dunns Mine; Outcrop 1

- $F_1$ not observed
- $F_2$
  - Upright non-cylindrical folds
  - Trends northwest – southeast
  - Axial plane cleavage
- $F_3$
  - Broad to open folds
  - Moderate plunge to southwest
  - Weak cleavage
Dunns Mine; Outcrop 1

F2 upright, web thickening in the hinges and thinning on limbs

Mineralisation; Dunns Mine

[Diagram showing mineralisation at Dunns Mine]

[Diagram showing mineralisation at Dunns Mine]
Mineralisation Dunn's Mine

Along strike of fault zone, peaking north

Above, Malachite in fault breccia

Left, Malachite in a microvein

Dunn's Mine Summary

- Limb of F3 anticline
- Brecciation to west and south
- Stratigraphic level anomalous Cu (UDC, 1979)
- Cu mineralisation in
  - Black siltstone (no veins)
  - Fault zone
  - Qtz-carb veins
  - Microveins in siltstone
- Cu mineralisation not in
  - Similar veins outside of black siltstone
  - Black siltstone of Rook Tuff
Conclusions

- 3 folding events have affected the Curdimurka Subgroup
  - $F_1$
    - Layer parallel
    - Southeast - directed transport
    - Confined to specific stratigraphic levels
  - $F_2$
    - Dominant regional structure (Delamarian)
    - Upright, non-cylindrical, tight to isoclinal
    - Trend northwest - southeast
  - $F_3$
    - Broad folds
    - Plunge to southwest

Conclusions

- $F_1$ is regional, occurring in the Curdimurka Subgroup along the NW Fault
- Highest grade mineralisation at Dunns Mine is controlled by an $F_2$ structure
Questions:

- are the different Zambian Cu deposits geochemically distinct?
- can we use geochemical and isotopic signatures to design vectors to hidden deposits?
- what implications does the chemistry of the ores have for ore forming and metal transporting processes?
- are there chemical or isotopic signatures that can be used for chem stratigraphic correlations?
Analytical techniques:

- Different sample sets analysed at three different labs for different element groups
- University of Tasmania: XRF major & trace analyses, pyrolysis C
- Becquerel: 'Au+28' procedure (mainly for Au to 5ppb & some REE
- ACME Vancouver: modified 4A/4B 40 element ICP procedure

This meeting

- chalcophile element geochemistry of mineralised and barren argillite ('Ore Shale', 'Ore Formation' etc)
- chemostratigraphy and C/O isotopes in Roan sediments from the Chambishi basin
Zambian Copper Belt Geochemistry: Part II 'Ore Shale' geochemistry

Peter McGoldrick, Mawson Croaker & David Broughton

Questions?

What are the ore-associated (chalcophile) elements?

Are there ore-associated elements present at elevated levels in low-Cu argillites that are indicators of mineralisation (halos)?

What implications does the metal tenor of the 'Ore Shale' mineralisation have for transport and trap processes?

Do the Lower Roan argillites have a chemistry that distinguishes them from other Katangan argillites?
Zambian Copper Belt Geochemistry: 
Part II 'Ore Shale' geochemistry

Peter McGoldrick, Mawson Croaker & 
David Broughton

Questions?
What are the ore-associated (chalcopyrite) elements?
Are there ore-associated elements present at elevated levels in low-Cu argillites that are indicators of mineralisation (halos)?
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Do the Lower Roan argillites have a chemistry that distinguishes them from other Katangan argillites?
Data sets

1. Nkana SOB DDH NS009:
   - 31 mineralised & unmineralised argillites

2. Mindola DDHs MX184 & MX188:
   - 17 mineralised argillites
Nkana SOB

Typical black carbonaceous ore shale from NS009
So parallel to main cleavage
NB Quartz-calcite veins
Geochemistry samples ca. 1m composites

Mindola

Ore Shale lithology from Mindola - dolomitic argillite, argillite, includes So-parallel carbonate veins
Geochemistry samples ca. 1m composites
Nkana: West Limb

'Ore Shale' equivalent from DDHs W30 & W43 through the western limb of the Nkana Syncline

19 samples:
  four with 0.1 to 0.6% Cu, others <0.1% Cu

Konkola

No. 3 shaft u/g samples:
  6 samples

KLB67 Konkola Barren Gap:
  11 samples
Elements

A series of cross-plots comparing chalcophile minor & trace elements with S (and Cu)

Cu, Co, Bi, Ag, Au, Zn, Pb, As, V, Ni, Mo, U & Th
'average shale' = 35 ppm Cu
'black shale' = 70 ppm Cu
'Aussie 'oil' shale' = 110 ppm Cu
'average shale' = 20 ppm Co
'black' shale = 10 ppm Co
Aussie 'oil' shale = 9 ppm Co

ATWA Drilling Group November 1st 2002

'average shale' = ~0.5 ppm Bi

AMRA Field Meeting Boulder November 15, 2002
'average shale' = ~2 ppb Au

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'average shale' = ~2 ppb Au

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[Diagram showing data points and labels: Nkana all 'shales', Mindola, Konkola, Konkola BG]

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[Diagram showing data points and labels: Nkana all 'shales', Mindola, Konkola]
'average shale' = ~100 ppm Zn
Aussie 'oil' shale = ~800 ppm Zn

 Zinc (ppm) vs. S

1 outlier @ 390 ppm Zn

AVERAGE Pb = ~20 ppm Pb
Aussie 'oil' shale = ~20 ppm Pb

 Lead (ppm) vs. S
'average shale' = 0.7 ppm Mo
'black' shale = 10 ppm Mo
Aussie 'oil' shale = 270 ppm Mo

'average shale' = 2.5 ppm U
Aussie 'oil' shale = 36 ppm U
**Thallium**

All samples analysed by XRF were below detection limit (~1 ppm)

Samples analysed by ICP-MS were 0.1 to ~1 ppm

Ave. shale ~1 ppm

**Organic Carbon**

Limited number of analyses to date:
- 4 Nkana mill feed samples
- 7 Mufulira samples
- 6 Konkola u/g samples
Organic Carbon (cont)

Nkana:
- total carbon 4.1 - 4.6 wt % ave: 4.2
- organic carbon 0.2 - 1.1 wt % ave: 0.7

Mfulira:
- total carbon 0.2 - 2.7 wt % ave: 1.1
- organic carbon 0.0 - 1.1 wt % ave: 0.4

Kokola:
- total carbon 0.0 - 1.8 wt % ave: 0.6
- organic carbon 0.0 - 0.2 wt % ave: 0.1

Conclusions I

- Cu, Co, Ag, Bi and Au (?Mo) are 'ore-association' elements:
  cf 'average shale':
  Cu = 100 to 1000x, Ag = ?100, Co = 50, Bi = ?20, Au = 1 to 10
- U is anomalous in ?distal' samples at Nkana and may also be an
  'ore-association' element (=broad halo)
- As, Sb, Ni, Pb, Tl and Zn in mineralised argillines are at levels
  < or = 'average shales'
- Of the 'ore-association' elements only Co is present at
  anomalous levels in both unmineralised and barren-gap samples
- Some black 'Ore Shales' are devoid of organic C
Conclusions II

- Cu, Co, U, Au (?and Bi & Mo) are an 'oxidised' fluid signature
- low Tl is consistent with an oxidised ore fluid
- low organic C in some deposits (e.g., Konkola) may indicate all reductant was exhausted during ore precipitation
- variable Au tenor has implications for Au transport and ore-formation
Zambian Copper Belt Geochemistry: Part IIa Konkola North

Nicky Pollington, Peter McGoldrick & David Selley
CODES

Konkola North with Geochemical Sample Locations
Simplified Geology for Kn6

- Mwashia - fine dark silts
- Shale with Grit - fine dark silt with oltz and tspar grit
- Kondaia Conglomerate
  - "Upper Ore Zone" - dark silt with common py - cpy
  - Mixed Sequence - silt, sand, conglomerate
- Arkois sandstone - conglomerate
  - OS2 - mixed dark silt and sand
  - "Ore Shale"
- Kafufye - sandstones and conglomerates

Argillite Geochemistry

- Database of over 150 multi element analyses has been compiled
- Chalcophile elements investigated for this presentation
  - Cu, Co, Bi, Ag, Au, Zn, Pb, As, V, Ni, Mo, U, Th
- Downhole variations from Mwashia to Footwall
- Downhole variations within the Ore Shale
- Comparison to "Average Shale"
Lithogeochemistry of Ore Horizon in Kn6

- Shale with 6F1F
- Karikolo Conglomerate "Upper Ore Zone"
- Mixed Sequence
- A-Hose QG2 "Ore Shale" Kefultya

Ore Shale Downhole Variation

- S content variable within the ore shale
- Supergene minerals such as Mal common on contacts with footwall and hangwall
- Commonly elevated Cu and reduced S at base where in contact with the footwall equifer
- Elevated V appears to follow same pattern - related to same supergene effects (?)
Ore Shale Downhole variation - Far South

- MnO and P2O5 enriched in southern zone.

Chalcophile Elements Normalised to "Average Shale"

- Sulphide Mineralised Ore Shale
  - Ag, Au, Cu, Co, Mo, Bi, V, U,
  - Ni, As, Pb, Sb, Zn

- Oxidised Ore Shale
  - Ag, Au, Cu, Co, Mo, Bi, V, U,
  - Ni, As, Pb, Sb, Zn

- Unmineralised Ore Shale
  - Au, Co, Mo, Bi, V, U,
  - As, Ni, Pb, Sb, Zn

Mwasha
Summary

- Co, Au, Ag, Bi, U, Mo are associated with mineralising fluid
- Ore Shale
  - enriched in Ag, Au, Cu, Co, Mo, Bi, V, U
  - Depleted in Ni, Pb, Sb, Zn
- Mild to intense supergene overprint complicates the
  geochemistry of the ore shale and detailed petrography is
  required before further data interpretation
- Supergene effects
  - Depletion of S and enrichment of Cu (V?)
  - Local development of MnO, PbO5 (+ Cu and Co)
Zambian Copper Belt Geochemistry:
Part III: Preliminary assessment of
chemostratigraphy and alteration geochemistry

Ross Large, Peter McGoldrick &
Mawson Croaker

Chemostratigraphy tested in two
Chambishi basin drill holes:
RCB1A and RCB2
**Ti - Zr patterns**

- Ore Shale commonly has a tight distribution: Ti/Zr = 22-26, Ti < 0.8wt%, Zr < 200ppm
- Upper Roan siliciclastics are more variable: Ti/Zr = 12-38, two distributions are suggested by the data, Ti/Zr ~ 18 and 35
- Mwashia shales are more Ti-rich than Ore Shales, with Ti/Zr = 30 to 36

---

**Lithogeochemistry of Upper Roan in RCB2**

**Carbonate content**
**RCB2: Carbonate Variation**

- Data set split into two groups:
  - Siliciclastics, LOI < 20 wt%
  - Carbonates, LOI > 20 wt%
- Carbonate content increases systematically up stratigraphy through the Upper Roan above the Ore Shale.

**Lithogeochemistry of Upper Roan in RCB2**

**Ti/Zr variation**
**Ti - Zr patterns**

- Immobile elements in carbonates are erratic - only use shales for lithostratigraphic correlations

**Lithogeochemistry of Upper Roan in RCB2**

**Na₂O variation**
RCB2: Na$_2$O

- Upper Roan siliciclastics average around 1.8 wt% Na$_2$O
- This equates to ~15 wt% albite in siliciclastics
- Discrete zones of albite alteration contain 5-7 wt% Na$_2$O (45-60 wt% albite)
- Carbonates commonly contain < 0.1 wt% Na$_2$O, except for a zone of albite-rich carbonates at 530-640m in RCB2
Lithogeochemistry of Upper Roan in RCB2

$K_2O$ variation

RCB2: $K_2O$

- Upper Roan siliclastics vary from 2.5 to 8 wt.% $K_2O$ (mean: 4.2 wt.%)
- This compares to a world average for shales of 3.2 wt.%
- Carbonates contain low $K_2O$: 0.1 to 2 wt.%
- There appears to be an increase in $K_2O$ toward the ore shale in the HW siliclastics
- The HW enrichment in $K_2O$ (4-8wt.%) is anomalous - could it be due to alteration?
Variation of Cu, Zn and Co in HW

- There is no Cu halo in hangingwall sediments to ore shale.
- Zn and Co show a gradual increase toward the Lower Roan contact
- Additional studies required to test these variations

Possible HW vectors to ore

- \( K_2O/Al_2O_3 \) ratio in siliciclastics
- Zn in siliciclastics
- Co in siliciclastics
Lithogeochemistry of Upper Roan in RCB1A

Ti/Zr variation
**C and O isotopes in carbonates**

- Carbonate-rich horizons in RCB1A and RCB2 were analysed for C & O isotopes at the University of Tasmania, CSL.
- Carbonate altered footwall arkoses from drill hole NM42 were also analysed.
- A set of carbonate-rich samples from the Nikana ore zone have been analysed by Mawson Croaker, and will be reported separately.

---

**O and C Isotopes of Carbonates RCB2**

\[ \delta^{18}O = 2.9 \]
\[ C = 2.2 \]
**C-O isotope relationships**

- Sedimentary & diagenetic carbonates have $\delta^{18}O = 20-28$ permil, $\delta^{13}C = -5$ to $-2$ permil, similar to early Prot. Sedimentary/diagenetic values.
- Ore-related carbonates are strongly depleted in both $^{18}O$ and $^{13}C$ ($\delta^{18}O = 8$-18 permil, $\delta^{13}C = -5$ to $-20$ permil).
- A halo of $^{18}O$ and $^{13}C$ depletion extends into the HW sediments above the ore shale for at least 100m.
- Further work needed to study footwall carbonates, but they appear to have the ore signature.
Isotope Interpretation

Isotope Modelling

T = 200°C, HCO₃⁻ dominant, δ¹³Cᵣ = -0 per mil
Preliminary isotope Interp

- The coupled C-O depletion associated with the mineralising event suggests:
  - A fluid with d$_{18}$O = 0 ± 5 permil
  - Moderate to high temperatures 150 - 350 °C
  - Involvement of organic carbon oxidation in the ore forming process
- The strong oxygen depletion in the albite-carbonate breccia zone suggests involvement of a much lighter 18O fluid; probably meteoric (d$_{18}$O = -10 permil?)
Towards Developing a Copper Belt Lithogeochem Vector Diagram

VHMS Alteration Box Plot
Large, Gemmell, Herrman, Paulick & Huston (2001)

Diagram notes:
- Fe, Mg, Na, K
- Least altered volcanics
- Diagenetic alteration
- Hydrothermal alteration
- Sub-trend

33. 34.
**Copper Belt mineral associations**

*after Barley (1960)*

- Background unmineralized Roan siliciclastics contain biotite, K-feldspar, albite, quartz, sericite and chlorite.
- Mineralised shale and siliciclastics commonly contain no albite (low Na₂O), and are enriched in one or more potassic minerals (biotite, K-feldspar or sericite). BUT, some few orebodies contain albite.
- Carbonates are principally dolomite, but some calcite and magnesite is also present.

**Enriched and Depleted elements**

- Enriched in ore zones: K₂O, and........?
- Depleted in ore zones: Na₂O, and........?
- SC AI Mk2 = \( \frac{K_2O \times 100}{(10 \times Na_2O)} \)
- SC AI Mk5 = \( \frac{(FeO + MgO) \times 100}{(FeO + MgO + Na_2O + K_2O + Al_2O_3/4)} \)
Feldspar is the Key

- Roan siliciclastics contain from 5 to 25 wt% detrital/diagenetic albite
- This albite is commonly replaced by K-feldspar during the Cu mineralisation of the Ore Shale
  \[ \text{NaAlSi}_3\text{O}_8 + K^+ = \text{KAlSi}_3\text{O}_8 + \text{Na}^+ \]
- A second generation of metasomatic albite, focussed along faults and breccia zones, is related to a later hydrothermal event (Darnley, 1960)
- Further petrographic and staining studies are needed to confirm these relationships

Preliminary Conclusions

- Immobile element ratios (Ti/Zr) can assist stratigraphic correlations
- The ore shales at Nkana has a unique Ti/Zr ratio
- There may be a hangingwall halo to ore, defined by K\(_2\)O/Al\(_2\)O\(_3\), Co and Zn in the siliciclastics
- There appears to be clear C-O isotope depletion halo in the carbonates surrounding ore
- C and O isotopes in carbonates may provide a useful vector to ore
Preliminary Conclusions

- At least two different alteration fluids have affected the sequence, having different C-O isotope characteristics.
- The ore shales are typically depleted in Na and enriched in K compared with normal shales (based on Nkana and Konkola North data).
- There is good potential to develop a lithogeochemical vector diagram, based on feldspar alteration, that may be useful for exploration.
Comment on Na$_2$O and K$_2$O

- In the uppermost Roan and Mwasha intersected in RCB1A, the siliclastics average 3.1% Na$_2$O and 2.7% K$_2$O.
- The stratigraphically lower siliclastics in the Roan (RCB2), closer to the ores, contain a lower mean Na$_2$O (2.2%) and higher mean K$_2$O (4.2%) content.
Nkana-Mindola Deposit, Zambia.

Carbon and Oxygen Isotopic Signature: Update

Mawson Croaken
PhD Student

NKANA-MINDOLA OREBODY

Ore Shale hosted - dolomitic Argillites, carbonaceous shale.

Cpy-brn-py.:

NE Lamb of Syncline
Inversion Monocline (Based on Chamney, 1974)
Buckett Dolomite Formation
Arrologo Chalcopyrite

Chambishi District
Mwambashi
Chambishi SE
Chibuluma
Nkana

Mining depth to ~5000 ft through use of 4 shafts

Nkana Syncline Project Area alone is ~90 Mt @ 2.56% Cu, 0.1% Co.
**RATIONALE**

Correlation of Cu-Co to carbonate rich lithologies - Sedimentary vs hydrothermal?

Is there an isotopic difference between mineralised Ore Shale veins, alteration and unmineralised Ore Shale.

Opportunity to pull apart 'apparently' complex carbonate-ore paragenesis.

Relationship to regional isotopic values.

**SAMPLES**

Mineralisation hosted in mainly in Ore Shale, minor upper FWS.
FUTURE DIRECTION

ALL samples similar values - Depleted $\delta^{13}C$

Barren Zones plot within sedimentary carbonate field.

Same C-O values as Korokora Orebody.

Detailed petrographic descriptions and mineral chemistry of carbonate lithologies.

Carbon and oxygen isotopes from FWS and West Limb, Dolomite pseudomorphs and Chambishi Dolomite carbonate beds from Mindola Pit.

Total carbon analysis (carbon species identification).

Modelling using mass balance - mixing between 2 different fluids; mixing between fluid and rock; fluid-rock interaction; and alteration of primary carbonate.
The geochronology of trace phosphates and its significance to mineralisation events in the Zambian Copperbelt

Galvin Dawson
(PhD student)
Centre for Global Metallogeny,
University of Western Australia

Aims of study

- Identify and characterise post-sedimentation phosphate minerals which can be isotopically dated
  - i.e. xenotime and monazite
- Determine the U-Pb age of phosphate minerals to "best precision" using SHRIMP – (Sensitive High Resolution Ion Microprobe)
- Relate phosphate age data, petrography and mineral chemistry to the evolution of the basin
- Characterise the mineralisation event(s) in the copperbelt
Important considerations

- Geochronology presented here were obtained from 4 SHRIMP sessions
  - Still in data collection stage of project (4-6 more sessions?)
  - Limited data collected from high-grade ore samples
- SHRIMP ages are preliminary provisional results only
  - Matrix corrections are still to be made to data
  - Individual ages may change by up to 15 Ma (<10 Ma?)
- Complexity of SHRIMP ages across copperbelt
  - Different ways to interpret SHRIMP data
- Trace element geochemistry in early stage of collection
  - No data is presented here
Regional Geochronology

Association of trace phosphates to mineralisation

- Things to consider...
  - Is there textural evidence for an association between trace phosphates and copper?
  - Is there a correlation between trace phosphate abundance and copper content?
  - Does this imply that the minerals are coeval and that dating trace phosphates will date mineralisation?
  - Do all copper-associated trace phosphates give one age
Textural evidence

Trace phosphate abundance vs copper

- Correlation between trace phosphates and Cu?
  - Abundance of zircon, monazite and xenotime recorded
- Strong correlation between trace phosphates and copper
  - Except at Mufulira
Trace phosphate abundance vs copper

- Both xenotime and monazite together don’t always correlate with copper
- One particular generation of either trace phosphate (or both) may be introduced with copper in the same fluid
- Rocks were permeable during the time ~615 Ma to ~475 Ma
- At Mufulira, the fluids that deposited copper may have only contained minor trace phosphates
  - Other non-mineralising fluids were richer in trace phosphates?
  - Is this a sampling bias?
- Mufulira can still be dated

Regional Geochronology

![Graph showing age (Ma) vs frequency]
### Preliminary Conclusions

- Multiple hydrothermal events are clearly evident in the basin
  - \( \sim 615 \text{ Ma}, \sim 560 \text{ Ma}, \sim 535 \text{ Ma}, \sim 500 \text{ Ma} \) and \( \sim 475 \text{ Ma} \)
- Textural association of trace phosphates and copper
  - Not definitive for a coeval relationship
- Correlation between trace phosphate abundance and copper
  - Except at Mululira
- Some trace phosphates and copper were introduced synchronously in the same fluids
- Mineralisation is *epigenetic* and can be dated
- Are there multiple mineralisation events...? in different parts of the copperbelt...?
  - at \( \sim 560 \text{ Ma}, \sim 535 \text{ Ma} \) and \( \sim 500 \text{ Ma} \)?
- The \( \sim 500 \text{ Ma} \) hydrothermal event may have been responsible for the most significant deposition of copper
- Possibly deposition/remobilisation of copper during each event?

### Table

<table>
<thead>
<tr>
<th>Event</th>
<th>Age (Ma)</th>
<th>Sample location</th>
<th>Cu mineral in assoc.</th>
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<tbody>
<tr>
<td>500 Ma</td>
<td>496 +/- 4</td>
<td>Mululira</td>
<td>cpy</td>
</tr>
<tr>
<td></td>
<td>501 +/- 4</td>
<td>Ndola East</td>
<td>py</td>
</tr>
<tr>
<td></td>
<td>501 +/- 5</td>
<td>Mululira</td>
<td>cpy</td>
</tr>
<tr>
<td></td>
<td>*502 +/- 2</td>
<td>Kansanahi</td>
<td>cpy</td>
</tr>
<tr>
<td></td>
<td>511 +/- 4</td>
<td>Mululira</td>
<td>cpy</td>
</tr>
<tr>
<td></td>
<td>*511 +/- 11</td>
<td>Kansanahi</td>
<td>cpy</td>
</tr>
<tr>
<td></td>
<td>*512 +/- 2</td>
<td>Kansanahi</td>
<td>cpy</td>
</tr>
<tr>
<td></td>
<td>515 +/- 4</td>
<td>Mululira</td>
<td>cpy</td>
</tr>
<tr>
<td></td>
<td>517 +/- 16</td>
<td>Mululira</td>
<td>cpy</td>
</tr>
<tr>
<td>535 Ma</td>
<td>525 +/- 4</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>539 +/- 12</td>
<td>Mululira</td>
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</tr>
<tr>
<td>560 Ma</td>
<td>560 +/- 11</td>
<td>Mululira</td>
<td>bn</td>
</tr>
</tbody>
</table>

*Re-Os and U-Pb ages taken from Hizman et al. (2006)*
Further Work

- Further SHRIMP work...
- Examine more 'ore related' samples to distinguish mineralising from non-mineralising events
- Integrate trace element geochemistry with SHRIMP geochronology
- Identify the relevance and significance of each hydrothermal event
CHAMBISHI BASIN progress report
(includes work from east of Kafue Anticline)

David Selley, Rob Scott, Stuart Bull, Mawson Croaker

Basin Architecture

- Basin growth during Lower Roan sedimentation
  - architecture of the mineralised package
  - fault systematics

- Relationship of basin geometry to mineralisation
  - association of mineralisation with basement highs
  - association of mineralisation with basin re-configuration
  - implications of basin geometry for size and shape of fluid cells

- Expression of syn-rift architecture in Lufilian geometry
  - can variation in style and geometry of Lufilian folds aid in defining syn-rift structures?
Chambishi Basin

- Widespread, high density drilling
  - 3-D control

- Diversity of hosts

- Pronounced thickness & facies variation in LR

- Distinct fold domains

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Chambishi Basin

- Widespread, high density drilling
  - 3-D control
- Diversity of hosts
- Pronounced thickness & facies variation in LR
- Distinct fold domains

Chibuluma West (Strat)

Upper Brecia Unit

Hangingwall Sandstone
Orebody Qtzite

Footwall Qtzite

Hangingwall Sandstone
Orebody Qtzite

Footwall Qtzite

Basement

Racial Boulder Bed

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**FW Thickness**

- Series of discrete sub-basins:
  - N thickening ramp to NE
  - pinch outs onto NW-trending basement highs in central zone
  - pinch out onto NNW-trending basement ridge to W

**Restored Basin**

- Faults propagate to surface in western portion, leading to compartmentalized basin system
- Physical hydrocarbon trap
**Basin Geometry**

- Ore located at periphery of basement ridges
  - FW pinchouts

**Sulfide-"Heavy Mineral" Association**

- Sulfides concentrate within heavy mineral bands
- Th-bearing phases appear elevated
- Causes:
  - zones of mechanical weakness
  - reduced conditions during alteration of Fe-bearing phases
  - polymerization of hydrocarbons
Sulfide-"Heavy Mineral" Association

- Intimate grain-scale textural relationships between Th-bearing phases and Cu-Fe sulfides

Mwambashi B

- Footwall-hosted mineralisation
- 8.4Mt @ 2.63%Cu, 0.08Co (1997)
- pronounced facies variation
- ore shale + LR "hangingwall" succession present
Stratigraphy and facies types

- Pronounced lateral facies variation throughout entire Lower Roan
- Extreme thickness variation throughout Lower Siliciclastic Package ("footwall sequence")
- Subtle thickness variation in OSH-"hangingwall siliciclastic" sequence
- Fundamental basin re-configuration at level of OSH

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Lower Siliciclastic Package

- broad 2-fold stratigraphic subdivision
  - basal alluvial-fluvial sequence
  - upper fluvice-deltaic sequence
    - persistent alluvial fan sedimentation in regions of limited accommodation space
- basement (granite) derived provenance persists throughout package
  - local source areas remain unchanged

Basal alluvial-fluvial sequence

Inner-mid fan / fluvial facies association

- Talus
  - angular granitic fragments
  - matrix poor
  - patchy feldspathic ait
- Stratified heavy mineral bearing sub-arkose
- Intercalated sandy debris flows
- Typically feldspar-calcite altered, locally pitted
**Mixed fluvio-deltaic sequence**

- abrupt increase in argillaceous component
- transition to subaqueous sedimentation
- liquefaction textures throughout
- ore horizon - parallel/x-strat clean sandstone
  - return to fluvial sedimentation
  - limited feldspathic alteration

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**“Ore Shale”**

- base defined by sharp to sericitic matrix
  - detrital clay rich matrix (muddy debris flow)?
  - alteration of feldspathic component?
- provenance changes to intrabasinal source
- flooding of older granitic source areas

**AMIRA P544**
**"Ore Shale" - "dolomitic facies"**

**Detrital fabrics & compositions**
- crenulate seams - crypt-algal lamination
- "condensed" relative to neighbouring carbonaceous
- coincides with condensed "footwall" and "hangingwall"

**Alteration & strain fabrics**
- increased alteration - silica-talc-sericite
- probable "tectonic" brecciation

---

**"Hangingwall" siliciclastics**

- textural and compositional similarities with lower fluvio-deltaic sequence
- increased dolomitic component implies persistent subaqueous (?)marine) conditions
- increased strain and alteration compared to Lower Siliciclastic Package
Breccia Facies

- Base of breccia equivalent to typical "ore shale"
- Abrupt change in clast composition from "FW"
- Intense carbonate-albite-talc-scapolite alteration
- Apparent relict internal sedimentary structure

Breccia Facies

- Apparent stratification
- Pebbly sandstone textures preserved
- Intercalations of monomictic breccia
Breccia Facies - upper contact

- Halite casts preserved at top of “upward fining sequence”
- Breccia fabrics and scapolite throughout
- Upper Roan dolomitic and chloritic shales

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Breccia Facies - Origin?

Sedimentary Origin
- Thickness = ore shale + siliciclastic hangingwall
  - No apparent loss or addition of stratigraphy
- Change in provenance = base of ore shale
- Apparent preservation of sedimentary textures and structure
- Partitioning of intense alteration to discrete, narrow cross-cutting domains

Non-sedimentary origin
- Rounded clast morphology not indicative of sedimentary origin
- Partitioning of alteration within breccia
- Monomictic breccias difficult to explain in terms of sedimentary origin
- Brecciation persists into Upper Roan

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- strong association of Cu with feldspar-calcite alteration
- broadly stratabound
  - finer, well stratified intervals
- some evidence for fracture control
Mineralisation - Feldspathic Alt.

- progressive textural destruction with increasing alteration
- locally transgressive alteration fronts
- apparent antithetic association of feldspar alt. intensity and Cu

Alteration at periphery of ore

- barren "ore horizon" at limits of ore body remains intensely altered
- lateral fluid flow through permeable media
- facies type alone does not provide a suitable trap
Basin Architecture

- thickness and facies variation provides detail of basin geometry
- complex array of E-W to NNW trending fault segments
- compartmentalised half graben system with blocks down-thrown to the N
- principal half grabens are linked by a NW trending convergent transfer array
- generation of a restricted, mildly subsident depocentre within the transfer zone

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Basin Architecture

- Highly restricted depocentre
- thin siliciclastic package
- capped by "dolomitic OSH facies"

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Basin Architecture

- wedge-shaped depression
- talus breccia within immediate footwall of half graben
- intercalated sandy debris flows and clean well-stratified sandstone
- no thickness variation in OSH

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Basin Architecture

- inner fan facies confined to head of transfer array
- debris shed from adjacent elevated basement block
- deposition of argillaceous facies within main depocentre

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Basin Architecture

- Limited lateral facies variation
- Widespread development of argillaceous fluvio-deltaic package
- Breccia units largely restricted to footwall of main growth fault

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Distribution of Mineralisation

- Distribution of Cu mineralisation strongly influenced by basin geometry
- Highest grades occur within transfer zone
  - Clean sandstone-dominated facies wedge out below OSH seal
  - Optimum hydrocarbon trap
- 'Deepest' part of transfer zone (conglomerate dominated) is low grade

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Key Elements of Mineralised System

- permeable host medium
- upper seal
- basin architecture to direct fluid flow

Key Elements of Mineralised System

- basin geometry and facies distribution provide optimum conditions for HC trap
- fluid flow as recorded by feldspathic alteration
- Ore Shule hosted mineralisation
- Ore is situated at fringes of "biothermal facies"
- Additional spatial association of ore with footwall pinch outs

**Chambishi SE**

- Preliminary work indicates basin evolution during "footwall deposition" was controlled by WNW to NNW trending growth faults
- Broadly SW dipping ramp with interference of NNW trending troughs
- Local significant modification during folding
Gu Distribution

- broad barren gap over intrabasinal high
  - coincides with change in facies to "dolomic ore shale"
- high grade domains coincide with fault step-overs and footwall pinch-outs at the periphery of the elevated block
- footwall geometry may also affect distribution of OSH mineralisation
- association of ore with systematic and predictable basin configurations

Syn-rift faults & fold geometry

- Regional fold geometry as indicated by map patterns and drilling reveals geometric association with syn-rift strata
- Lufilian fold patterns to the level of the Mwashia can be used as an effective targeting tool
**Key Findings**

- Position of Cu mineralisation in Chambishi Basin is strongly influenced by rift architecture coeval with deposition of the "footwall succession" (FW ore bodies at least)

- Fluid flow responsible for mineralisation was directed principally through permeable (coarse-grained) "footwall" strata
  - lack of reductant in "hangingwall succession"?
  - lack of focussing mechanism?

---

**Key Findings**

- **Transfer systems or fault intersections provide optimum sites for Cu mineralisation**
  - sites of subdued accommodation development and complex fault geometry: 3-D FW "pinch outs"
  - sites of sediment input: coarse-grained permeable strata
  - physical hydrocarbon traps
  - focus sites for hydrothermal fluids

- **Change in basin configuration at Ore Shale times provides transgressive seal to underlying basin compartments**
Nkana-Mindola Deposit, Zambia.
Basin Architecture Progress Update

Mawson Croaker
PhD Student

RATIONALE

Basin architecture provides a framework to understand relationships between: Deformation, Distribution of Cu-Co and sulphide phases, Geochemical halos and alteration and metasomatic processes.

Ultimately identification of key processes involved in formation of giant 'Shale' hosted sedimentary copper deposits - GENETIC MODEL: i.e. Diagenetic, synorogenic, late hydrothermal or combination of these mechanisms.
BASIN ARCHITECTURE

Can basin architecture be recognised at Nkana-Mindola? YES (A work in progress)

Nkana-Mindola is a jigsaw puzzle, with missing pieces however use of

Sedimentology
Structure
Existing mine data
Previous work

Limitations do exist -

At Mindola and Mindola North poor control from data available on depth to Basement / SCB high deformed, work ongoing.
Limited old drill core from surface drilling exists.
Underground exposure predominantly limited to immediate footwall or has been whitewashed.

NKANA - MINDOLA

Nkana-Mindola Cu-Co hosted in 'Ore Shale' and upper MCF.
One orebody in Basal Quartzite member
One of the largest Cu producers on the Copperbelt.

Ore bodies cpy-bn-py - vertical and lateral general zonation.
Over 33 km strike length 'Ore Shale'.
~ 16 km is < 1.8% Cu
Economic mineralisation only along eastern limb.
'Ore Shale' along the West Limb is mineralised 1% Cu (cpy-py)
FOOTWALL - Mindola Clastic Formation

Since May 2002 - developing better understanding and controls on relationship of basement to Lower Roan deposition.

MCF - Alluvial-fluvial to deltaic

Significant thickness variations of the Mindola Clastic Formation-Footwall Sequence.

Footwall facies thickness, geometries and facies types assist with defining 'basin margins'.

No accurate orientation of original basin structures to date.

ORE SHALE - Kitwe Formation

Only relative small thickness variations of Ore Shale and Hangingwall sequence.

Laterally continuous fine grained units.

Major northern and southern facies variations.

Localised massive 'dolomitic' facies changes in the lower Ore Shale coincide with pinch outs and thinning of footwall.

Facies variations in the hangingwall sequence appear to be minor – restricted by availability of data.

Complex depositional environment - Fluvial-deltaic, Shallow marine, Carbonates, limited evaporites.
BASEMENT CONTROL

Basement-Lower Room contact map geometry very useful for areas of potential early basin margins.

Abrupt changes in NW basement strike coincide with thinning or pinching and facies variations of footwall sequence.

Ore Shale facies changes — 'massive Dolomitic facies' or arenaceous ss.

Massive Dolomitic Zones — uneconomic down dip changes in Ore Shale Facies.

Kitwe Barren Gap, no distinct basement geometry change PUT down dip footwall thinning, facies changes and Ore Shale facies changes.

Fold geometries influenced by basement.

BASIN EVOLUTION

Facies, facies variations and thickness changes indicate two major basin generation phases for the Lower Room.

Also clearly recognised by Söley at Chibiluma, Chambishi and

Stage 1. Basin initiation — deposition of Mindola Clastic Formation.

Small, compartmentalised half-graben basins, approximate widths in order of 2-3 km.

Stage 2. Basin Reconfiguration — deposition of Kitwe Formation

Larger, more extensive basin, fine grained sequence.

No proximal facies typical of active fault controlled basin margins.
WHERE TO NEXT with BASIN ARCHITECTURE

Ascertain 3D geometry of small basins - if possible.

Refine sedimentology of the upper Kitwe Formation.

Understanding possible lithological variations of footwall for West Limb.

Compile structural domains.

Understand distribution and trends in Cu-Co - basin structure vs Lufilian inversion.

Nkana Synclinorium Project at SOB focus of detailed work to provide accurate relationships to deformation, mineralisation and alteration.

Do other footwall orebodies exist at NKM? If not, why not?

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- ZAMANGLO: Peter Mann and staff.
- AMIRA SPONSORS, CODES STAFF AND CSM.
- JUNE PONGRATZ.
Stratigraphy, Regional Alteration and Mineralization Patterns of the Zambian Copperbelt

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Colorado School of Mines

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Important Points

-Punctuated tectonic events during basin evolution
-Zambian and DRC orebodies appear spatially coincident with first- (NW) and lower order (eg, NE) basin-controlling faults
-major extension occurred during Lower Roan and upper Mwashia/Grand Conglomerate time
-progress from first-cycle clastics to platform carbonates and sabkhas to deeper water siltstones-mudstones

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Important Points

-early brine movement throughout L. Roan
-complex breccias: salt dissolution/collapse, associated with major faults = fluid pathways
-glaciation (Grand Cgl), associated extension caused destabilizing sea level drop
-alteration and mineralization present throughout sequence – regional zoning?
-major Lufilian deposits formed in L. Roan, U. Roan and Mwashia

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Drill holes, west section
L. Roan,
W. Copperbelt
Bedding-plane salt crusts, Mindola Pit

U. Roan – Kundelungu, W. Copperbelt
L. Roan Mineralization, E. Copperbelt

Sabkha textures, Upper Roan

Enterolithic “chicken wire” texture, anhydrite-dolomite-pyrite
Upper Roan Breccias, E. Copperbelt

Dolomite clast in breccia

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Crackle bx - mosaic bx - conglomeratic bx transition

Brecciated clast in breccia
Congolese "Mines Group" mineralization in Upper Roan, Mufulira

Mwashia sandstone and feldspathic alteration
Summary – Lower Roan

- footwall: controlled by NE to NW faults
- post - ore shale/mudseam time = change to more argillaceous & carbonate sediments, punctuated coarse clastic input (sheet sands)
- feldspar (dolomite) alteration, hematite
- orebodies develop in basement and footwall arkoses/conglomerates (Lubembe), arenaceous sands (Chib), “ore shales”, hangingwall traps, and the regionally altered sandstones (TFQ)

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Summary – Upper Roan

- extreme thickness and facies changes near/within breccia complexes, elsewhere laterally continuous
- dolomite-feldspar-anhydrite-scapolite-(pyrite)
- breccias are spatially associated with major faults, contain brecciated clasts, intrabasinal provenance, unusually altered versus other conglomeratic rocks
- DRC – type mineralization in algal dolomites

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Summary - Mwashia

- deeper water sedimentation, sandstone records tectonic event
- gabbros and volcanics (W. Zambia) at end
  Mwashia time = renewed extension
- Mwashia rocks commonly transposed,
  possible large scale repetition
- dolomite/calcite (feldspar) alteration, local
  vein mineralization, transition from pyrite to
  pyrrhotite at top

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Continued Work

- refine sequence stratigraphic correlations,
  especially in Konkola-Congo-Mufulira area
- U-Pb dating of gabbros (UR and footwall)
- large scale structural and alteration patterns
- petrographic/isotopic/geochemical study of
  breccias, alteration
- Re-Os dating of sulfides to constrain timing
  of alteration-mineralization

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Important Results to Date -
Towards a Unified Geologic and Exploration Model

Murray W. Hitzman
Colorado School of Mines

Outline

- Sedimentary architecture / structure
- Alteration and lithogeochemistry
- Mineralization
- A Genetic Model for the Zambia Copperbelt
- Implications of the Model
- Remaining problems and future work to solve them.

Synthesis
Sedimentary Architecture and Structure

- Sedimentary architecture of the Lower Roan indicates it was deposited in an extensional (rift) environment.

- Basal sediments are arkosic conglomerates and sandstones derived from granitic basement in a fan-delta environment.

- “Ore shale” represents a starved basin and occurs at a major change in basin configuration.
Sedimentary Architecture / Structure

- First-order, NW-trending faults (Konkola, Nchanga syncline, east side Chambishi basin) and third-order faults (Chambishi, Lusombe) are recognized.

- These faults controlled Lower Roan sedimentation; the first order faults appear to have continued to have controlled some aspects of sedimentation up into the lower Kundelungu.

Sedimentary Architecture / Structure

- The Upper Roan is a mixed carbonate-siliciclastic sequence with punctuated extensional tectonic phases recognized by coarse siliciclastic layers.
Sedimentary Architecture / Structure (cont.)

- The Upper Roan contains abundant breccias making tracing of stratigraphy throughout the Upper Roan extremely difficult.
- Origins of the breccias are diverse and probably include:
  - Sedimentary
  - Dissolution / collapse
  - Intrusive-related
  - Tectonic
  - Combinations of events
- Upper Roan breccias (combined with alteration of Upper and Lower Roan sediments) probably indicate significant thicknesses of halite-bearing evaporites were once present in the Upper Roan.

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Sedimentary Architecture / Structure (cont.)

- The Roan-Mwashia sequence is relatively thin (1-2 km) in the Copperbelt; evaporites could have increased section to 3 km.
- The Mwashia grades upward from a carbonate-rich base to dominantly siltstones. It apparently served as a regional "seal."
- The Grand Conglomerate serves as a regional marker unit. It appears to consist of both glacial diamicrites and turbidites (indicating tectonically active basin conditions?).

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Synthesis
Gabbro intrusions are concentrated in the Upper Roan section but are recognized from the basement to the Grand Conglomerate. Dating elsewhere in northern Zambia suggests ages of 765-740 Ma.

Gabbro intrusions appear to cluster adjacent to first-order faults; therefore magnetics may aid in locating these faults (e.g., Chambishi basin).

Zambian Copperbelt does NOT occupy a major basin.
Alteration and Mineralization

Alteration and Lithogeochemistry

- Alteration is recognized in the Katangan sequence from at least the basal portion of the Mwasha down into the basement.

- Both potassic and sodic styles of alteration are observed.
Alteration and Lithogeochemistry (cont.)

- Potassic alteration produces fine-grained potassium feldspar (commonly confused with albite during logging) and provides the potassium for later (?) biotitization.
- Potassic alteration appears to be concentrated in siliciclastic lithologies which were probably more porous and permeable.
- Sodic alteration produces albite and scapolite. It is well developed in the Upper Roan and locally in clean sandstones near the base of the section. Sodic alteration is also present adjacent to gabbro bodies and in some carbonate units (scapolitized).
- It appears that potassic alteration generally predates sodic alteration.

Mineralization

- Zambian Copperbelt mineralization is fundamentally controlled by oxidation change.
Mineralization (cont.)

- The location of footwall orebodies is controlled by the sedimentary architecture related to third order faults and the presence of sedimentary "seals."

- Ore shale orebodies are controlled by the presence of carbonaceous (relatively reducing) lithologies and adjacent (generally stratigraphically below) permeable lithologies.

- Arenaceous (and probably footwall) orebodies controlled by the former presence of hydrocarbons (natural gas and petroleum) which served as reductants. These reductants were in physical traps.

Mineralization - Footwall Orebodies

- The location of footwall orebodies is controlled by the sedimentary architecture related to third order faults and the presence of sedimentary "seals."

Synthesis
Mineralization - Ore Shale Orebodies

Impermeable seal

orebody

Permeable siliciclastic sediments

- Ore shale orebodies are controlled by the presence of carbonaceous (relatively reducing) lithologies and adjacent (generally stratigraphically below) permeable lithologies.

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Mineralization - Arenaceous Orebodies

seal

orebody

- Arenaceous (and probably footwall) orebodies controlled by the former presence of hydrocarbons (natural gas and petroleum) which served as reductants. These reductants were in physical traps.

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Synthesis
Genetic Model for the Zambian Copperbelt

Key Ages

- 870 Ma  Nchanga Granite (basement)
- 765  Volcanic rocks in Mwamia
- 765 - 740  Gabbros
- 735  Volcanic rocks in Grand Conglomerate (Sturtian glaciation)
- 650  Initial metamorphism of Katangan sequence
- 670 - 620  Shinkolewwe U deposit
- 645  Albite-Cu veins at Musosili
- 615  Xenotime-monazite ages - Mufulira
- 560  Xenotime-monazite ages - Copperbelt: Hook Granite
- 535-470  Xenotime-monazite ages - Copperbelt
- 510 - 490  Vein Cu-Mo-U mineralization (Kansanshi)
- 495  Cooling below 300°C blocking T for Ar in biotite
- 470  Cooling below blocking T for Ar in muscovite

Synthesis
Lower Roan Sedimentation

- Extensional environment (post 870 Ma) leads to complex fluvial/alluvial basal section (lower Roan) dominated by basement derived arkose.

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Lower Roan Sedimentation

- Coarse basal siliciclastics covered by mixed sequence of siltstones, rare shales ("Ore Shale"), and carbonates.

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Synthesis
Lower - Upper Roan Sedimentation

- Covering of basement topography leads to more mature, layer-cake sedimentary geometry with mixed marine (?) siliciclastic-carbonate facies overlain by sabhka carbonate facies.
- Punctuated extensional events provide coarse siliciclastic input.

Upper Roan Sedimentation

- Probable restriction of basin leads to evaporite (gypsum + halite) precipitation.

Synthesis
Mwashia Sedimentation

Mwashia consists of basal carbonate-rich sediments grading up to siltstones.

Lowermost Kundelungu + Gabbros

- Extensional event (745-740 Ma) with intrusion of gabbros.
- Close to time of Grand Conglomerate—“Snowball Earth.”
- Extensional event probably caused thermal maturation and migration of hydrocarbons. This event may also have allowed incursion of water (glacial, meteoric?), evaporite movement and dissolution, and brine formation.

Synthesis
Initiation of Lufilian Deformation (circa 650 Ma)

- Salt tectonics continue during earliest Lufilian deformation (probably around 650 Ma).
- Continued brine formation and movement downward.
- Breccia formation (collapse and tectonic) in Upper Roan section.

Lufilian Deformation (650 - 500 Ma)

- Continued compressive stress and dissolution.
- Brines continue to sink into Upper and Lower Roan sequence.
- Mineralization occurring during this time - reaction of oxidized, metal- and sulfur-rich brines with local oxidation traps (carbonaceous sediments and gas/oil accumulations).

Synthesis
Lufilian Deformation (~540 - 510 Ma)

- Continued deformation results in upright tight folding in Lower Roan sequence nucleated on early faults.
- Structural decoupling near base of Mwashia.
- Deformation in upper sequence largely recurrent folds and low-angle (thrust) faults.
- Deformation provides energy for renewed brine movement and escape in basement and overlying rocks.

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Basin-scale Alteration

- Upper and Lower Roan sections highly altered from brines ("pickled")
- General pattern of upper soda alteration and lower potassic alteration with hematite

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Synthesis
Implications of the Model

- Whole basin hydrothermal system.
- Dominant fluid flow pattern is downward.
- Downward flow probably concentrated along first-order original basin-bounding faults; would probably alter gabbros.
- Flow within sedimentary sequence is lateral and controlled by porous and permeable units (coarser siliciclastics).

Synthesis
Implications of the Model (cont.)

- Basin-scale alteration pattern.

- Dominant alteration zones are potassic and sodic. Appears that sodic best developed at higher level and potassic in more basal position.

- May not be deposit-specific alteration patterns.

Implications of the Model (cont.)

- Delineation of reduced zones within the basin is critical.

- Any type of reduced zone may be favorable:
  - Carbonaceous sediments
  - Physical gas or petroleum trap
Implications of the Model (cont.)

- Multiple deposit types may be present at multiple stratigraphic horizons:
  - Zambian Copperbelt type
  - Congo Copperbelt type
  - Kipushi type
  - Kansanshi type

Zambian Copperbelt

- Zambian Copperbelt — Ore deposits in carbonaceous sedimentary layers and physical gas/oil traps in Lower Roan.

Synthesis
• Congo Copperbelt —
  Ore deposits in stratiform breccia zones (gas traps?) and fetid dolostones (carbonaceous) in Upper Roan equivalent sediments.

• Southern Congo / Namibia —
  Ore deposits in cross stratral breccia pipes (paleo salt domes) charged with gas/oil cutting Mwashia and Kundelungu sequence.
Implications of the Model (cont.)

- Northern Zambia / Southern Congo —
  Tectonically-induced fluid escapeways into the reduced Mwashia, (e.g. Kansanshi, Shinkolobwe)

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- Global exploration for Copperbelt-type systems should focus on:
  - Basins which contained salt.
  - Basins where salt underwent dissolution to form brine which caused large-scale, intense alteration.
  - Search for reducing zones within such basins.

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Synthesis
Remaining problems and future work to solve them.

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Remaining Problems / Future Work

- Source of mobile reductants?
- Utilize further stratigraphic investigations and investigations of heavy minerals

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Remaining Problems / Future Work

- Geometry of different basin-scale alteration zones?
- Age of different alteration zones?
- Mine existing data and additional fieldwork.
- Detailed petrographic studies.

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Remaining Problems / Future Work

- Are there geochemical vectors to ore?
- Continue major and trace element analyses.
- Continue C, O, and S isotopic studies to look for changes caused by oxidation change during sulfide precipitation.

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Synthesis
Remaining Problems / Future Work

- What is the source of cobalt (which differentiates Copperbelt from other systems)?
- Continue whole rock and trace element studies of gabbros. Preliminary work shows least altered gabbros with up to 60 ppm Co; depletion in altered gabbros?

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Remaining Problems / Future Work

- Geochemistry of ore fluid?
- Utilize stable mineral assemblages and alteration assemblages to try and calculate.
- Calculate possible ore fluids at different temperatures and salinities.

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Synthesis
Remaining Problems / Future Work

- Degree of metamorphic mineral redistribution?
- Utilize and expand geochronological database.

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Synthesis
Ndola West Update
Setting and genesis of sandstone-hosted deposits east of the Kafue Anticline

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Aims

- Characterise mineralised interval at Ndola West
  - geochemistry, C- & O-isotopes (carbonates)
  - facies associations / stratigraphic context
    - regional correlations
    - controls on basin architecture and facies distribution

- Origin and timing of copper mineralisation
Summary of Key Findings

- Katangan series at Ndola West
  - dominantly or entirely Lower Roan
  - section divided into (i) Footwall, (ii) Ore and (iii) Hanging wall formations
- “Ore formation” represents an abrupt transgression-regression cycle that heralded a significant change in the character of Lower Roan sedimentation
- disseminated Cu-sulfides mainly hosted by relatively clean sandstones in upper part of “Ore formation”
  - high porosity aquifer between less permeable units
  - overlain by dolomite deposited during final stages of marine regression
  - underlain by thinly bedded turbidites* reflecting maximum flooding during prior transgression (*closest facies equivalent to Ore Shale within Ndola West succession)

Summary of Key Findings (cont...)

- Hanging wall and lower part of Ore formation significantly more argillaceous than Footwall formation
- Increased mica (clay) content interpreted to reflect both (i) increased subsidence rates and (ii) change from distributed intra-basinal faulting to faulting localised at basin margins
  - Footwall: fluvial sedimentation within highly compartmentalised (intra-basinal fault-controlled?) network of sub-basins
  - Hanging wall: loss of intra-basinal topography, facies more laterally extensive, basin-wide subsidence on major bounding faults
  - high clay/mica content of Hanging wall suggests it may have acted as a regional seal during subsequent hydrocarbon(?) and hydrothermal fluid migration within the basin
Summary of Key Findings (cont.)

- Textural relations indicate deposition of disseminated Cu-sulfides occurred after formation of diagenetic (qtz + fsp) overgrowths on detrital grains but prior to significant folding and regional cleavage development.

- New 517±17 Ma age (SHRIMP Xt) for similar (pre-folding) sandstone-hosted Cu at Mufulira suggests deposits formed as a result of lateral (Cu-bearing) fluid migration initiated during the early stages of Lufilian compressional orogenesis.

Ndola West prospect – location

Data sources:
2001: KTO00DD1, DD4, CD4 deft. 1 & 2 (NE limb of Ndola West syncline)

2002: KTO01DD1–6 (Stepping out up to 1400 m along strike to NW on both NE and SW limbs of syncline)
Stratigraphy (NE limb of syncline)

(Lower Roan)

Hanging wall

"Ore formation"

Footwall

Basement

After Scott (May 2002)

Major element geochemistry

- Higher average mica content of both Ore and Hanging wall formations clearly indicated by elevated Al, K and Mg contents
Stratigraphic correlations at Ndola West

- **NE limb of Ndola West synform**
  - Excellent lateral continuity of units within stratigraphic interval tested by drilling (distance of ~1400m along strike)

- **SW limb of Ndola West synform**
  - Equivalent stratigraphic interval *not fully tested* due to unforeseen structural complexities
  - Hanging wall sequence appears similar
  - Differences in footwall succession (e.g., presence of thick poorly sorted argillaceous sst *not present on NE limb*), interbedded with or underlying pink heavy-mineral stratified sandstone

Stratigraphic correlations: NW limb syncline
**Stratigraphic trends**

- **Hanging wall formation** (Lower Roan) with marine transgression
- **Ore formation** (Lower Roan) with regression and marine transgression
- **Footwall formation** (Lower Roan) with fluvial

---

**“Footwall formation”**

- Dominated by relatively clean medium-coarse grained and pebbly arkosic sandstone
- Deposited in braided fluvial system
- Limited data indicate significant facies/thickness variations within the Lower Roan from SW to NE
- Sedimentation patterns strongly influenced by local topography, consistent with observations elsewhere in the Copperbelt
"Ore formation"

- <20–45 m thick, abrupt transgression-regression cycle that heralded a significant change in the character of Lower Roan sedimentation
- <8 m thick arkosic sandstone and lower 1–2 m of overlying dolomite (upper Ore formation) hosts the only significant Cu-sulfides (Bn and/or Cc (2ndry) >> Cpy)
- Increase in mica content of sandstones across lower part of Ore formation (i.e. immediate footwall to mineralisation) interpreted to reflect transition to deeper water conditions.
  - transgressive sequence capped by distinctive unit of thinly interbedded siltstone, shale and sandstone with turbiditic character
  - turbidites interpreted to represent local maximum flooding surface in the Lower Roan
  - closest facies equivalent to Ore Shale east of Kafue anticline
  - coarser grained (sandstone) beds locally host stratabound carbonate alteration and minor disseminated copper similar to Ore Shale at Korkola

Main Geochemical trends within Ore Formation

Drill hole: KIT00DD04

Anglo Americas geochemical data, (NR = incomplete digestion of silicates)

Note:
- progressive increase in mica content (K, Al) across footwall to mineralisation
- elevated carbonate content of Ore formation (NB. Mn levels support higher carbonate contents originally. Core is strongly pitted, especially in footwall, where patches of original carbonate alteration (Ca, Mg) have been leached)
“Hanging wall formation”

- here considered part of the Lower Roan but interpreted as Upper Roan by Anglo America
- monotonous poorly stratified sequence of argillaceous sandstone and siltstone, grossly similar to argillaceous base of Ore formation

- Whole rock geochemical data suggests systematic change in mica composition from Footwall to Hanging wall.
  - Increase in MgO / Al₂O₃ ratio of mica
  - Decrease in K₂O / Al₂O₃ ratio of mica
  - Hanging wall sediments originally more dolomitc

Whole rock geochemical data provided by Anglo America, N.D. partial sample digestion
Carbonate alteration

• Although extensively leached, patchy to locally pervasive carbonate (± biotite) alteration is developed throughout Ore formation and much of the Footwall formation at Ndola West
  – Immediate footwall to stratabound Cu mineralisation characterised by extensive zone carbonate veining and alteration
  – Predates cleavage development
• Planned investigation of C- and O-isotopic systematics of footwall carbonates will complement predominantly hanging wall sourced data from the Chambishi Basin (McGoldrick & Large, this report).

Patchy, disseminated and pervasive stratabound carbonate alteration in immediate footwall to ore horizon
"Late-stage" albite alteration

- associated with coarse xtaline to fibrous qtz+alb veins
- overprints disseminated Cu-sulfides
- predates cleavage (folding)
  - within mineralised zone
    - albite+tremolite clots in bleached alteration haloes around veins
    - veins may contain Cu-sulfides, but earlier disseminated Cu-sulfides depleted around veins
  - elsewhere
    - veins contain haematite not Cu-sulfides

Stratigraphic correlations NE of Kafue anticline

- Important similarities between Ore Formations at Ndola West and Mufulira
  - stratigraphic position marks transition from clean to dirty (mica-rich) sandstones
  - deposition during abrupt transgression-regression cycles (3 cycles at Mufulira, 1 at Ndola West)
  - formations comprise identical facies
    - poorly sorted argillaceous sst, thinly bedded silt/shale dominated turbidites, well sorted clean heavy mineral stratified sst (major host to Cu-ores), massive chlorite
Age and origin of sandstone-hosted copper mineralisation NE of Kafue Anticline

- Gross geometry and textural relations of stratabound copper ores at both Mufulira and Ndola West indicate mineralisation occurred after early diagenesis and prior to significant folding and regional cleavage development (i.e. main stage Luflilian Orogeny).

- Scott (May 2002) suggested a late-stage diagenetic origin for the ores because:
  - No evidence for either macro- or micro-scale structural control on ore fluid introduction (metal distribution), implying rocks were relatively porous.
  - Luflilian deformation in the Copperbelt occurred under greenschist facies conditions (implying low rock porosity).
Age constraints

- 517±17 Ma SHRIMP age for xenotime apparently intergrown with chalcopyrite along heavy mineral bands at Mufulira (G. Dawson, pers. comm.) refines previously reported microprobe ages (534±92 Ma, 529±68 Ma) from same sample (Scott, May 2002).

- Formation of xenotime requires significant fluid flux (McNaughton, May, 2002)
  - regardless of its relationship to copper, xenotime overgrowths imply relatively open circulation of fluids occurred during at least the early stages of Lufilian deformation

- Metamorphic grade and microstructural character of subsequent Lufilian deformation at Mufulira, requires
  - rocks were not deeply buried, or
  - significant reaction enhanced permeability at the onset of compressional deformation in order to account for apparently open fluid circulation at that time

Hydrocarbons and copper

- Preferential copper development along heavy mineral bands at Mufulira and elsewhere, and specifically the nucleation of Cu-sulphides on zircon and monazite grains requires the presence of a localised reductant.

- Away from mineralised areas, heavy mineral bands are typically haematite-rich and represent an oxidising micro-environment

- Thermochemical fixing of hydrocarbons around radioactive heavy minerals could trap/concentrate a suitable reductant within these bands

- Consistent with previous studies implicating prior hydrocarbon impregnation in the formation of sandstone-hosted deposits (e.g. Annels, 1979).
Model for sandstone-hosted deposits

- Gross similarities in character and stratigraphic position of Cu ores at Mufulira and Ndola West suggests the following features were important in the formation of these deposits:
  - relatively clean sandstone host-rocks capped or sandwiched between less permeable units providing favourable aquifers for both hydrocarbons and Cu-bearing fluids
  - preferential fluid flow (relative to footwall) within the ore formations may have been promoted by proximity to a major regional seal (overlying argillaceous sandstones) and their greater (basin-scale) lateral continuity compared to sandstone units in the footwall (deposited in fault-compartmentalised sub-basins)

Model for sandstone-hosted deposits

- Prior impregnation of sandstone aquifers by hydrocarbons is favoured as a mechanism for sulfate reduction and development of chemical traps to precipitate the copper ores
- Particularly at Ndola West, the reduced siltstone/shale-dominated package (i.e. Ore Shale facies equivalent) immediately below the mineralised horizon may have originally contained organic matter and provided a local hydrocarbon source
- New age constraint from Mufulira suggests mineralisation occurred in response to migration of Cu-bearing fluids initiated and driven by compressional orogenesis during the early stages of the Lufilian Orogeny
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