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P544 - Proterozoic Sediment Hosted Copper Deposits

December 2002

Centre for Ore Deposit Research –
University of Tasmania
Colorado School of Mines

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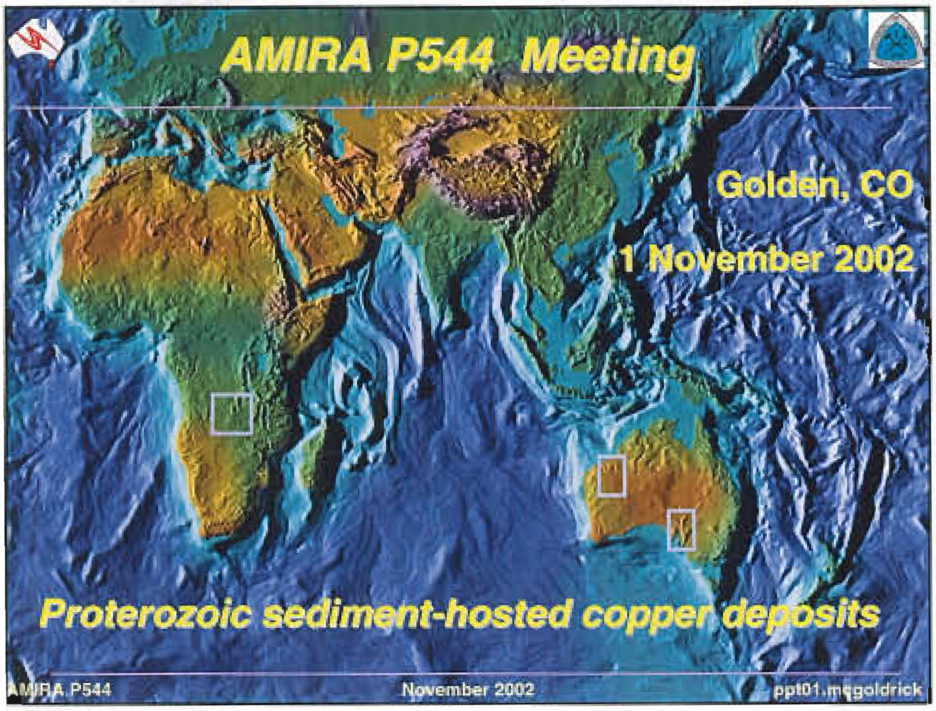
P544 – Proterozoic Sediment-hosted Copper Deposits

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

Contents



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, CSM (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 Mackay, 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
- 2002 Annual Report due January 2003
- 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 Mackay (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 Konkola 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

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 - Kafue Anticline
- Chambishi Basin
  - basement topography
  - (growth faults)
  - ore siting

Copperbelt deformation history
- structural history of Katangan cf Muva & Lufubu
- thrust at top of Mwashia

Orebody geometry/geology
- Nkana
- Konkola North
- Chambishi basin deposits
- arenite-hosted deposits

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

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Sponsors Meeting Golden November 2002

Meeting Format

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

- Chambishi basin deposits
- ZCB regional stratigraphy
- Review & synthesis

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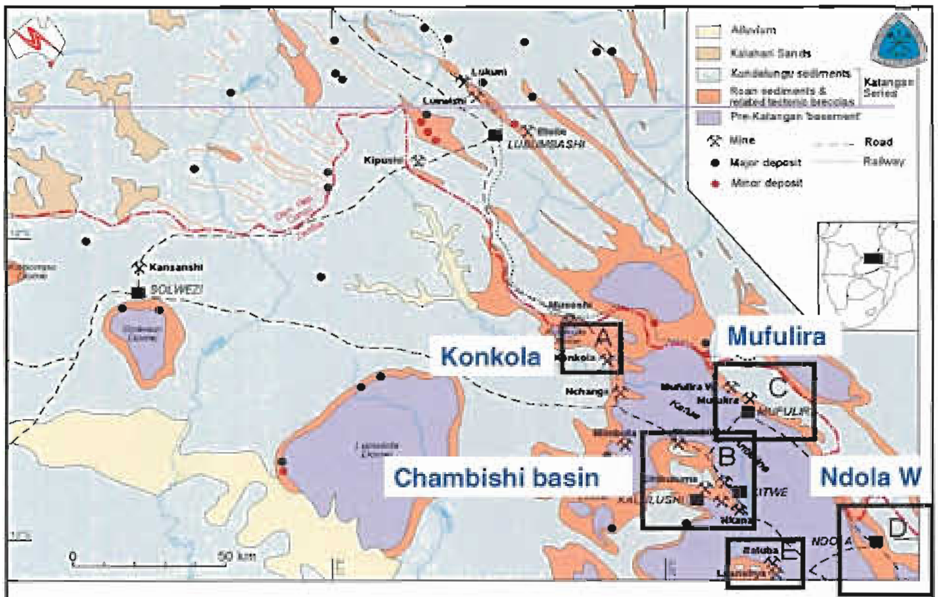

Principle Areas of Study

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?

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Key findings: this meeting

Argillite-hosted deposits:

- Cu, Co, Ag, Bi and Au (?Mo) are 'ore-association' elements
- As, Sb, Ni, Pb, Tl and Zn are at levels < or = 'average shales'
- 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

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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

Key findings: this meeting (con)

Roan Chemostratigraphy:

- Upper Roan siliciclastics are K_2O-rich & K_2O/Al_2O_3 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 Nkana/Mindola ores have the lightest C & O isotope signature
- hence C & O isotopes may be vectors to ore

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Key findings: this meeting (con)

Geochronolgy

- all xenotime ages (so far) are consistent with all mineralisation being epigentic
- 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

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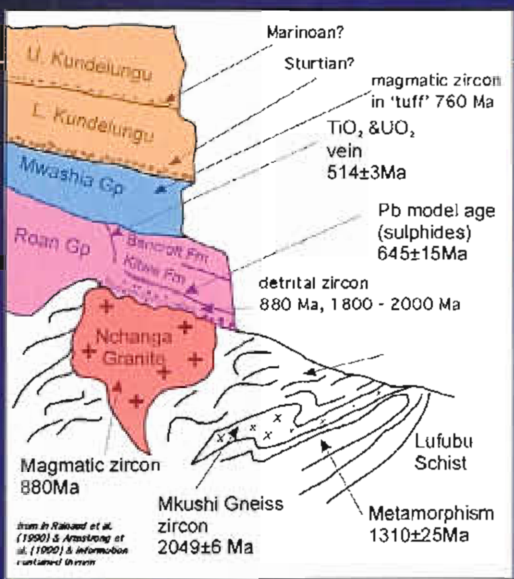
Key findings: this meeting (con)

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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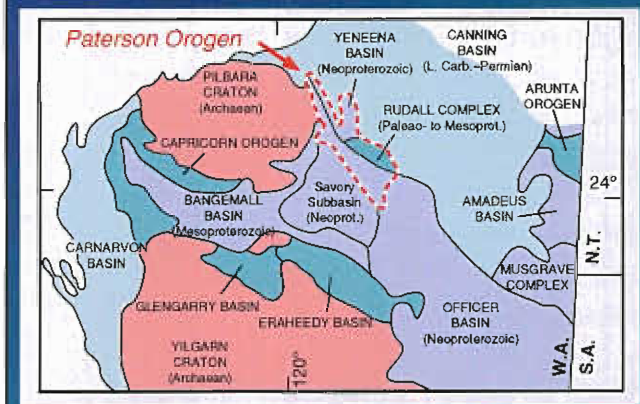
Geological development and mineralisation Yeneena Basin – Paterson Orogen, W.A.

Robert Scott
Centre for Ore Deposit Research

CODES / CSM AMIRA PROJECT P544 — NOVEMBER MEETING, 2002

Paterson Orogen



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

Phanerozoic
Post- c.1600 Ma
Pre- c.1600 Ma
Archaean

Paterson Orogen

- Paterson Orogen consists of three main elements:
  - Rudall Complex (Palaeo- to Mesoproterozoic, >2015–1765 Ma)
  - Yeneena Supergroup (Neoproterozoic, <1250–816 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

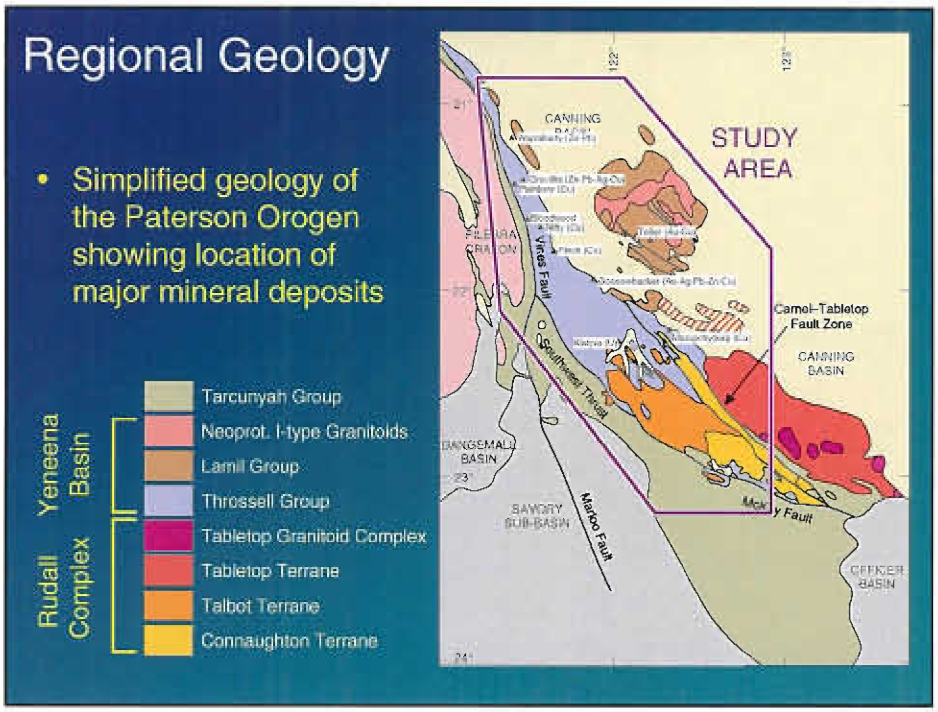
- Neoproterozoic sedimentary rocks of the Yeneena Basin, within the Paterson Orogen, host the giant Telfer Au-Ag deposit, stratabound copper deposits (e.g. Nifty) and carbonate-replacement Zn-Pb deposits (Warrabarty)
- The age, setting, structural evolution and mineral endowment of the Yeneena Basin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

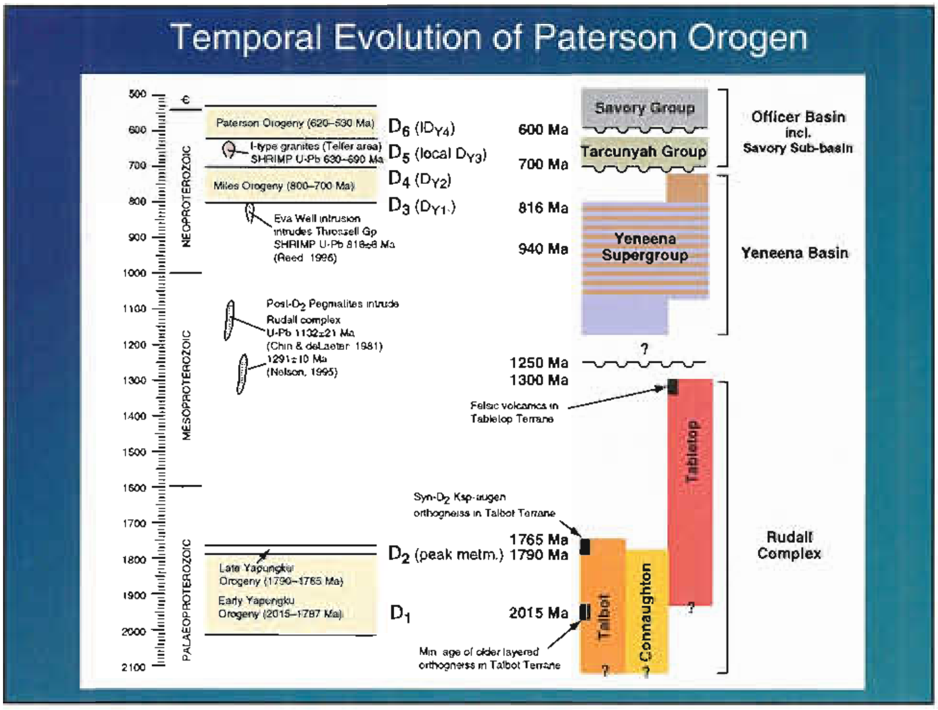
Aims

- 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
Tarcunyah Group
Neoprot. I-type Granitoids
Lamil Group
Throssell Group
Tabletop Granitoid Complex
Tabletop Terrane
Talbot Terrane
Connaughton Terrane
Yeneena Basin
Rudall Complex
CANNING BASIN
STUDY AREA
PILBARA CRATON
Vines Fault
Camel–Tabletop Fault Zone
CANNING BASIN
Southwest Thrust
BANGEMALL BASIN
SAVORY SUB-BASIN
Manoo Fault
OFFICER BASIN


Temporal Evolution of Paterson Orogen
NEOPROTEROZOIC
MESOPROTEROZOIC
PALAEOPROTEROZOIC
Paterson Orogeny (620–530 Ma)
I-type granites (Telfer area) SHRIMP U-Pb 630–690 Ma
Miles Orogeny (800–700 Ma)
Eva Well intrusion intrudes Throssell Gp SHRIMP U-Pb 816±6 Ma (Reed 1996)
Post-D2 Pegmatites intrude Rudall complex U-Pb 1132±21 Ma (Chin & deLaeter 1981) 1291±10 Ma (Nelson, 1995)
Late Yapungku Orogeny (1790–1765 Ma)
Early Yapungku Orogeny (2015–1787 Ma)
D6 (IDY4)
D5 (local DY3)
D4 (DY2)
D3 (DY1)
D2 (peak metm.)
D1
600 Ma
700 Ma
816 Ma
940 Ma
1250 Ma
1300 Ma
1765 Ma
1790 Ma
2015 Ma
Felsic volcanics in Tabletop Terrane
Syn-D2 Ksp-augen orthogneiss in Talbot Terrane
Min. age of older layered orthogneiss in Talbot Terrane
Savory Group
Tarcunyah Group
Yeneena Supergroup
Tabletop
Talbot
Connaughton
Officer Basin incl. Savory Sub-basin
Yeneena Basin
Rudall Complex

Metal Endowment

- Telfer (Au-Cu) *Malu 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) *Broadhurst 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 *Broadhurst Formation, Throssell Group*
  - 140 Mt @ 0.5% Cu, including 51.3 Mt @ 1.0% Cu, 0.04% Co
- Warrabarty (Zn–Pb) *Broadhurst Formation, Throssell Group*
  - sub-economic
- Kintyre (U) *Yandagooge Formation, Rudall Complex*
  - 36,000 t U_3O_8 @ 1.5–4.0 kg U_3O_8 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 D_2 (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, dolerite 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 sulfidic shale, minor sandstone and dolomite
  - records rapid subsidence of Yeneena Basin

View west along Nifty Pit. Steeply S-dipping dolomitic 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 Telfer, 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

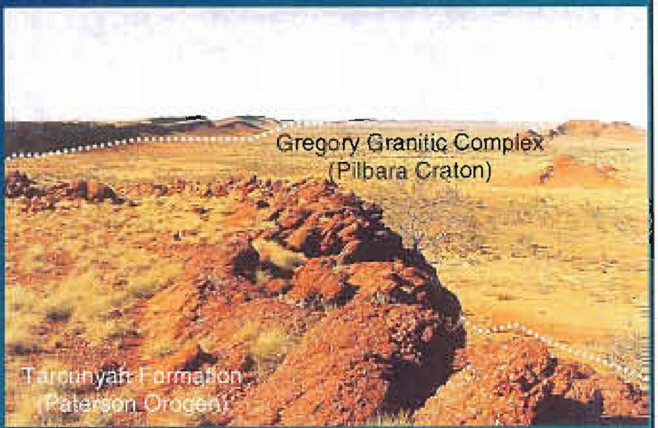
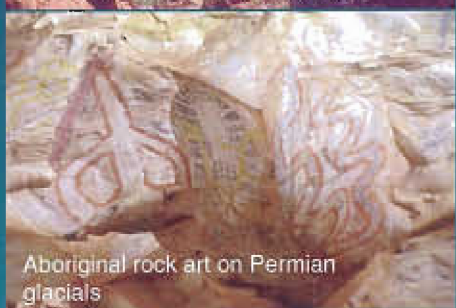


Photo (looking south): Williams and Trendall (1998)

Canning Basin (Permian)

- Permian fluvioglacial 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 Lamil Groups, consistent with possible underlying crustal weakness (i.e. northern continuation of Camel–Tabletop fault zone)

Mesas of Permian glacials. View west from above Christmas Pool.



Aboriginal rock art on Permian glacials

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 (D_{Y2}) affecting the Throssell Group (i.e. main phase of basin inversion during Miles Orogeny, regional D_4)
  - 717±5 Ma $^{40}Ar/^{39}Ar$ 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 framboidal pyrite
  - occurs within the hinges of D_{Y2} folds, along the associated cleavage and faults and within syn-D_{Y2} pressure shadows and cleavage parallel veins

Maroochydore
YNC-82, 144 m

Nifty
THRD 780 W1
386–396 m

Mineralisation styles

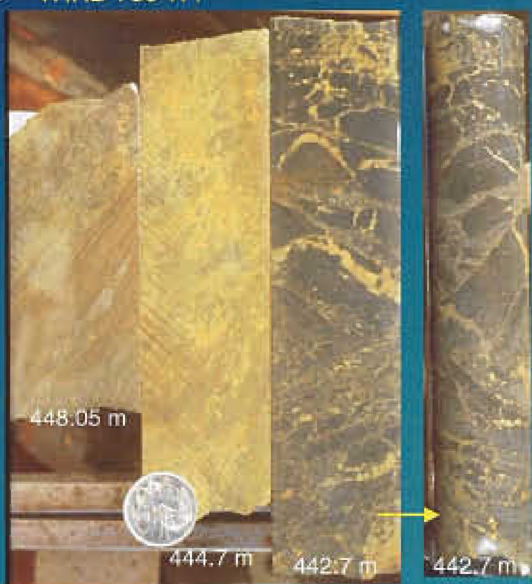
- Maroochydore
  - chalcopyrite predominantly disseminated or precipitated in dilational sites
- Nifty
  - massive chalcopyrite replacive, associated with intense quartz-dolomite alteration
  - lesser disseminated and vein-hosted mineralisation

Nifty
THRD 780 W1

Mineralisation styles

Nifty
THRD 780 W1

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



Deposit comparisons

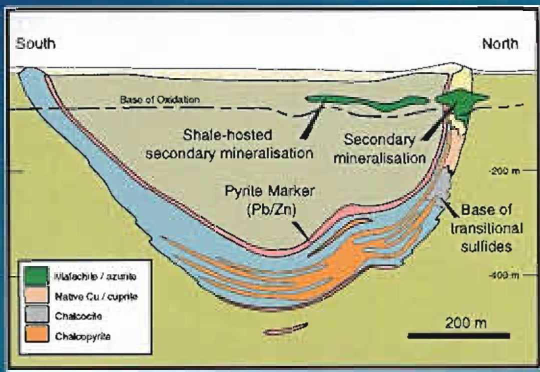
- Fluid inclusions
  - inclusions from syn-mineralisation veins at Maroochydore and Nifty have similar salinities (8–27 eq. wt % NaCl), homogenisation temperatures (180°–450°C) and estimated trapping temperatures (median values: 360°–440°C), consistent with epigenetic mineralisation at greenschist facies metamorphic conditions
- Sulfur isotopes
  - (i) diagenetic framboidal and (ii) pre- to syn-mineral euhedral pyrite:
    - (i) $\delta^{34}S$ +16 to –27 ‰ (ii) $\delta^{34}S$ +3.8 to –12 ‰ (Nifty)
    - (i) $\delta^{34}S$ –22 to –31 ‰ (ii) $\delta^{34}S$ –4.0 to –10 ‰ (Marooch.)
  - chalcopyrite:
    - $\delta^{34}S$ +6 to –6 ‰ (Nifty)
    - $\delta^{34}S$ –13 to –23 ‰ (c.g., Maroochydore)
    - $\delta^{34}S$ –25 to –31 ‰ (f.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_{Y2} 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_2S activity and decreased fO2 due to interaction between Cu-bearing fluid and sulfidic sediments
- At Nifty, Anderson (1999) argues
  - homogeneous sulfur source for chalcopyrite and coeval (euhedral) pyrite
  - H_2S dominant in the fluid phase not sourced from host rocks
  - syn-D_{Y2} mineralisation with fluids ascending thrusts interpreted to intersect the hinge and north limb of the Nifty 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 D_{Y2} folding
- Lateral rather than vertical fluid flow implied.



Idealised cross-section of the Nifty ore body showing mineralogical zonations (Hooper, 2002)

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

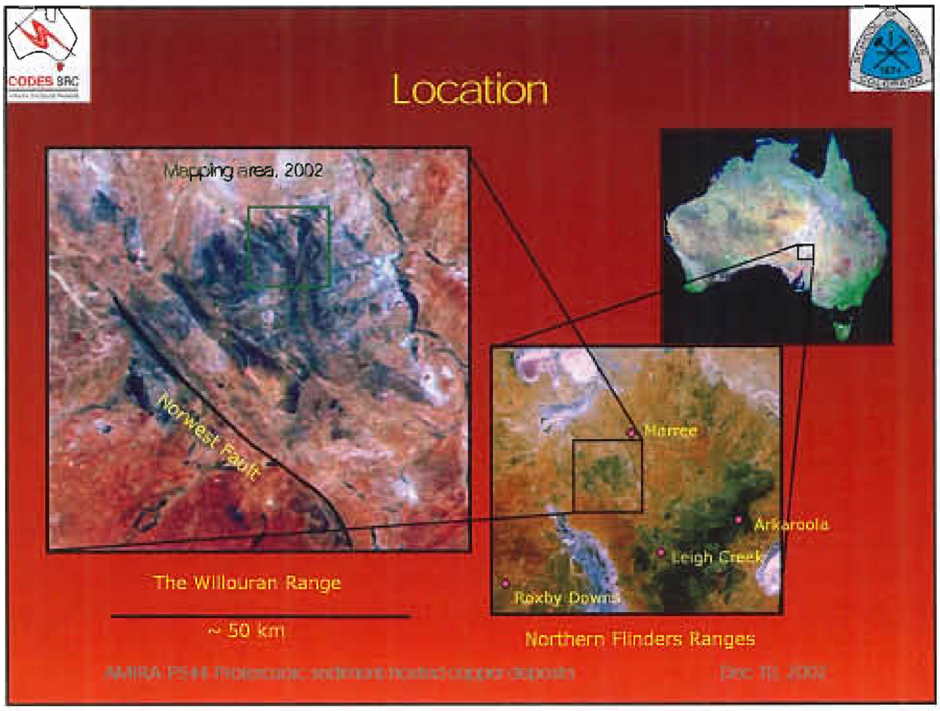
- Bruce Hooper, Ivan Jerkovic, Phil Shields (Straits Resources)
- Rio Tinto Exploration
- Leon Bagas (Geological Survey of Western Australia)
- Alistair Reed (Mineral Resources Tasmania)

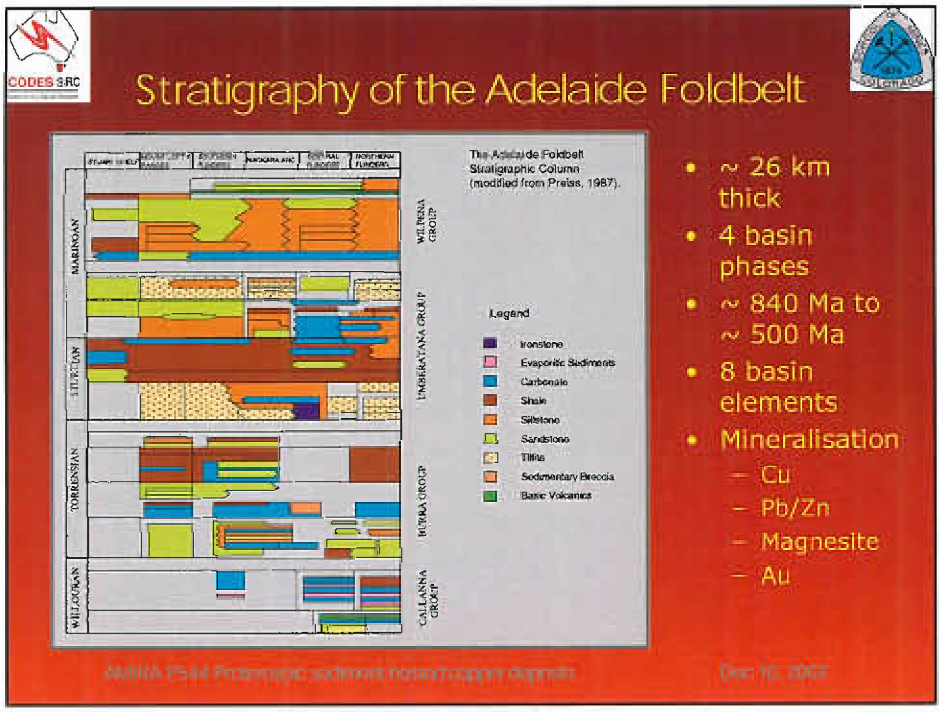
Structure of the Curdimurka Subgroup, northern Willouran Range, South Australia.

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

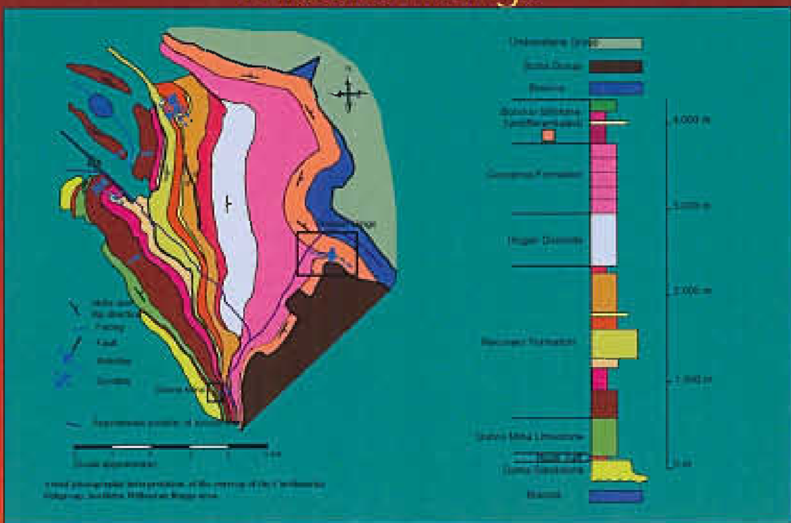

CODES SRC
Location
Mapping area, 2002
Norwest Fault
The Willouran Range
~ 50 km
Marree
Arkaroola
Leigh Creek
Roxby Downs
Northern Flinders Ranges
AMIRA P544 Proterozoic sediment hosted copper deposits
Dec 10, 2002

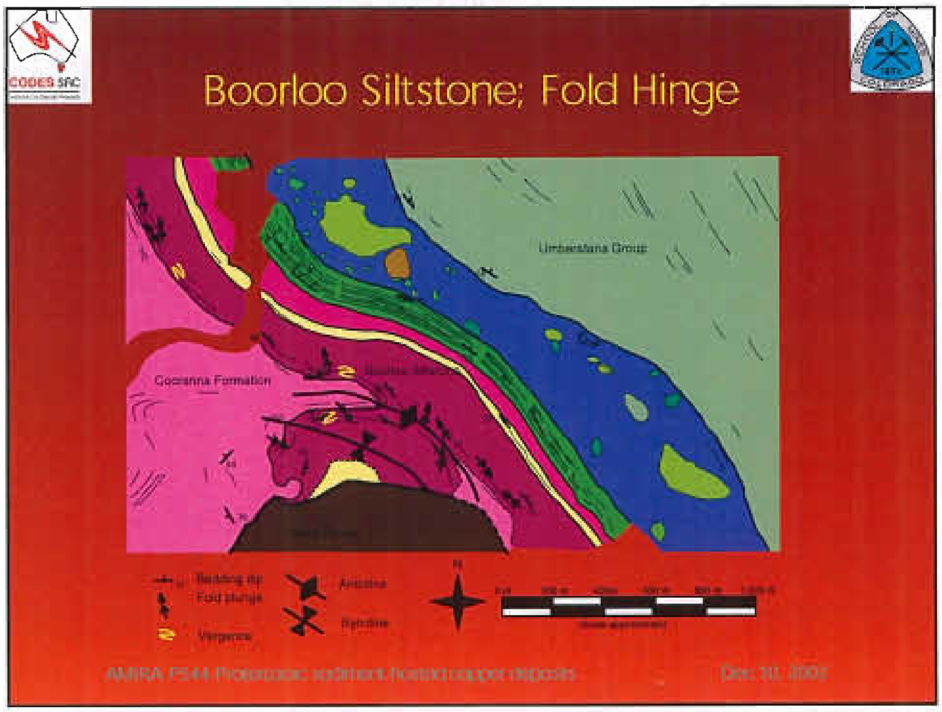

CODES SRC
Stratigraphy of the Adelaide Foldbelt
The Adelaide Foldbelt Stratigraphic Column (modified from Preiss, 1987).
MARINOAN
STURTIAN
TORRENSIAN
WILLOURAN
WILPENA GROUP
UMBERATANA GROUP
BURRA GROUP
CALLANNA GROUP
Legend
Ironstone
Evaporitic Sediments
Carbonate
Shale
Siltstone
Sandstone
Tillite
Sedimentary Breccia
Basic Volcanics
• ~ 26 km thick
• 4 basin phases
• ~ 840 Ma to ~ 500 Ma
• 8 basin elements
• Mineralisation
– Cu
– Pb/Zn
– Magnesite
– Au
AMIRA P544 Proterozoic sediment hosted copper deposits
Dec 10, 2002

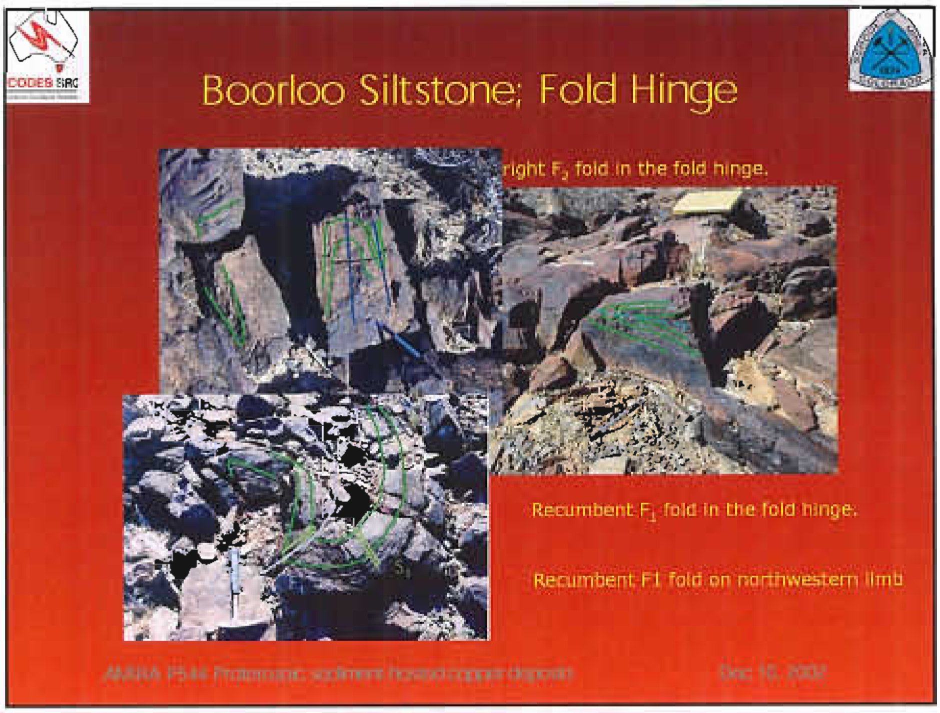
Introduction

- 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_1?)
- Cu mineralisation has a structural control

Geology of the northern Willouran Range




Boorloo Siltstone; Fold Hinge
Umberatana Group
Cooranna Formation
Bedding dip
Fold plunge
Vergence
Anticline
Syncline
N
AMIRA P544 Proterozoic sediment hosted copper deposits
Dec 10, 2002


Boorloo Siltstone; Fold Hinge
right F2 fold in the fold hinge.
Recumbent F1 fold in the fold hinge.
Recumbent F1 fold on northwestern limb
AMIRA P544 Proterozoic sediment hosted copper deposits
Dec 10, 2002

CODES SRC

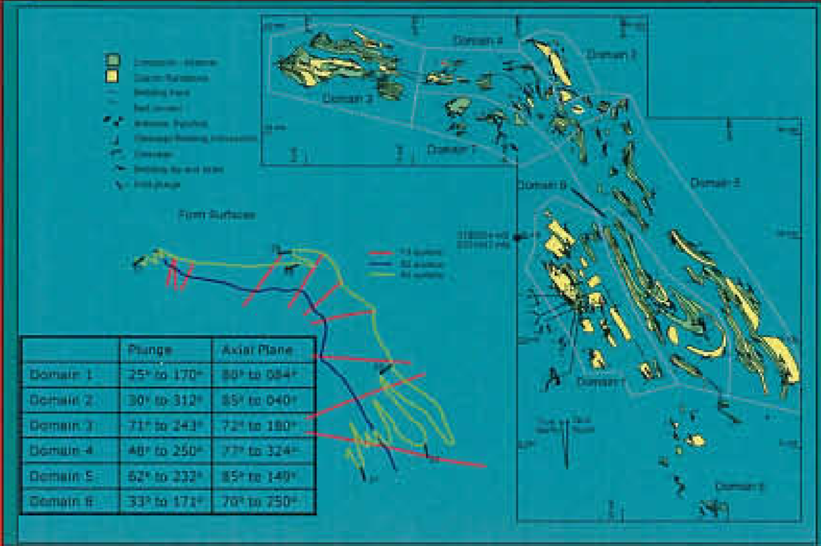
F_1 - Boorloo Siltstone

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

CODES SRC

F_1 Regionally – Norwest Fault

Dunns Mine; Outcrop 1.



	Plunge	Axial Plane
Domain 1	25° to 170°	80° to 084°
Domain 2	30° to 312°	85° to 040°
Domain 3	71° to 243°	72° to 180°
Domain 4	48° to 250°	77° to 324°
Domain 5	62° to 232°	85° to 140°
Domain 6	33° to 171°	70° to 250°

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, with thickening in the hinges and thinning on limbs

Mineralisation; Dunns Mine

Mineralisation Dunns Mine

Along strike of fault zone, looking north

Above, Malachite in fault breccia

Left, Malachite in a microvein

Dunns Mine Summary

- Limb of F_2 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 (Delamerian)
  - Upright, non-cylindrical, tight to isoclinal
  - Trend northwest – southeast
- F_3
  - Broad folds
  - Plunge to southwest

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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

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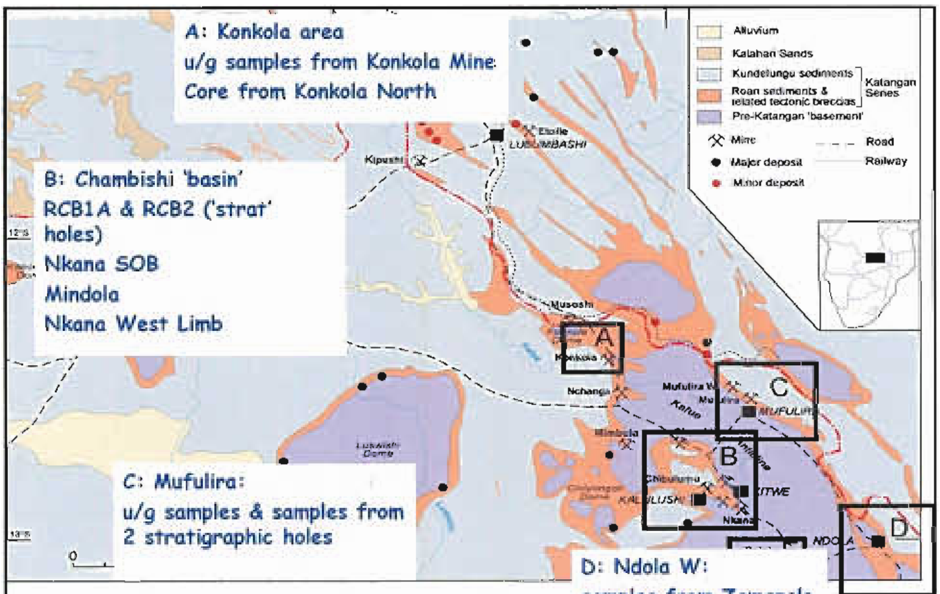
Questions:

- 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 process?
- are there chemical or isotopic signatures that can be used for chemostratigraphic correlations?



Sample locations

Analytical techniques:

- Different sample sets analysed at three different labs for different element groups
- University of Tasmania: XRF major & trace analyses, pyrolysis C
- Becqueral: '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 frommthe Chambishi basin

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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

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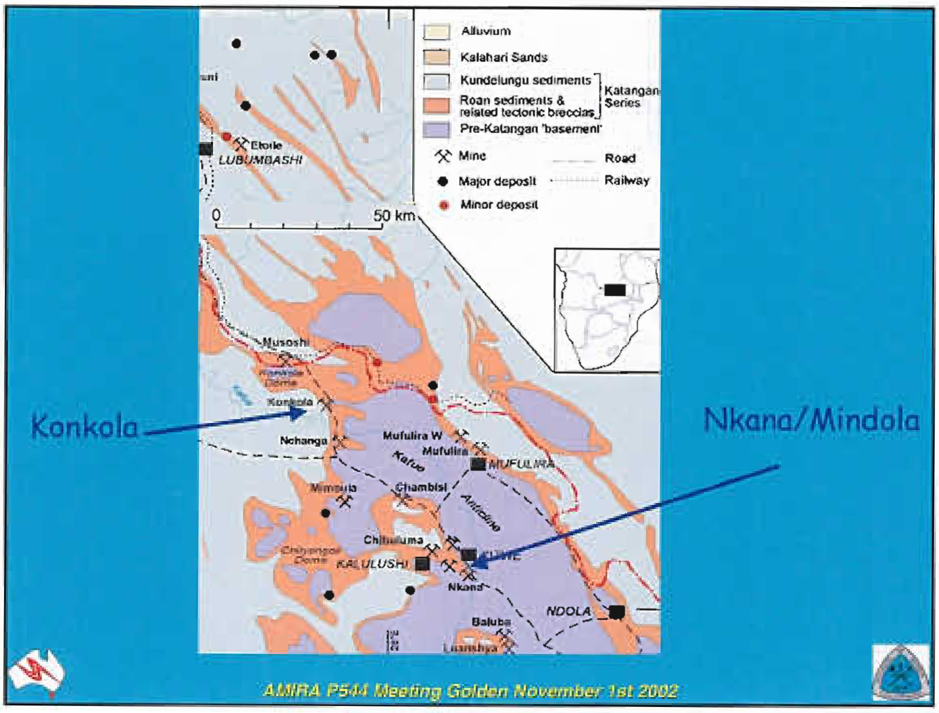
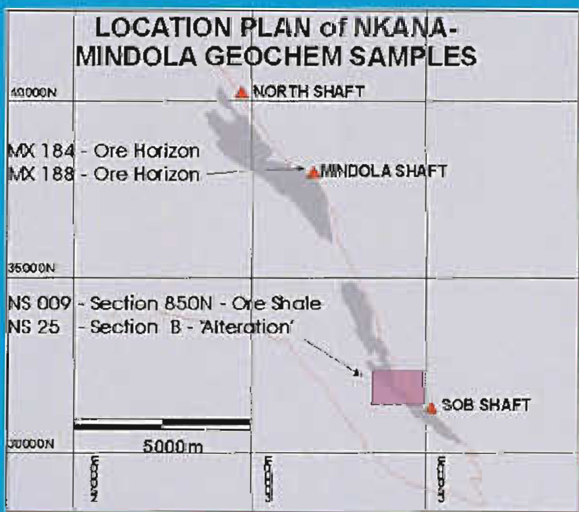


Data sets

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

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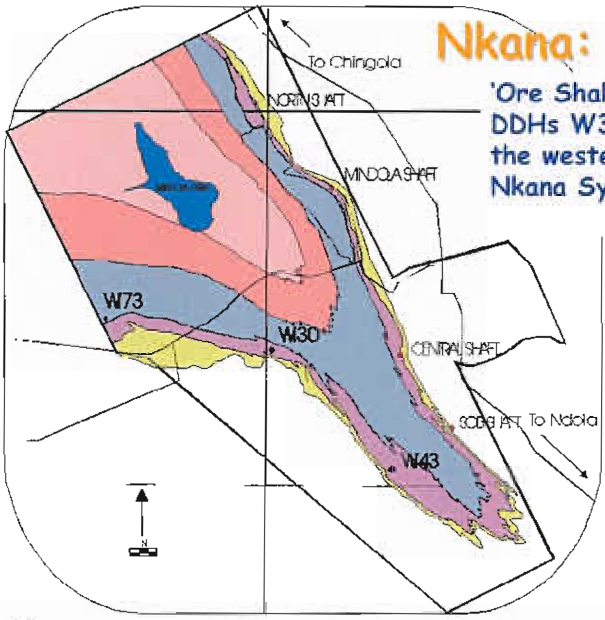
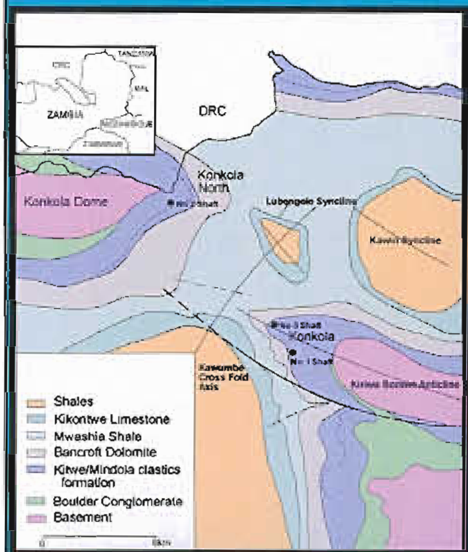


Nkana: West Limb

'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

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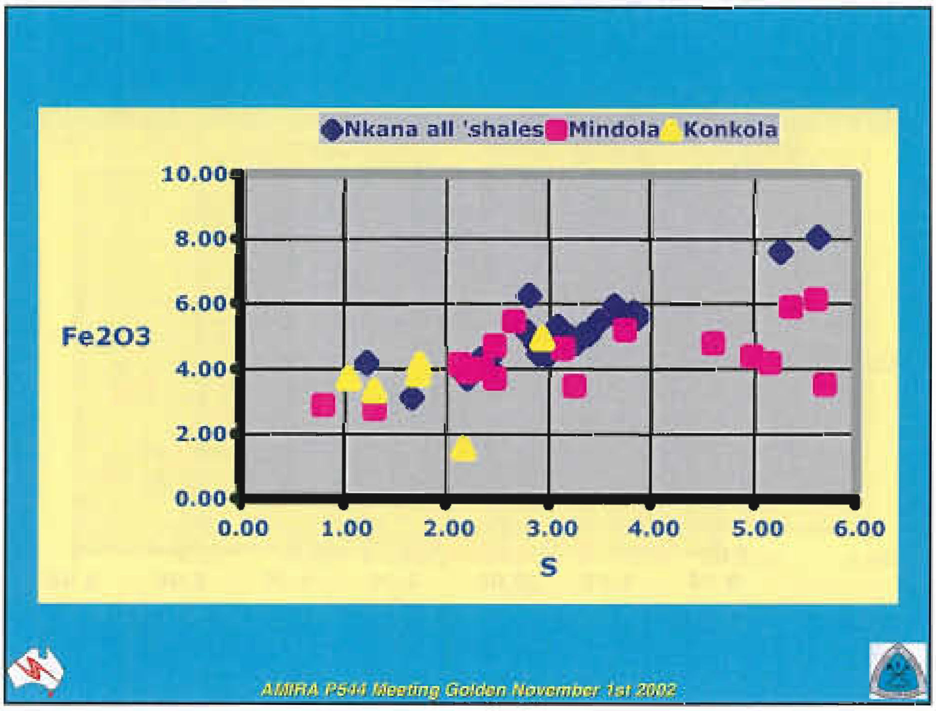
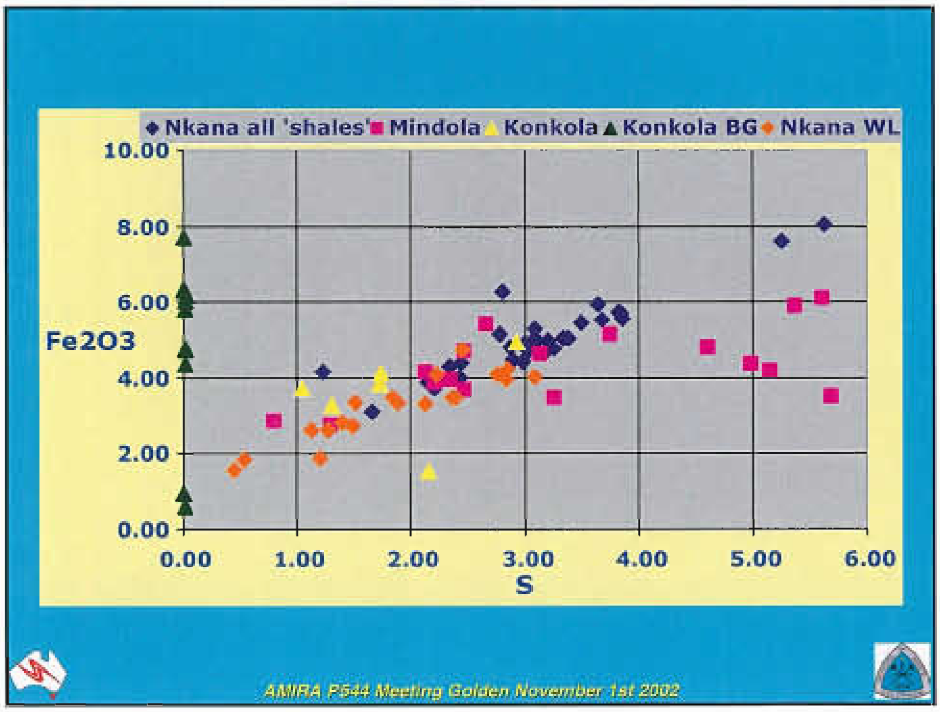
Elements

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




◆ Nkana all 'shales' ■ Mindola ▲ Konkola ▲ Konkola BG ◆ Nkana WL
10.00
8.00
6.00
Fe2O3
4.00
2.00
0.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
S
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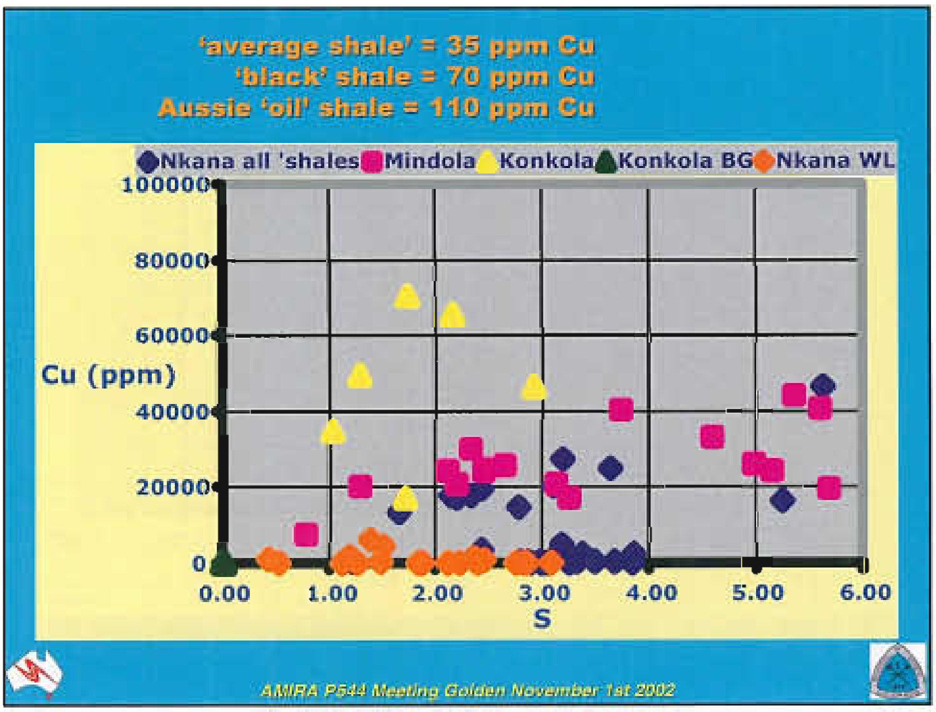
'average shale' = 35 ppm Cu
'black' shale = 70 ppm Cu
Aussie 'oil' shale = 110 ppm Cu
Nkana all 'shales Mindola Konkola Konkola BG Nkana WL
100000
80000
60000
Cu (ppm)
40000
20000
0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
S
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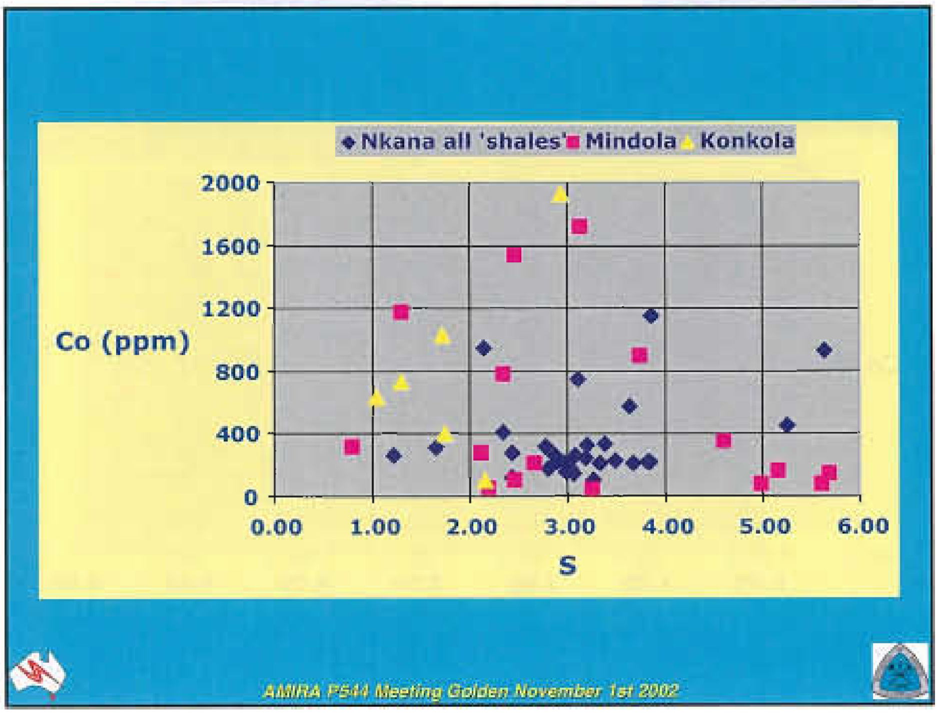
Nkana all 'shales' Mindola Konkola
Co (ppm)
2000
1600
1200
800
400
0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
S
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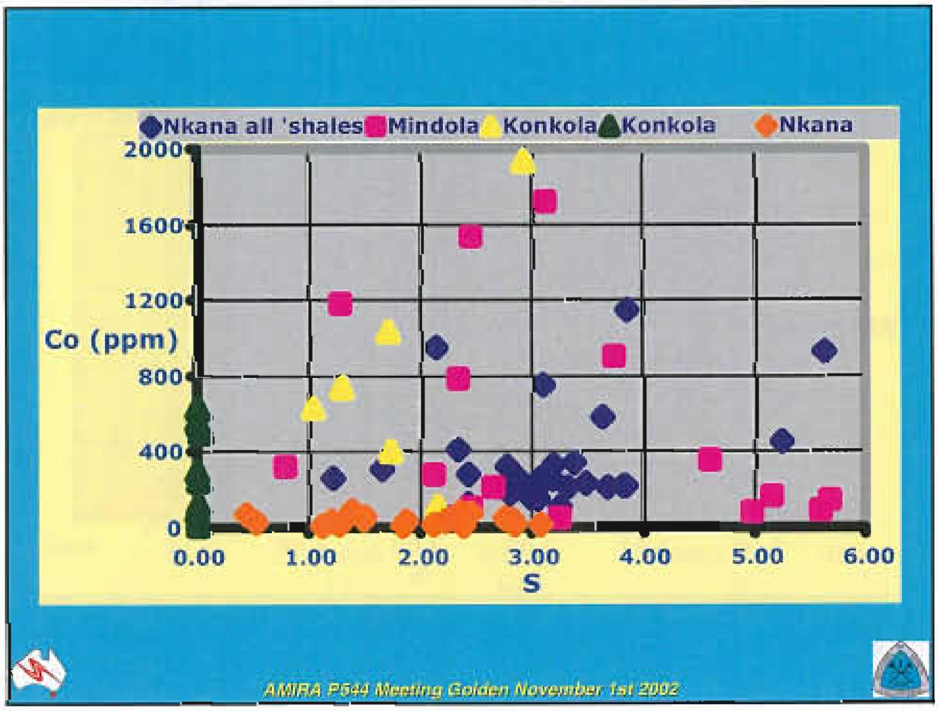
Nkana all 'shales Mindola Konkola Konkola Nkana
Co (ppm)
2000
1600
1200
800
400
0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
S
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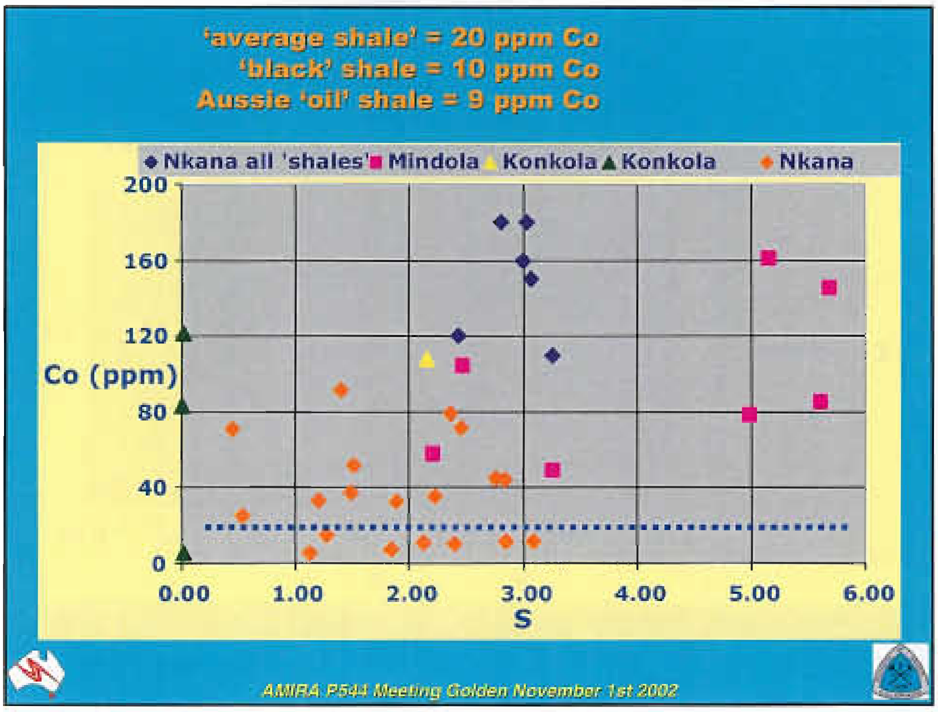
'average shale' = 20 ppm Co
'black' shale = 10 ppm Co
Aussie 'oil' shale = 9 ppm Co
Nkana all 'shales' Mindola Konkola Konkola Nkana
200
160
120
80
40
0
Co (ppm)
0.00 1.00 2.00 3.00 4.00 5.00 6.00
S
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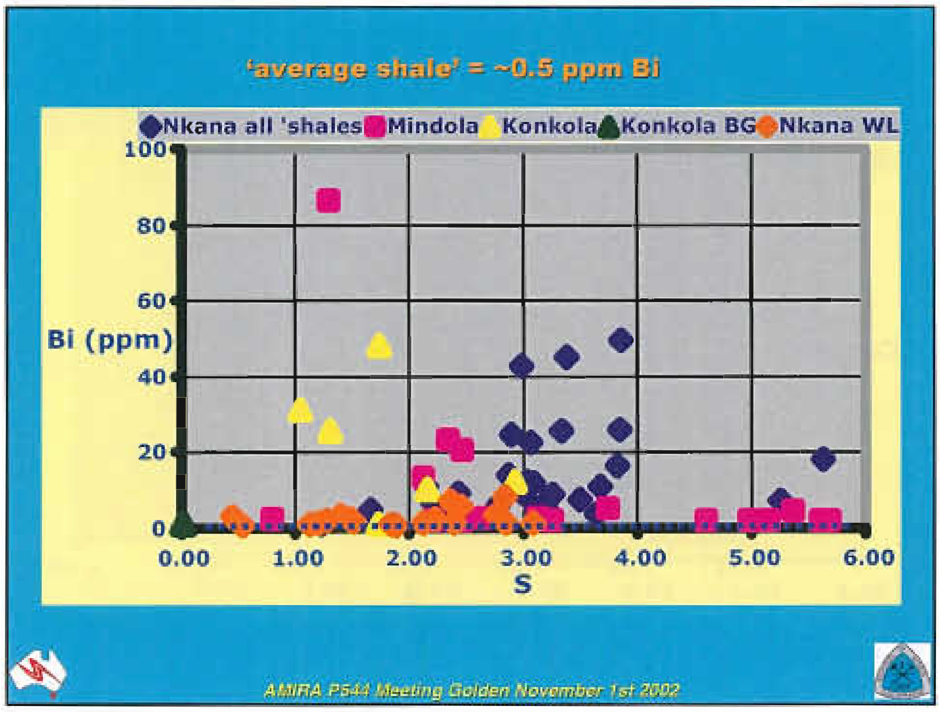
'average shale' = ~0.5 ppm Bi
Nkana all 'shales Mindola Konkola Konkola BG Nkana WL
100
80
60
40
20
0
Bi (ppm)
0.00 1.00 2.00 3.00 4.00 5.00 6.00
S
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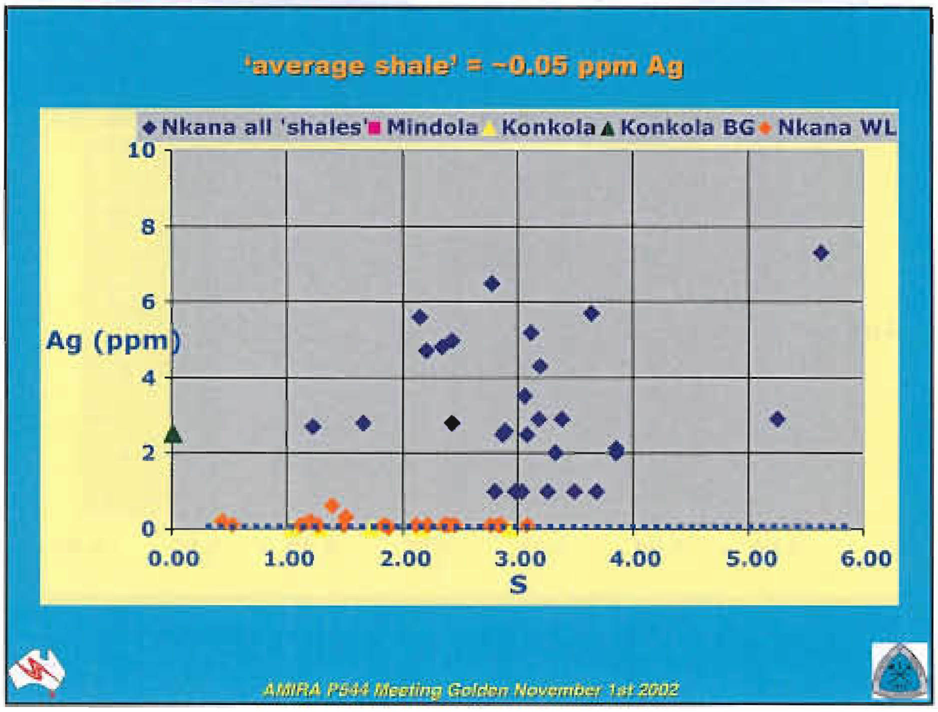
'average shale' = ~0.05 ppm Ag
Nkana all 'shales' Mindola Konkola Konkola BG Nkana WL
Ag (ppm)
10
8
6
4
2
0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
S
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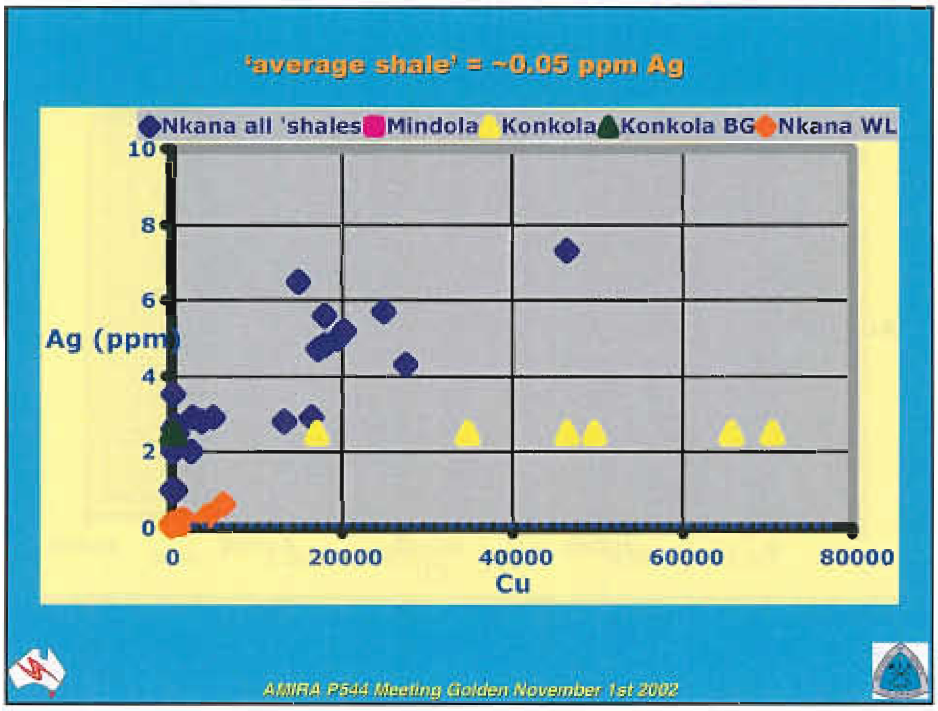
'average shale' = ~0.05 ppm Ag
Nkana all 'shales Mindola Konkola Konkola BG Nkana WL
Ag (ppm)
10
8
6
4
2
0
0
20000
40000
60000
80000
Cu
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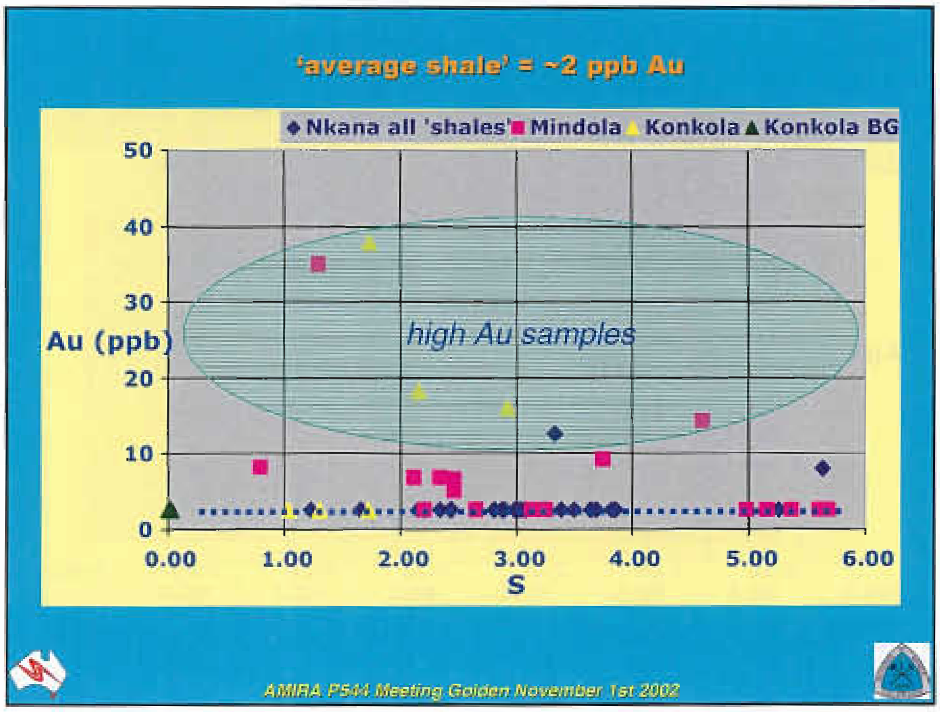

'average shale' = ~2 ppb Au
Nkana all 'shales'
Mindola
Konkola
Konkola BG
high Au samples
Au (ppb)
S
50
40
30
20
10
0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
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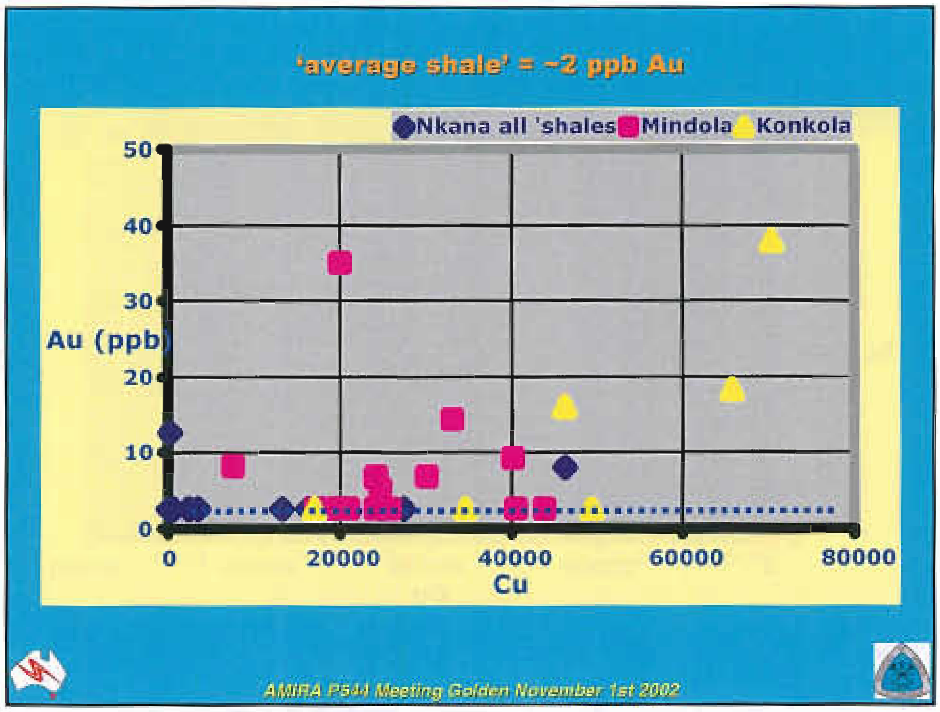

'average shale' = ~2 ppb Au
Nkana all 'shales
Mindola
Konkola
Au (ppb)
Cu
50
40
30
20
10
0
0
20000
40000
60000
80000
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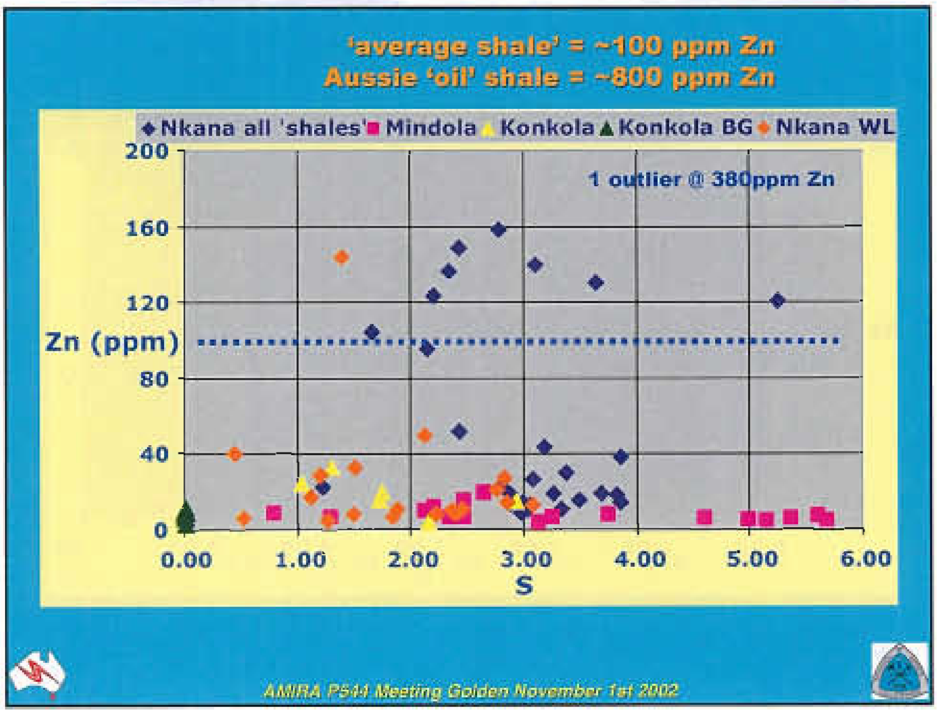

'average shale' = ~100 ppm Zn
Aussie 'oil' shale = ~800 ppm Zn
Nkana all 'shales' Mindola Konkola Konkola BG Nkana WL
1 outlier @ 380ppm Zn
Zn (ppm)
200
160
120
80
40
0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
S
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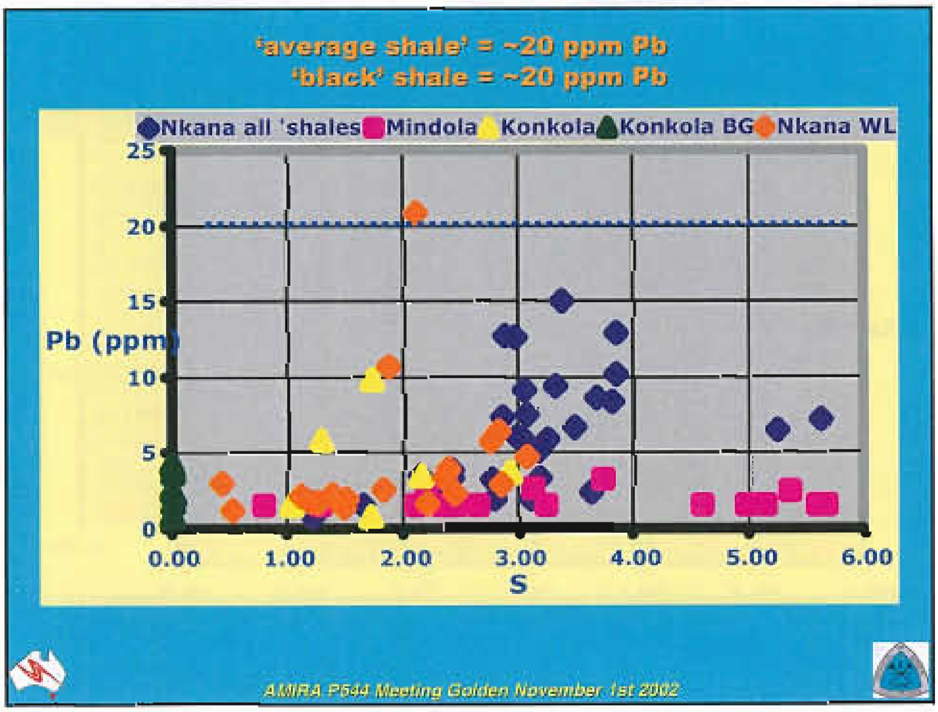

'average shale' = ~20 ppm Pb
'black' shale = ~20 ppm Pb
Nkana all 'shales Mindola Konkola Konkola BG Nkana WL
Pb (ppm)
25
20
15
10
5
0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
S
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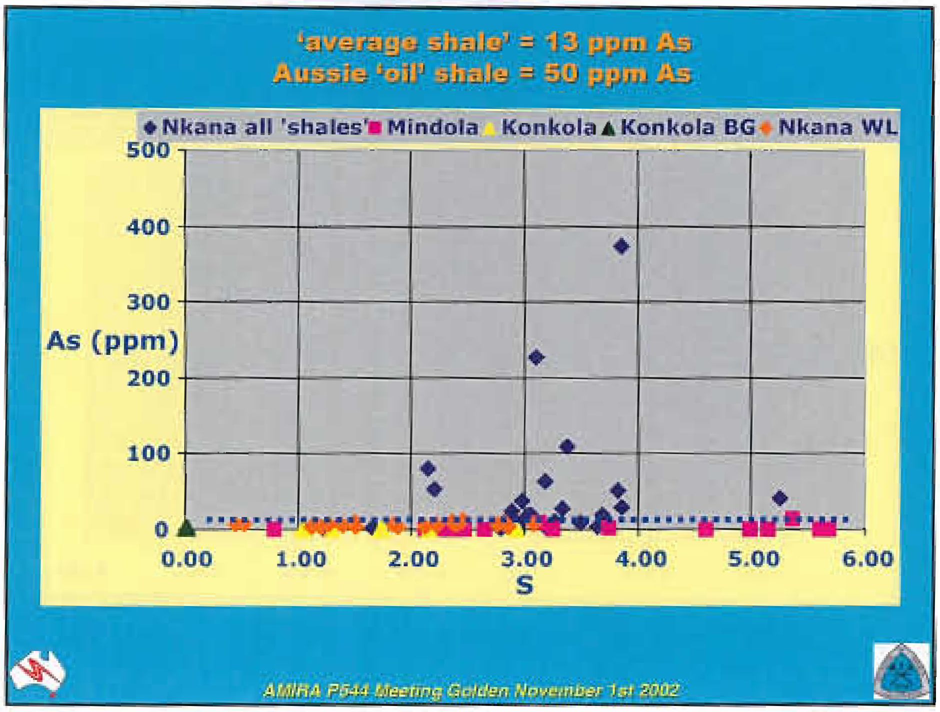
'average shale' = 13 ppm As
Aussie 'oil' shale = 50 ppm As
Nkana all 'shales' Mindola Konkola Konkola BG Nkana WL
As (ppm)
500
400
300
200
100
0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
S
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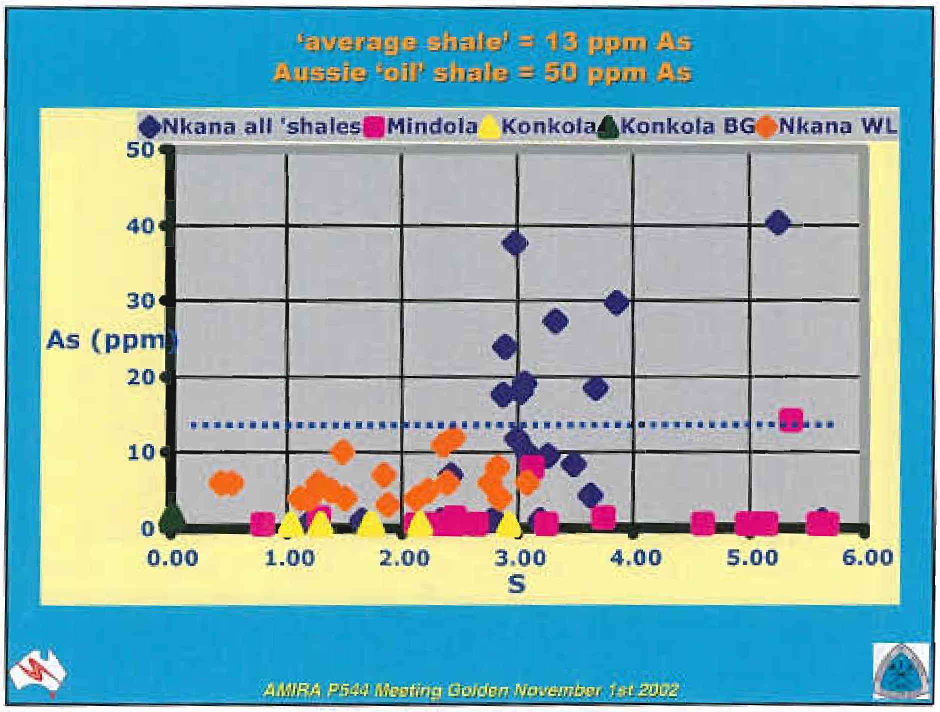
'average shale' = 13 ppm As
Aussie 'oil' shale = 50 ppm As
Nkana all 'shales Mindola Konkola Konkola BG Nkana WL
As (ppm)
50
40
30
20
10
0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
S
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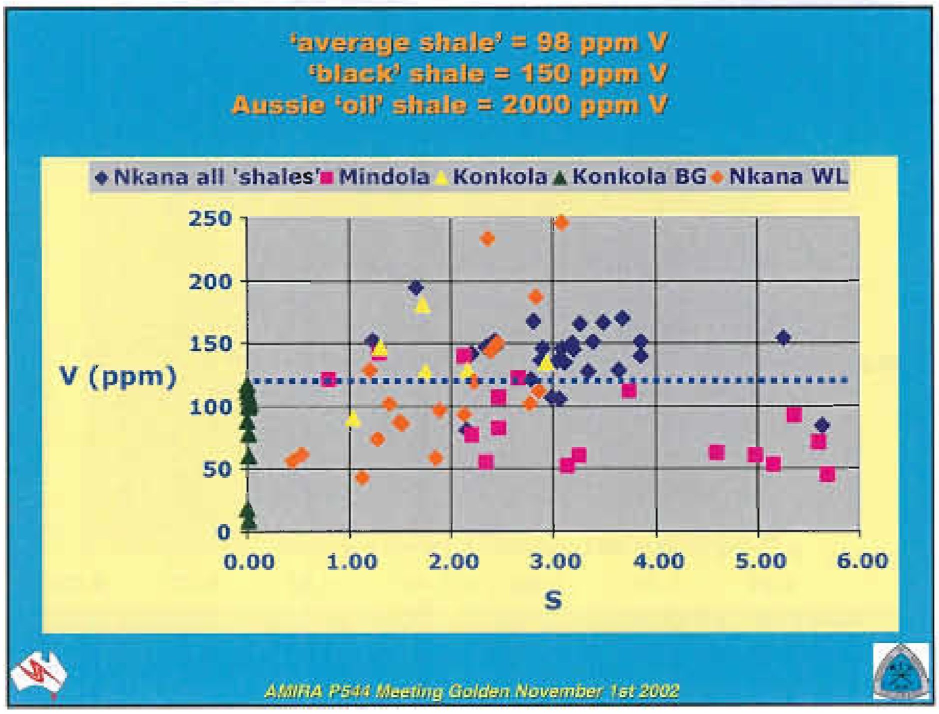
'average shale' = 98 ppm V
'black' shale = 150 ppm V
Aussie 'oil' shale = 2000 ppm V
Nkana all 'shales'
Mindola
Konkola
Konkola BG
Nkana WL
V (ppm)
S
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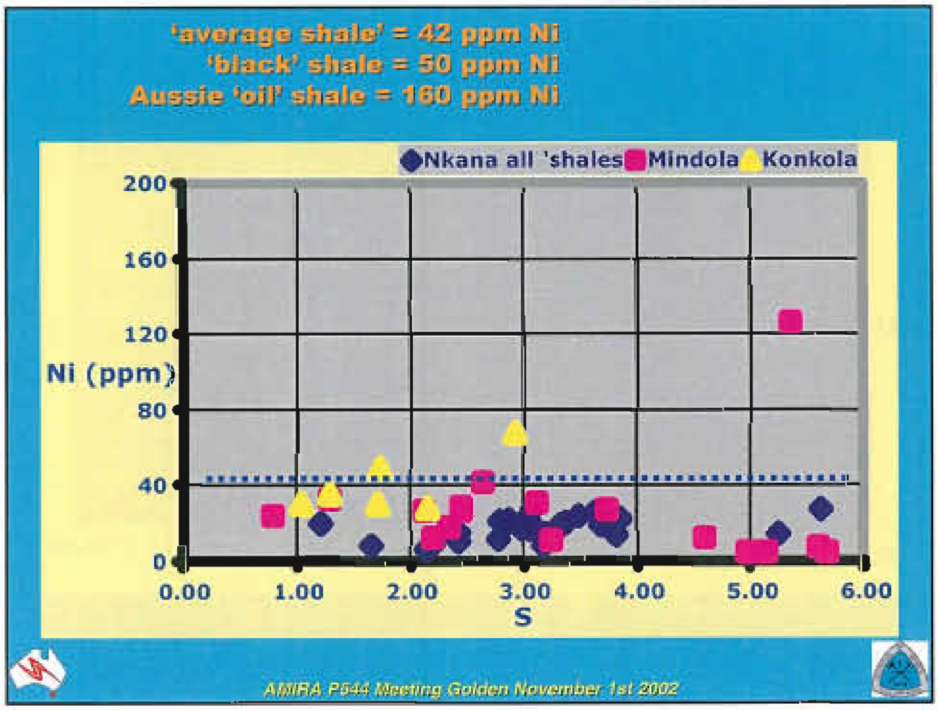
'average shale' = 42 ppm Ni
'black' shale = 50 ppm Ni
Aussie 'oil' shale = 160 ppm Ni
Nkana all 'shales
Mindola
Konkola
Ni (ppm)
S
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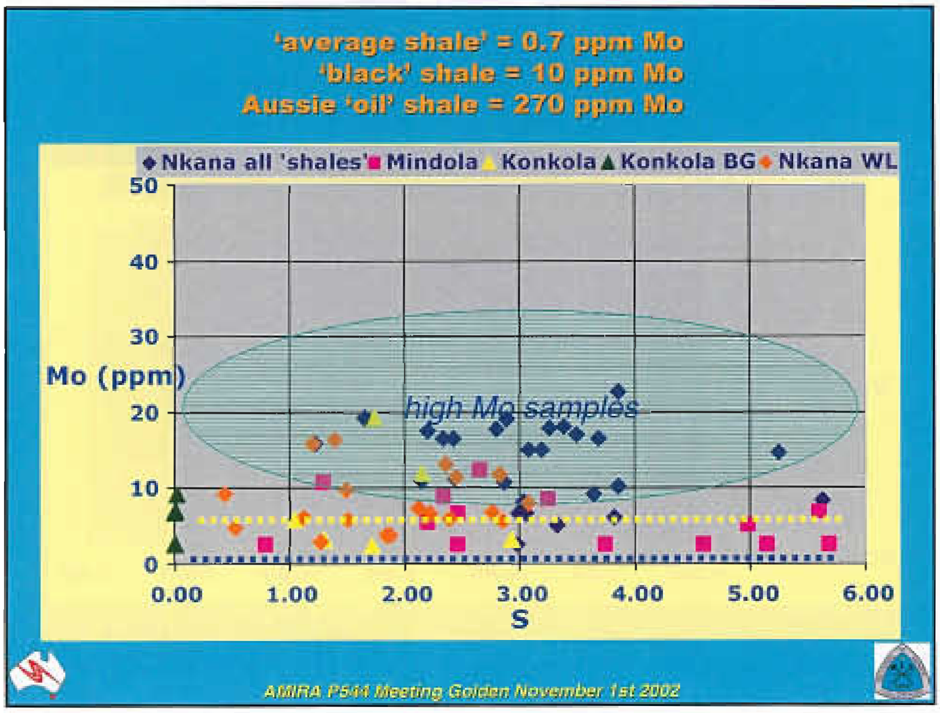
'average shale' = 0.7 ppm Mo
'black' shale = 10 ppm Mo
Aussie 'oil' shale = 270 ppm Mo
Nkana all 'shales' Mindola Konkola Konkola BG Nkana WL
Mo (ppm)
high Mo samples
0
10
20
30
40
50
0.00
1.00
2.00
3.00
4.00
5.00
6.00
S
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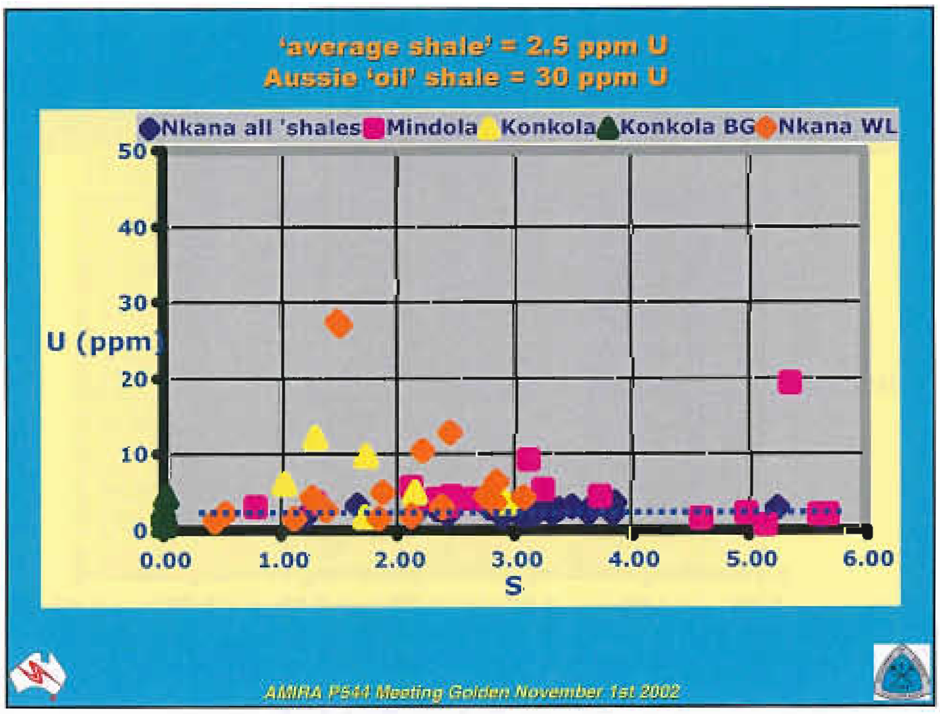
'average shale' = 2.5 ppm U
Aussie 'oil' shale = 30 ppm U
Nkana all 'shales Mindola Konkola Konkola BG Nkana WL
U (ppm)
0
10
20
30
40
50
0.00
1.00
2.00
3.00
4.00
5.00
6.00
S
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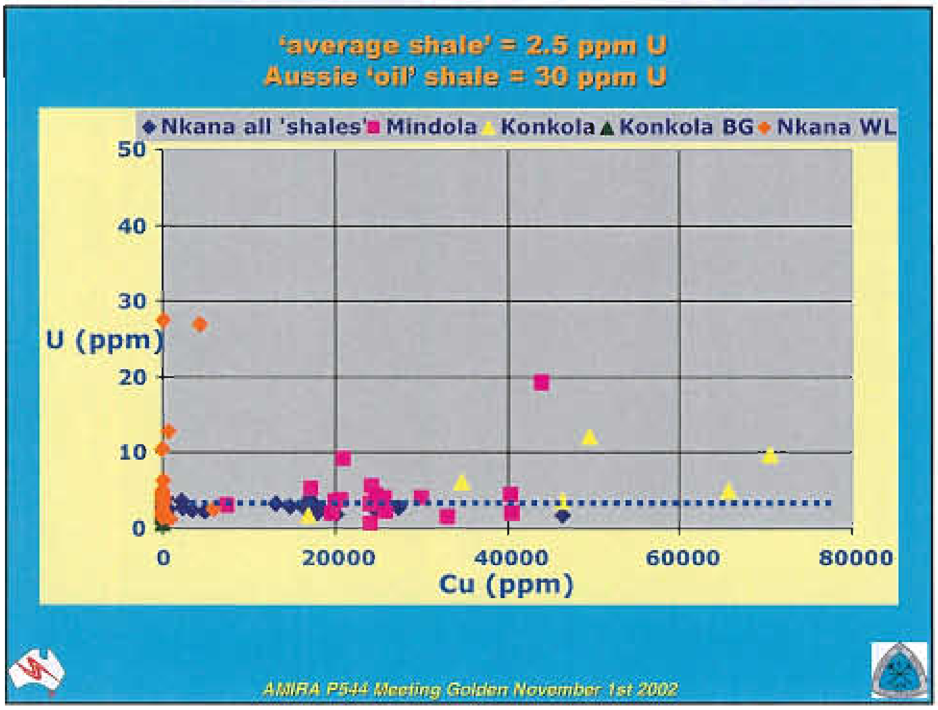
'average shale' = 2.5 ppm U
Aussie 'oil' shale = 30 ppm U
Nkana all 'shales' Mindola Konkola Konkola BG Nkana WL
U (ppm)
0
10
20
30
40
50
Cu (ppm)
0
20000
40000
60000
80000
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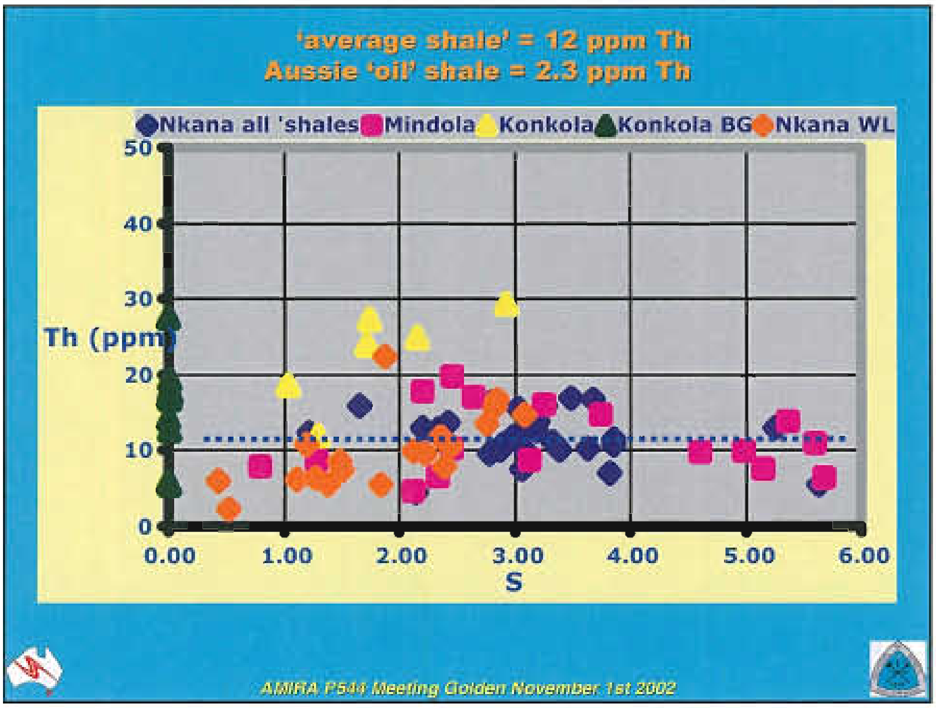
'average shale' = 12 ppm Th
Aussie 'oil' shale = 2.3 ppm Th
Nkana all 'shales Mindola Konkola Konkola BG Nkana WL
Th (ppm)
0
10
20
30
40
50
S
0.00
1.00
2.00
3.00
4.00
5.00
6.00
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Thallium

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

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Organic Carbon

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

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Organic Carbon (con)

Nkana:

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

Mufulira:

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

Konkola:

- 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 argillites 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

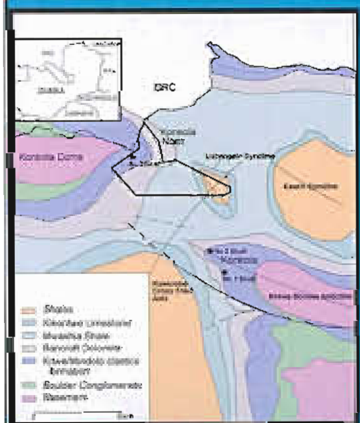
Clonclusions II

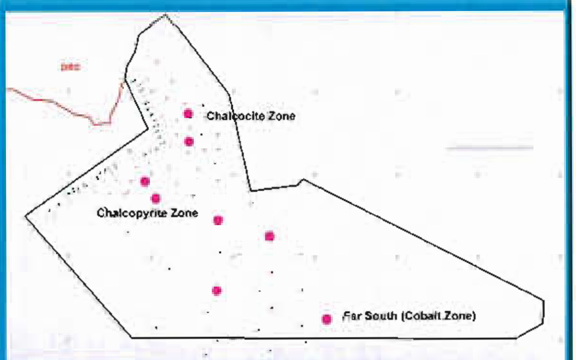
- Cu, Co, U, Au (?and Bi & Mo) are an 'oxidised' fluid signature
- low Tl is consistent with an oxidised ore fluid
- low organic C in some deposits (e.g., Konkola) may indicate all reductant was exhausted during ore precipitation
- variable Au tenor has implications for Au transport and ore-formation

Zambian Copper Belt Geochemistry:
Part IIa Konkola North

Nicky Pollington, Peter McGoldrick &
David Selley
CODES

Konkola North with Geochemical Sample Locations





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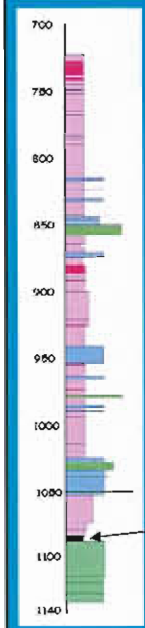
Simplified Geology for Kn6

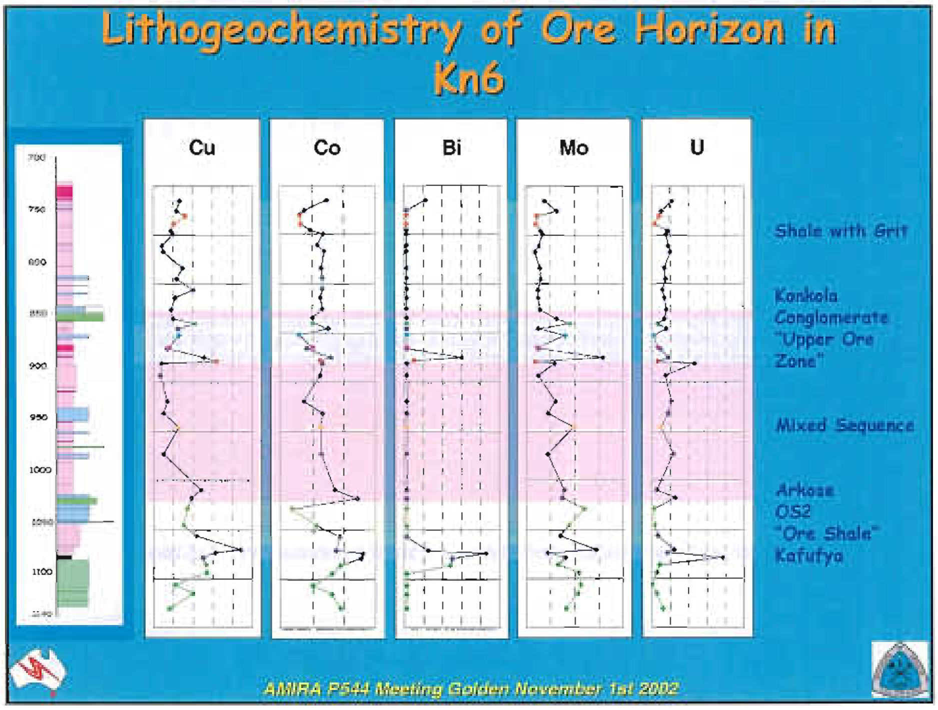


- Mwashia – fine dark silts
- Shale with Grit – fine dark silt with qtz and fspar grit
- Konkola Conglomerate
- "Upper Ore Zone" – dark silt with common py +- cpy
- Mixed Sequence – silt, sand, conglomerate
- Arkosic sandstone – conglomerate
- OS2 – mixed dark silt and sand
- "Ore Shale"
- Kafufya – 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
Cu
Co
Bi
Mo
U
Shale with Grit
Konkola Conglomerate "Upper Ore Zone"
Mixed Sequence
Arkose
OS2 "Ore Shale" Kafufya
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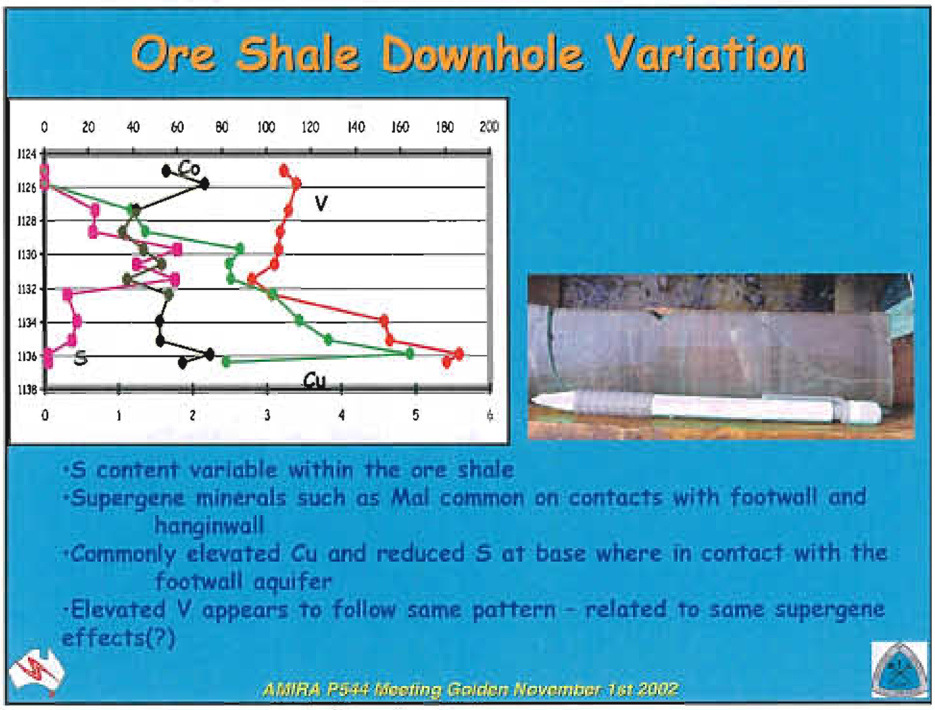
Ore Shale Downhole Variation
0 20 40 60 80 100 120 140 160 180 200
1124 1126 1128 1130 1132 1134 1136 1138
0 1 2 3 4 5 6
Co
V
S
Cu
·S content variable within the ore shale
·Supergene minerals such as Mal common on contacts with footwall and hanginwall
·Commonly elevated Cu and reduced S at base where in contact with the footwall aquifer
·Elevated V appears to follow same pattern - related to same supergene effects(?)
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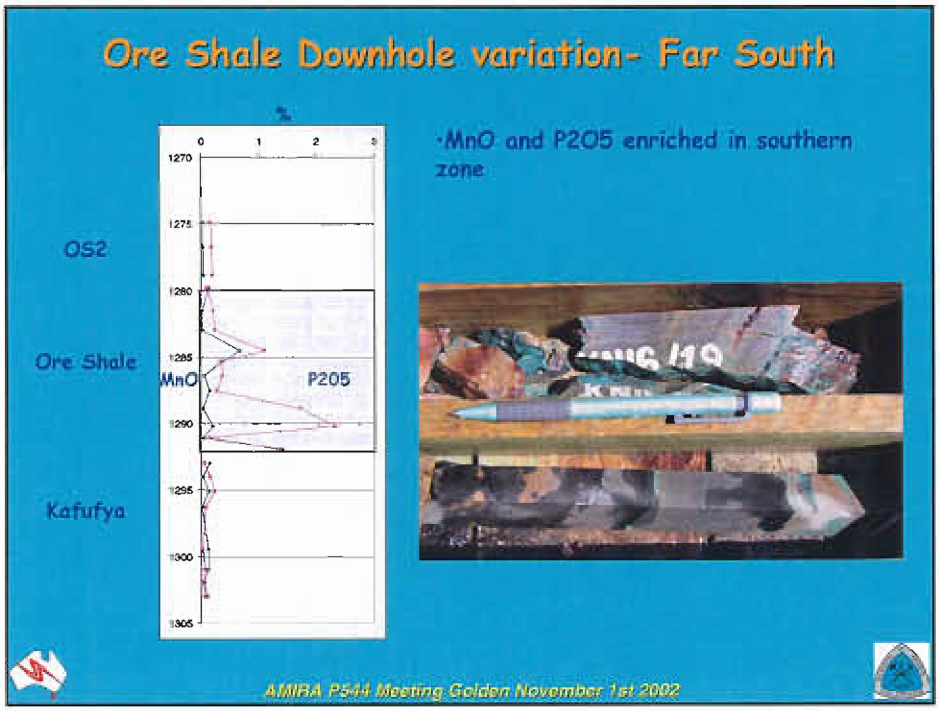
Ore Shale Downhole variation- Far South
%
0
1
2
3
1270
1275
1280
1285
1290
1295
1300
1305
OS2
Ore Shale
Kafufya
MnO
P205
·MnO and P2O5 enriched in southern zone
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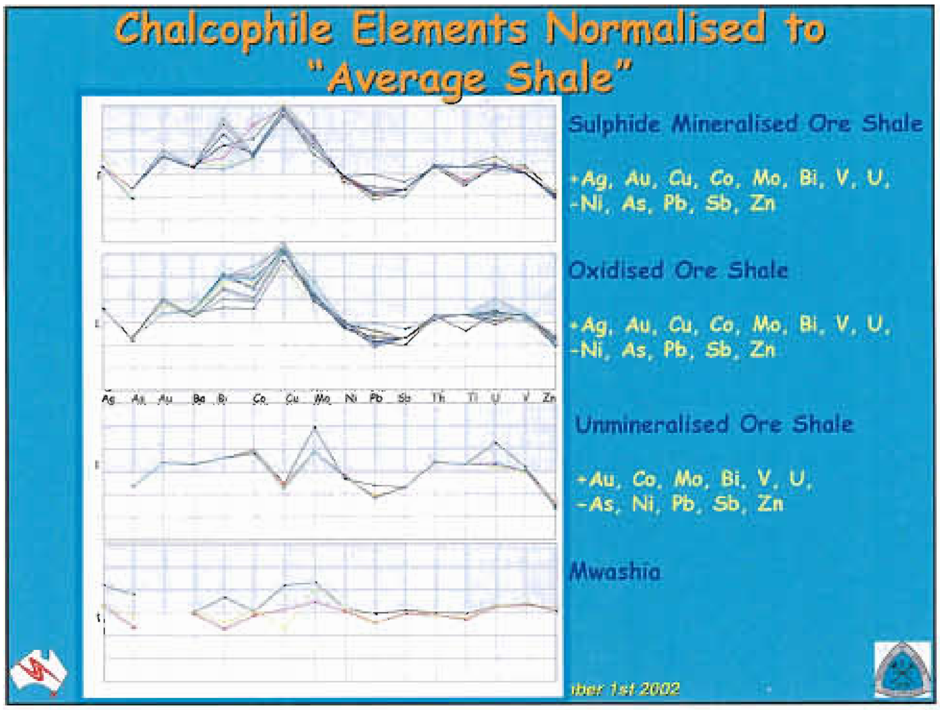
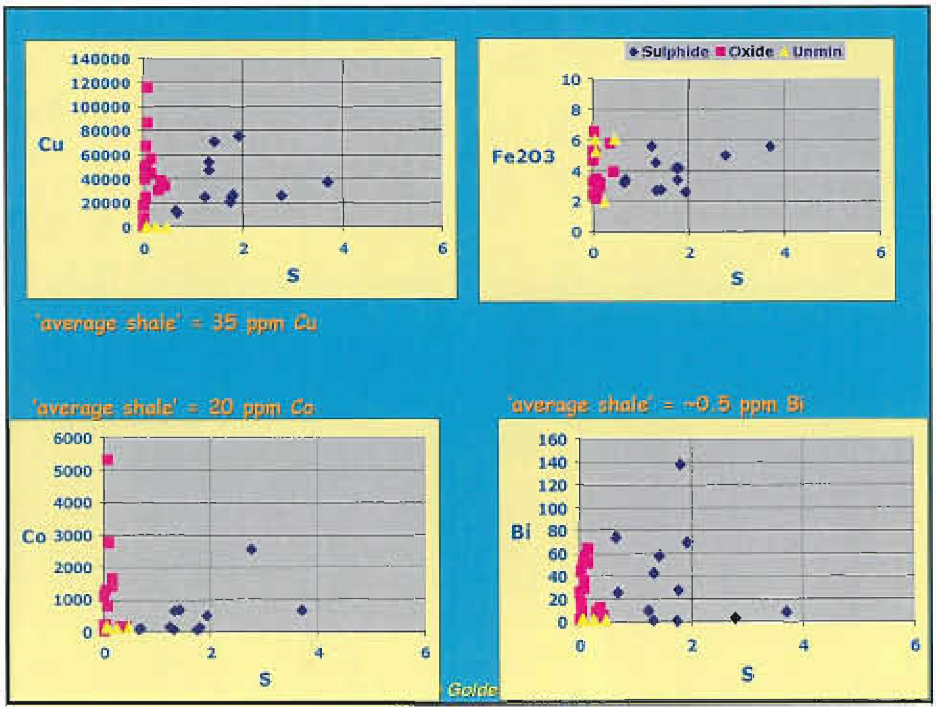
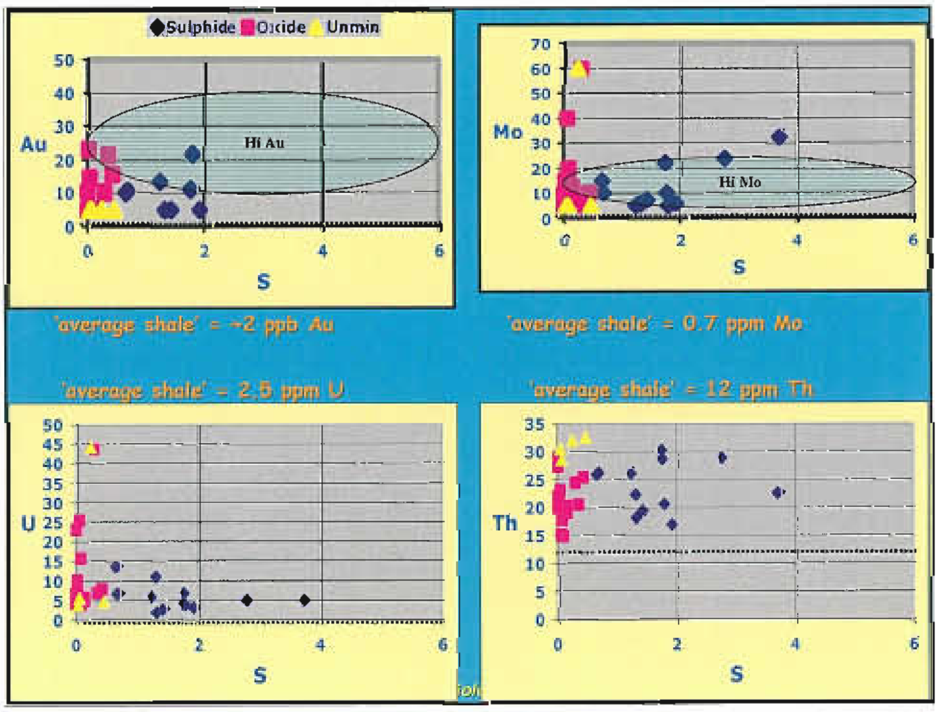

Chalcophile Elements Normalised to "Average Shale"
Ag
As
Au
Ba
Bi
Co
Cu
Mo
Ni
Pb
Sb
Th
Ti
U
V
Zn
Sulphide Mineralised Ore Shale
+Ag, Au, Cu, Co, Mo, Bi, V, U,
-Ni, As, Pb, Sb, Zn
Oxidised Ore Shale
+Ag, Au, Cu, Co, Mo, Bi, V, U,
-Ni, As, Pb, Sb, Zn
Unmineralised Ore Shale
+Au, Co, Mo, Bi, V, U,
-As, Ni, Pb, Sb, Zn
Mwashia


Cu
S
Sulphide Oxide Unmin
Fe2O3
S
'average shale' = 35 ppm Cu
'average shale' = 20 ppm Co
'average shale' = ~0.5 ppm Bi
Co
S
Bi
S


Sulphide Oxide Unmin
Au
Hi Au
S
Mo
Hi Mo
S
'average shale' = ~2 ppb Au
'average shale' = 0.7 ppm Mo
'average shale' = 2.5 ppm U
'average shale' = 12 ppm Th
U
S
Th
S

Summary

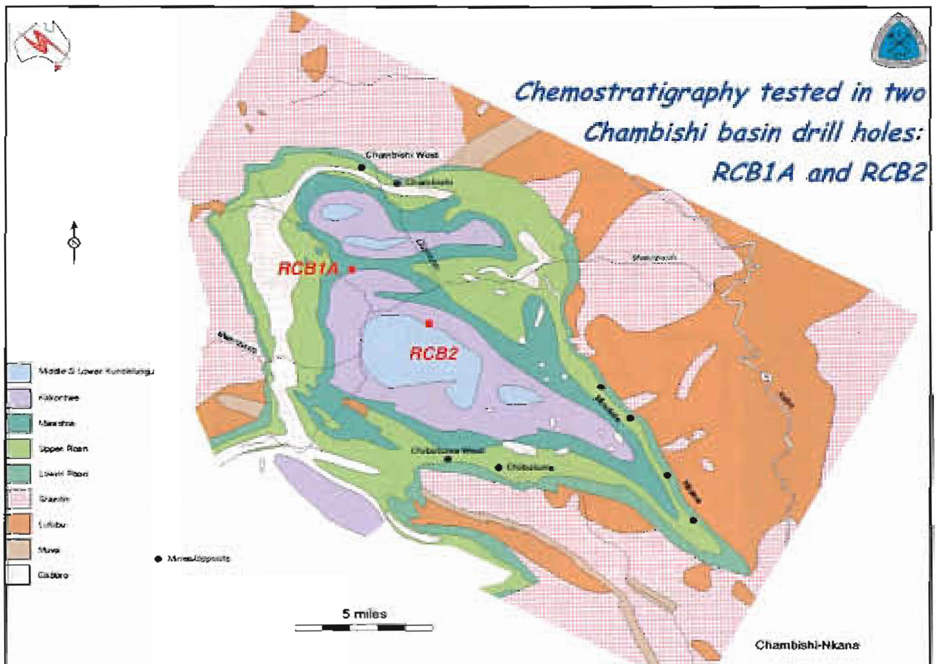
- Co, Au, Ag, Bi, U, Mo are associated with mineralising fluid
- Ore Shale
  - enriched in Ag, Au, Cu, Co, Mo, Bi, V, U
  - Depleted in Ni, Pb, Sb, Zn
- Mild to intense supergene overprint complicates the geochemistry of the ore shale and detailed petrography is required before further data interpretation
- Supergene effects
  - Depletion of S and enrichment of Cu (V?)
  - Local development of MnO, P2O5 (+- Cu and Co)

Zambian Copper Belt Geochemistry:
Part III: Preliminary assessment of chemostratigraphy and alteration geochemistry

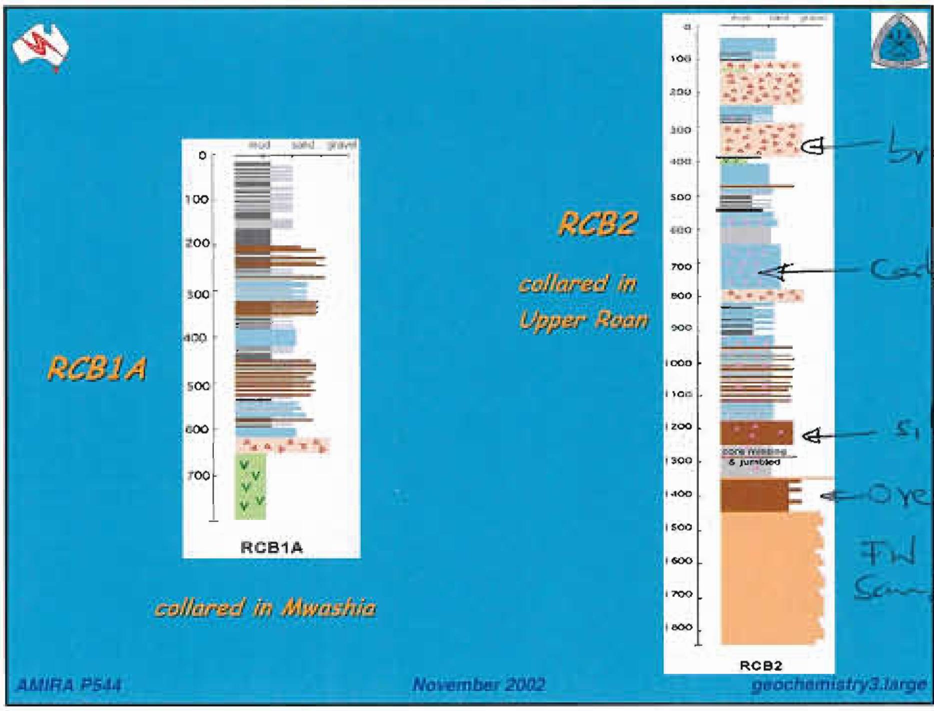
Ross Large, Peter McGoldrick & Mawson Croaker

1.

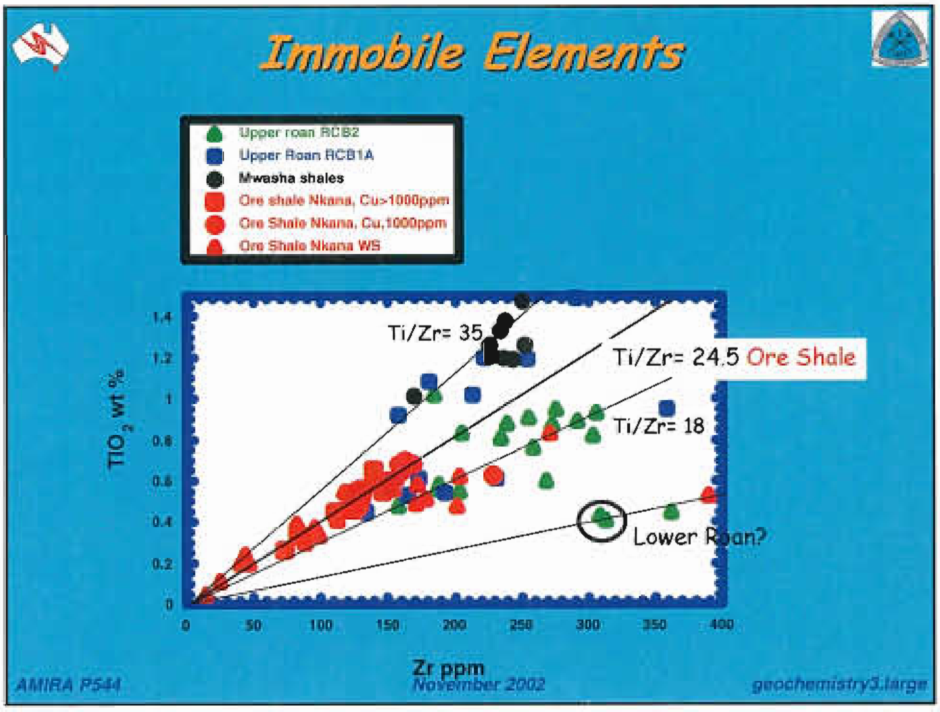
Chemostratigraphy tested in two Chambishi basin drill holes: RCB1A and RCB2



2.



breccia zones.
carbonate
siltstones
Ore zone
FW Sandstones.



4.

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

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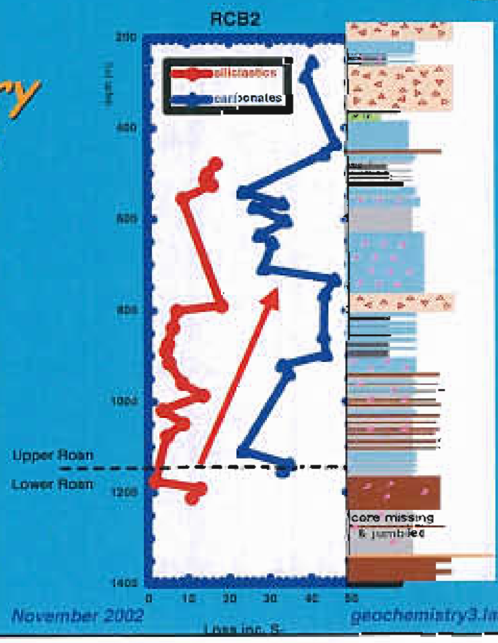
5.

Lithogeochemistry of Upper Roan in RCB2

Carbonate content



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6.

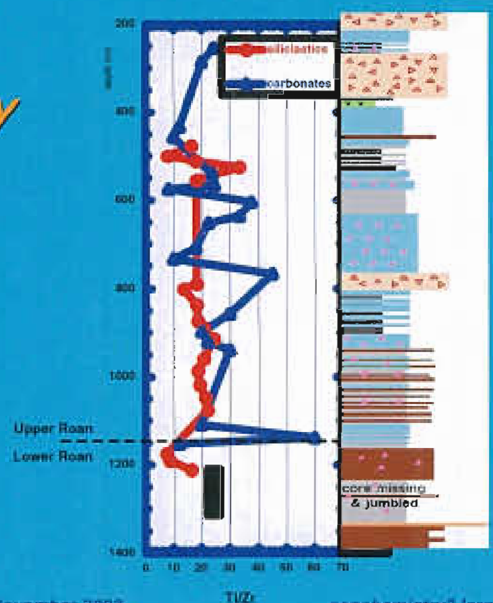
RCB2: Carbonate Variation

- 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.

7.

Lithogeochemistry of Upper Roan in RCB2

Ti/Zr variation



8.

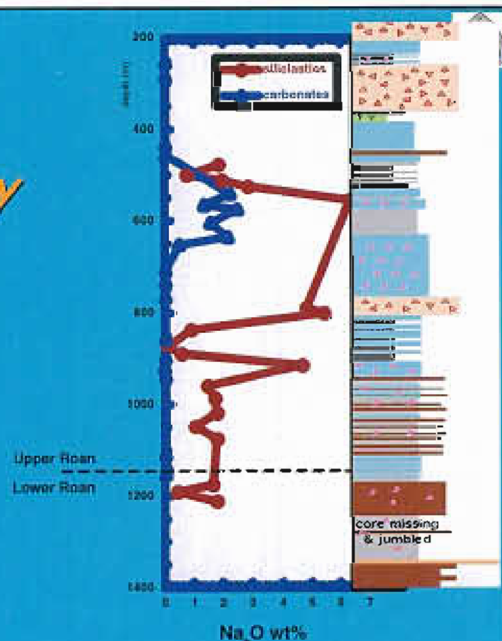
Ti - Zr patterns

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

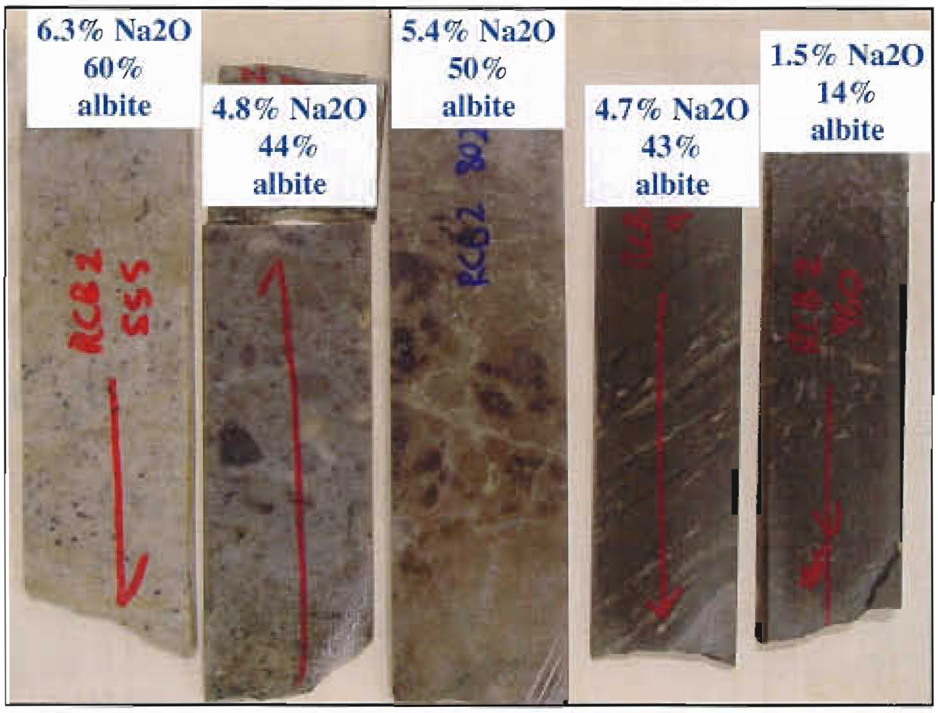
9.

Lithogeochemistry of Upper Roan in RCB2

Na_2O variation



10.



11.

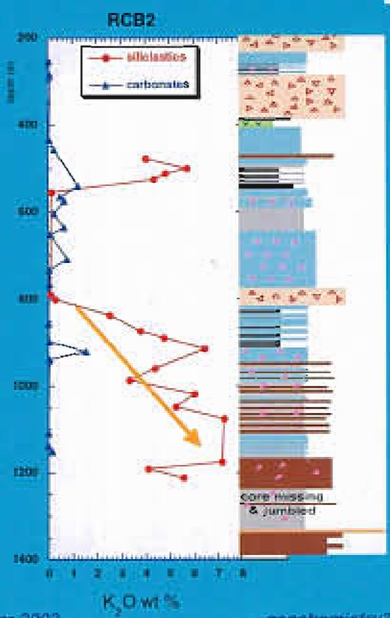
RCB2: Na_2O

- Upper Roan siliciclastics average around 1.8 wt% Na_2O
- This equates to ~ 15 wt% albite in siliciclastics
- Discrete zones of albite alteration contain 5-7 wt% Na_2O (45-60 wt% albite)
- Carbonates commonly contain < 0.1 wt% Na_2O, except for a zone of albite-rich carbonates at 530-640m in RCB2

12.

Lithogeochemistry of Upper Roan in RCB2

K_2O variation



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13.

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?

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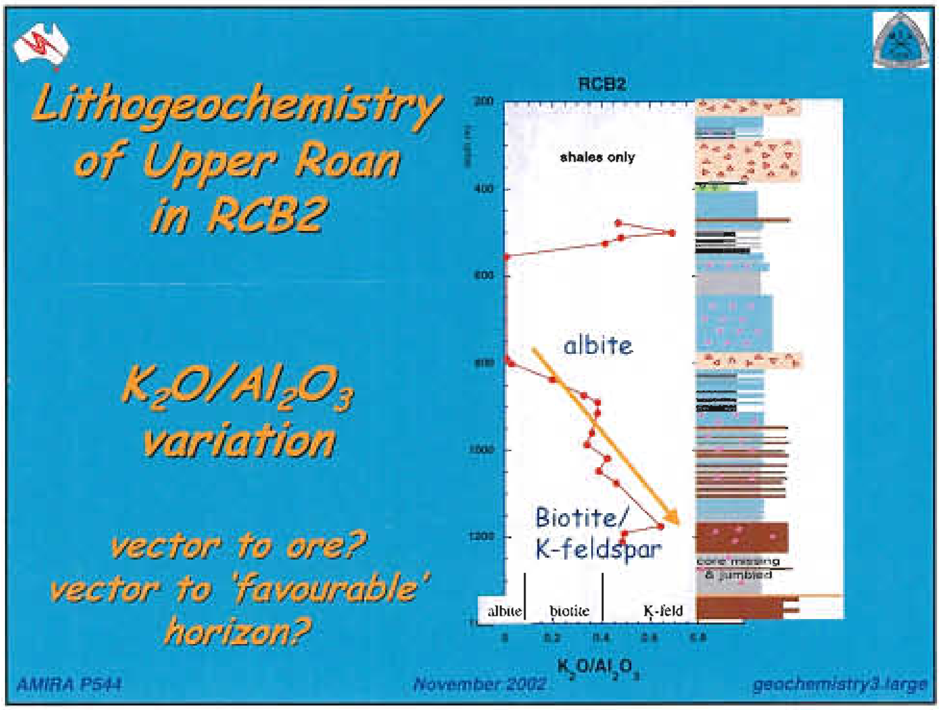
14.


Lithogeochemistry of Upper Roan in RCB2
K2O/Al2O3 variation
vector to ore?
vector to 'favourable' horizon?
RCB2
shales only
albite
Biotite/ K-feldspar
core missing & jumbled
albite
biotite
K-feld
K2O/Al2O3
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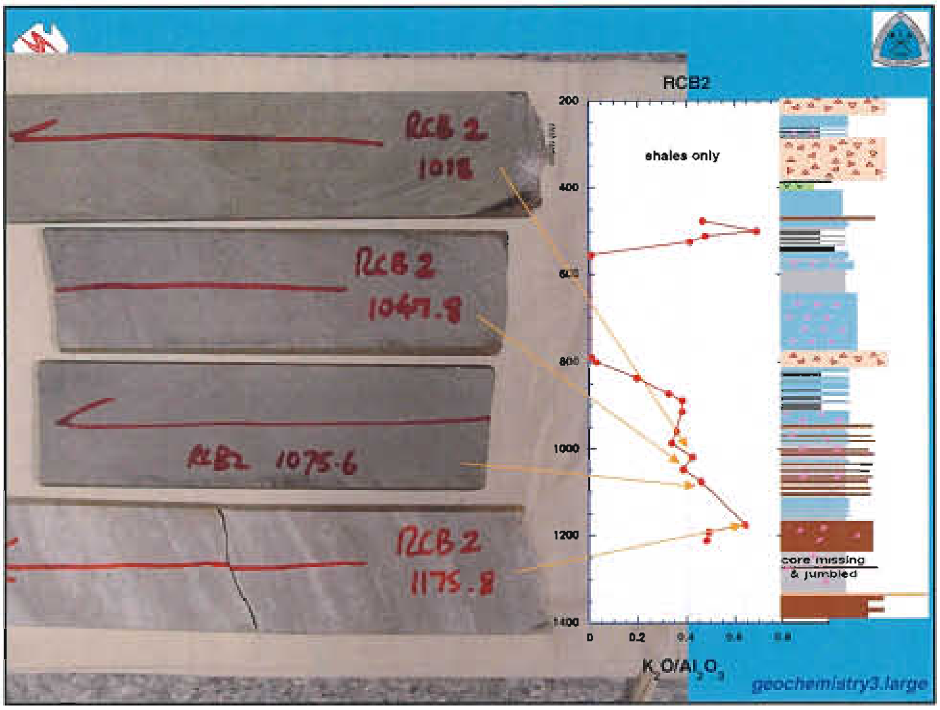
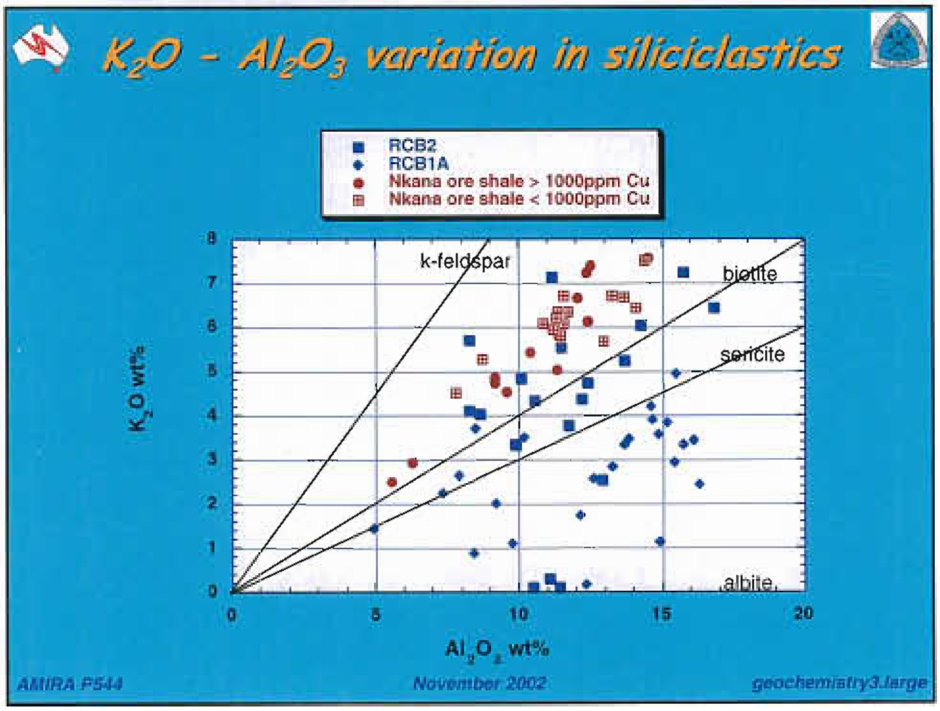
15.


RCB2 1018
RCB2 1047.8
RCB2 1075.6
RCB2 1175.8
RCB2
shales only
core missing & jumbled
K2O/Al2O3
geochemistry3.large

16.


K2O - Al2O3 variation in siliciclastics
RCB2
RCB1A
Nkana ore shale > 1000ppm Cu
Nkana ore shale < 1000ppm Cu
k-feldspar
biotite
sericite
albite
K2O wt%
Al2O3 wt%
0
5
10
15
20
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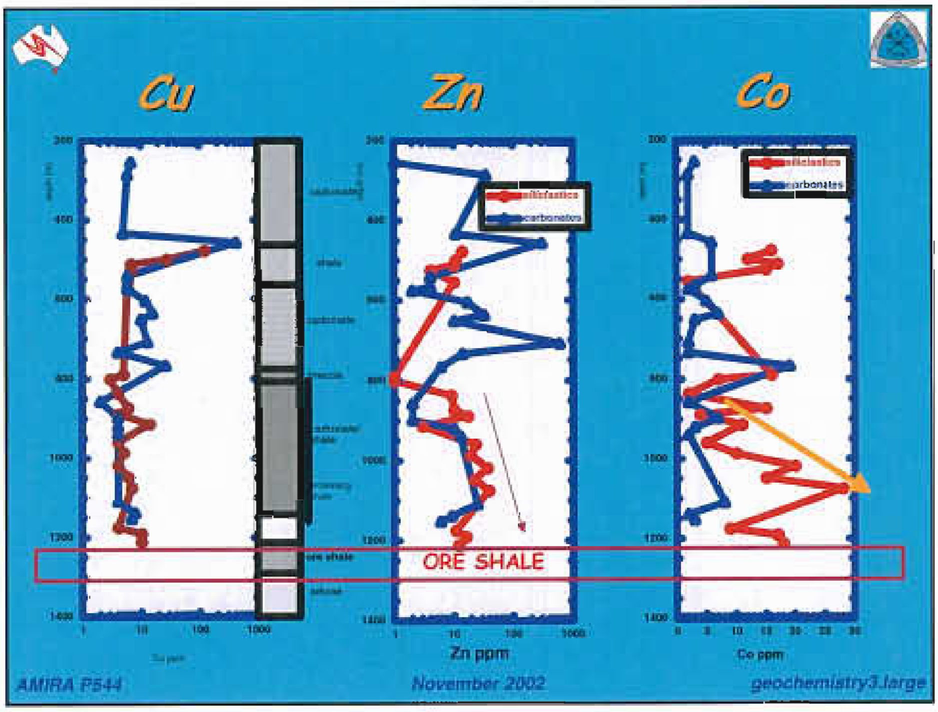
17


Cu
Zn
Co
ORE SHALE
Zn ppm
Co ppm
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18.

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

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19.

Possible HW vectors to ore

- K_2O/Al_2O_3 ratio in siliciclastics
- Zn in siliclastics
- Co in siliclastics

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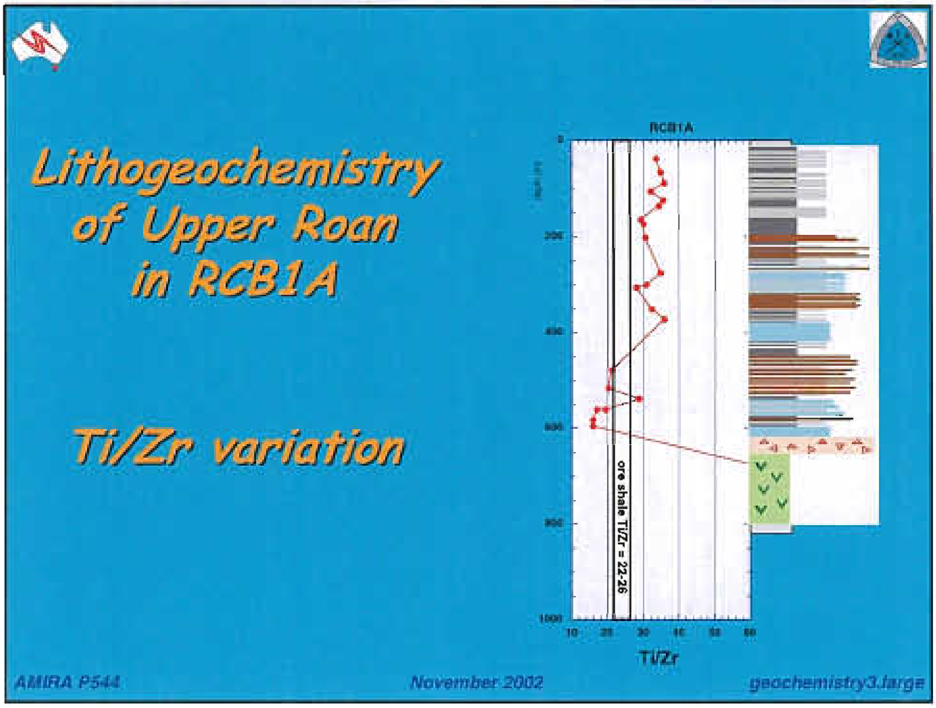
20.


Lithogeochemistry
of Upper Roan
in RCB1A
Ti/Zr variation
RCB1A
ore shale Ti/Zr = 22-26
Ti/Zr
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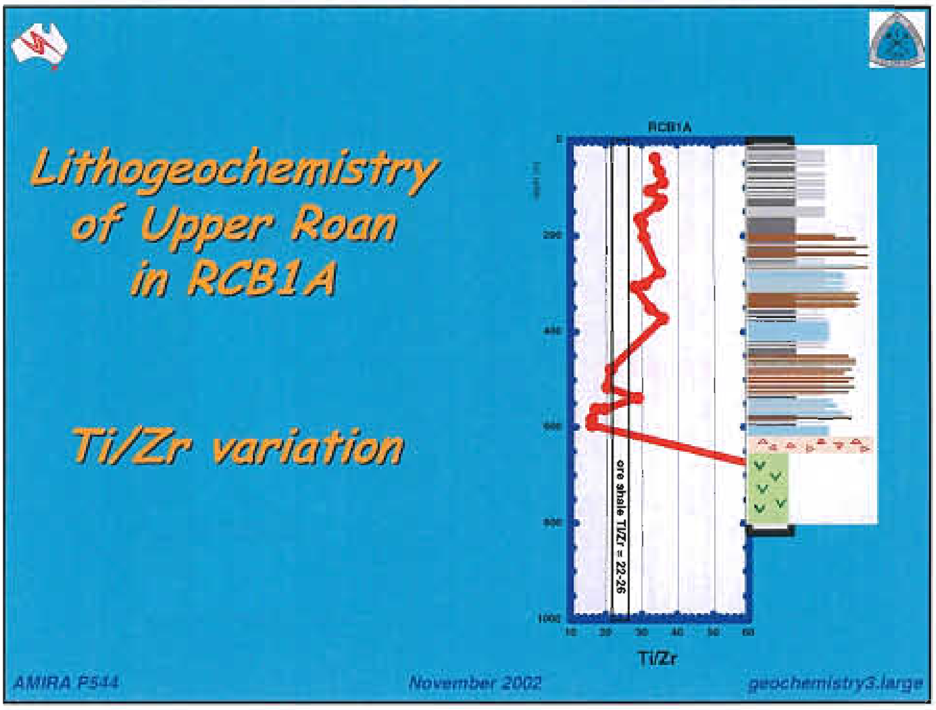
geochemistry3.large

21.


Lithogeochemistry
of Upper Roan
in RCB1A
Ti/Zr variation
RCB1A
ore shale Ti/Zr = 22-26
Ti/Zr
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22.

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 NN42 were also analysed
- A set of carbonate-rich samples from the Nkana ore zone have been analysed by Mawson Croaker, and will be reported separately

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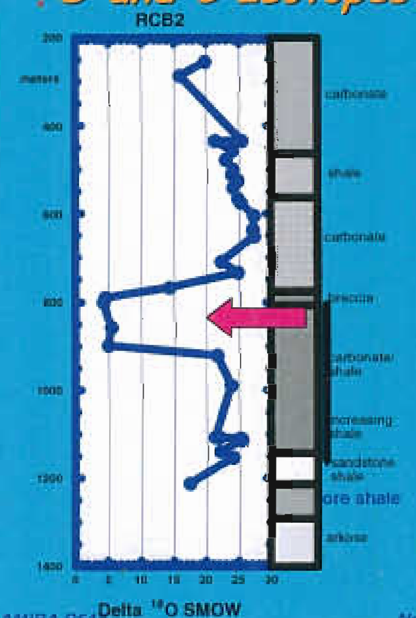
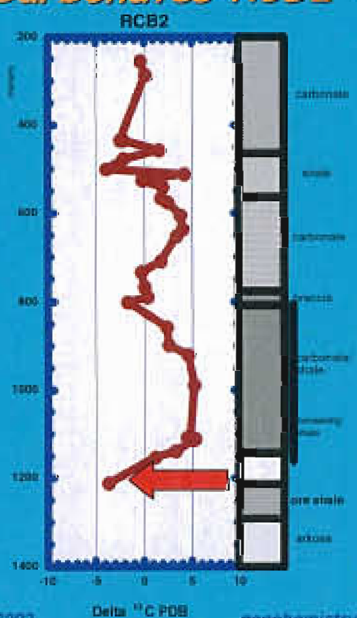
23.

O and C Isotopes of Carbonates RCB2





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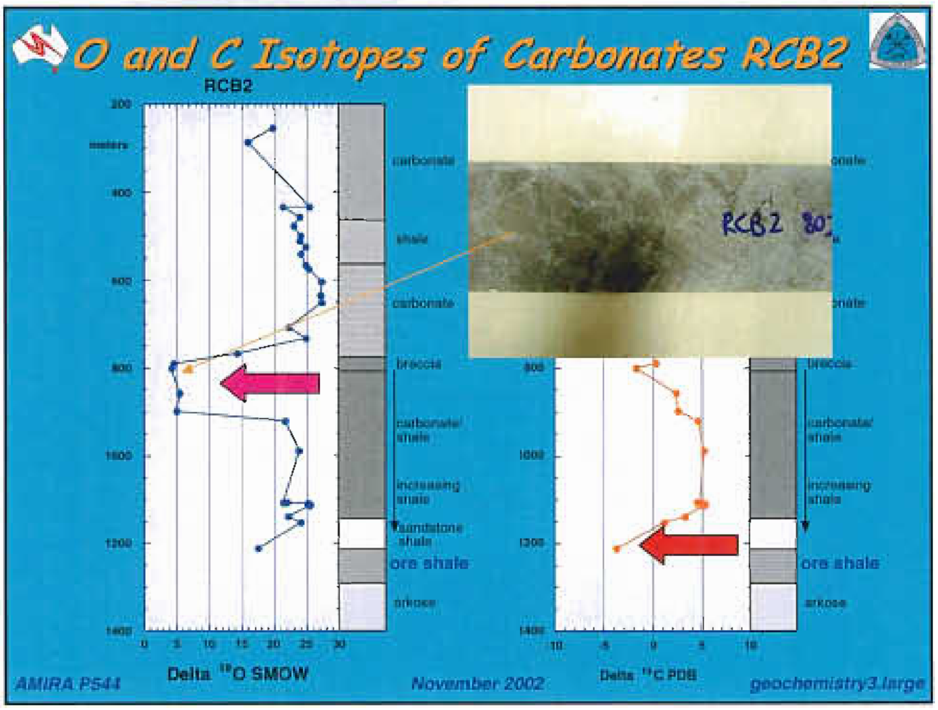
24.

mean O = 23.9,
C = 2.2,


O and C Isotopes of Carbonates RCB2
RCB2
meters
carbonate
shale
carbonate
breccia
carbonate/ shale
increasing shale
sandstone shale
ore shale
arkose
Delta 18O SMOW
Delta 13C PDB
RCB2 80
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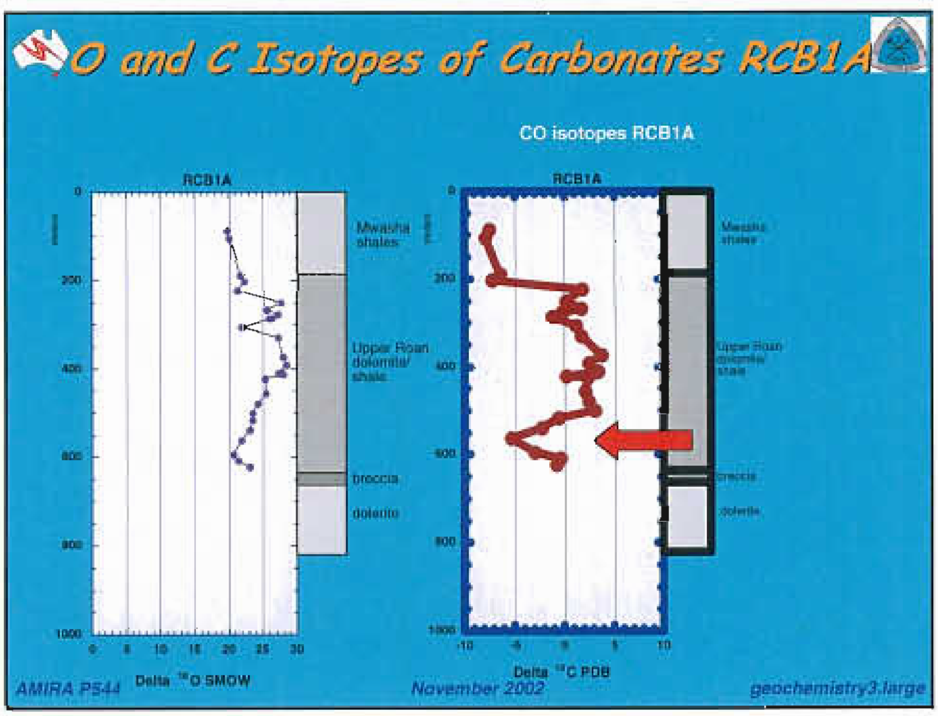
25.


O and C Isotopes of Carbonates RCB1A
CO isotopes RCB1A
RCB1A
Mwashia shales
Upper Roan dolomite/ shale
breccia
dolerite
Delta 18O SMOW
Delta 13C PDB
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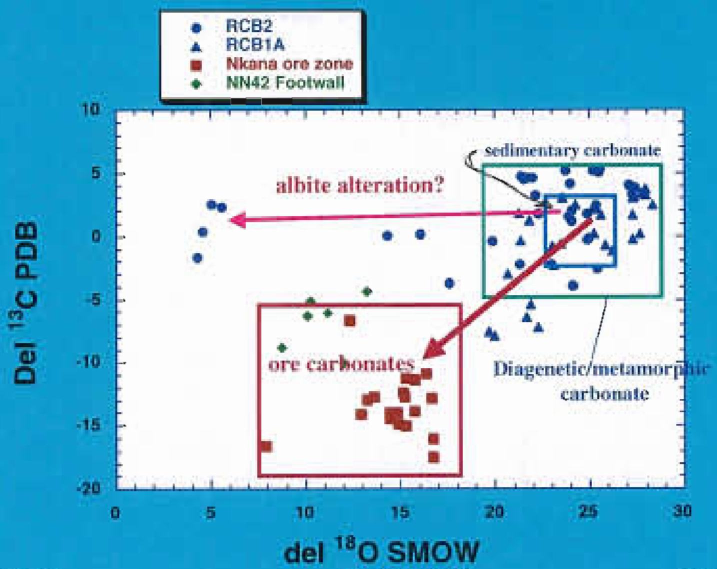
26.

C-O isotope relationships



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27.

Comments on C-O isotopes

- Sedimentary & diagenetic carbonates have $d^{18}O$ = 20-28 permil, $d^{13}C$ = +5 to -2 permil, similar to early Prot. Sedimentary/diagenetic values
- Ore-related carbonates are strongly depleted in both ^{18}O and ^{13}C ($d^{18}O$ = 8-18 permil, $d^{13}C$ = -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

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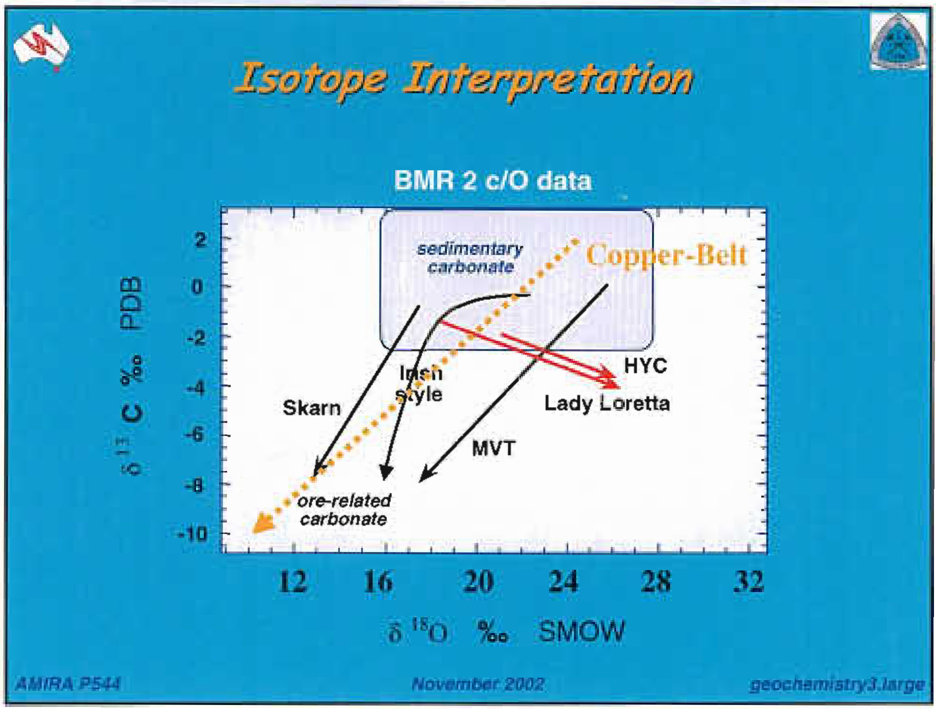
28.



Isotope Interpretation
BMR 2 c/O data
sedimentary carbonate
Copper-Belt
HYC
Lady Loretta
Irish style
Skarn
MVT
ore-related carbonate
2
0
-2
-4
-6
-8
-10
12
16
20
24
28
32
δ 13 C ‰ PDB
δ 18O ‰ SMOW
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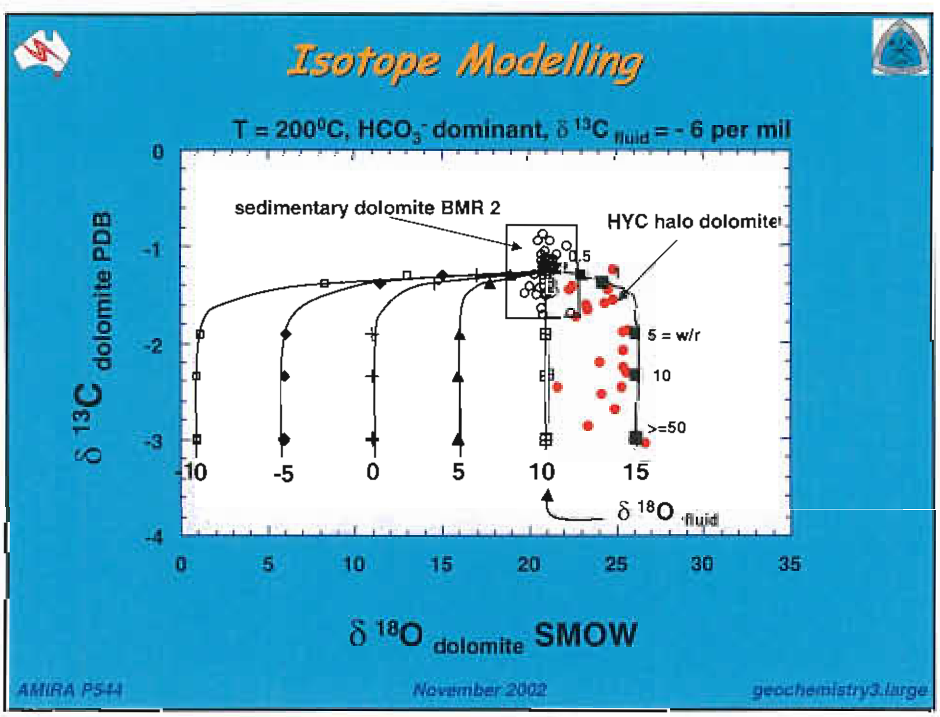
29.



Isotope Modelling
T = 200°C, HCO3- dominant, δ 13C fluid = - 6 per mil
sedimentary dolomite BMR 2
HYC halo dolomite
0.5
5 = w/r
10
>=50
-10
-5
0
5
10
15
δ 18O fluid
0
-1
-2
-3
-4
0
5
10
15
20
25
30
35
δ 13C dolomite PDB
δ 18O dolomite SMOW
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30.

Preliminary isotope Interp

- The coupled C-O depletion associated with the mineralising event suggests:
  - A fluid with d^{18}O = 0 $\pm$ 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 ^{18}O fluid: probably meteoric (d^{18}O = -10 permil?)

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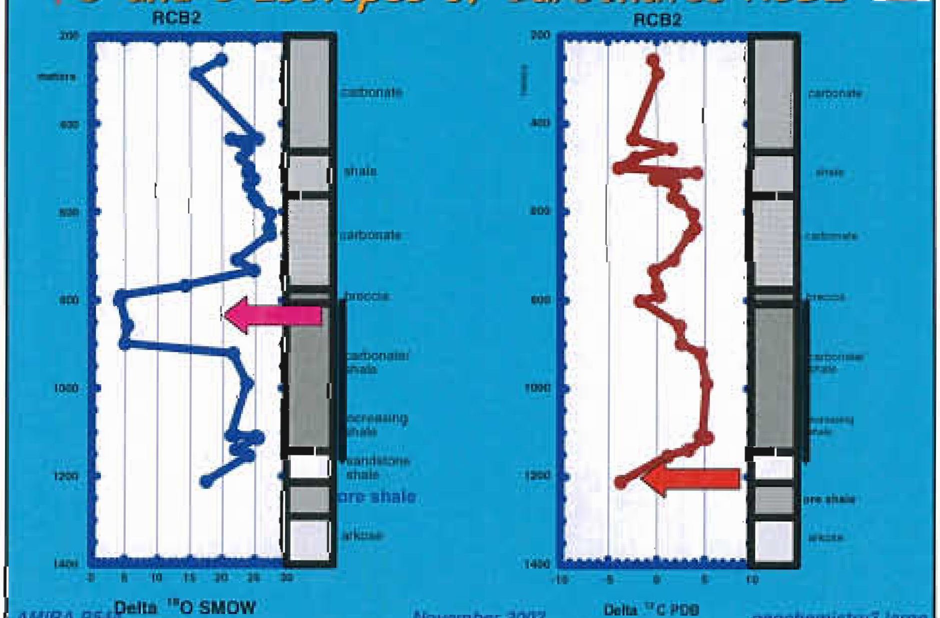
31.

O and C Isotopes of Carbonates RCB2



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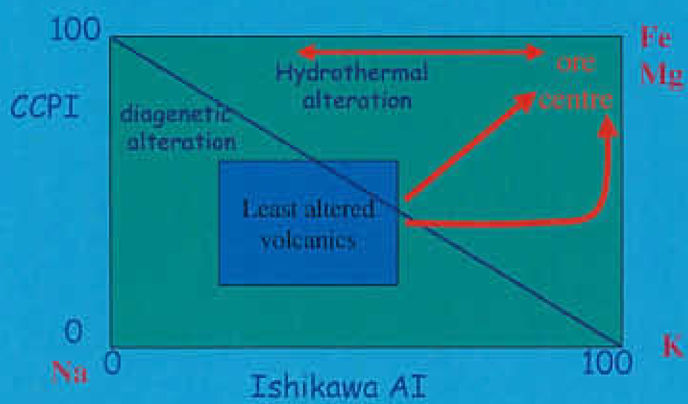
32.

Towards Developing a Copper Belt Lithogeochem Vector Diagram

33.

VHMS Alteration Box Plot

Large, Gemmell, Herrman, Paulick & Huston (2001)



Put minerals on diagram

34.

Copper Belt mineral associations

after Darnley (1960)

- Background unmineralized Roan siliciclastics contain biotite, K-feldspar, albite, quartz, sericite and chlorite
- Mineralised shale and siliciclastics commonly contain no albite (low Na_2O), and are enriched in one or more potassic minerals (biotite, K-feldspar or sericite). BUT, some fw orebodies contain albite
- Carbonates are principally dolomite, but some calcite and magnesite is also present

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35

Enriched and Depleted elements

- Enriched in ore zones : K_2O, and…….?
- Depleted in ore zones: Na_2O, and………?
- SC AI Mk2 = $K_2O \times 100$
- $\cancel{K_2O + (10xNa_2O)}$

- SC AI Mk5 = $(FeO + MgO) \times 100$
- $(FeO + MgO + Na_2O + K_2O + Al_2O_3/4)$

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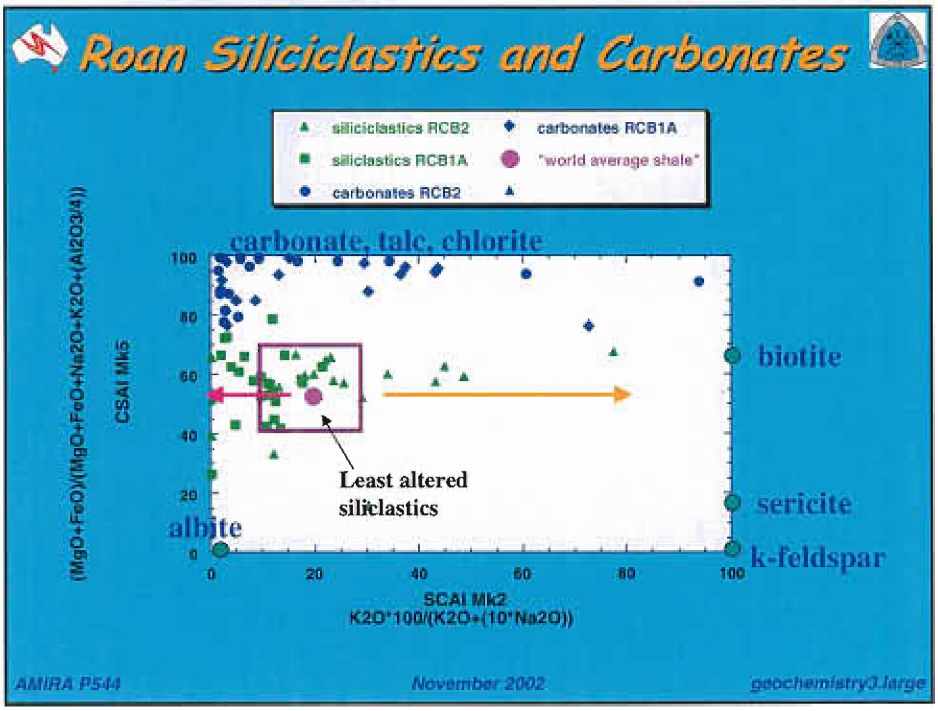
36.


Roan Siliciclastics and Carbonates
siliciclastics RCB2
carbonates RCB1A
siliclastics RCB1A
"world average shale"
carbonates RCB2
carbonate, talc, chlorite
(MgO+FeO)/(MgO+FeO+Na2O+K2O+(Al2O3/4))
CSAI Mk5
biotite
Least altered
siliclastics
sericite
albite
k-feldspar
SCAI Mk2
K2O*100/(K2O+(10*Na2O))
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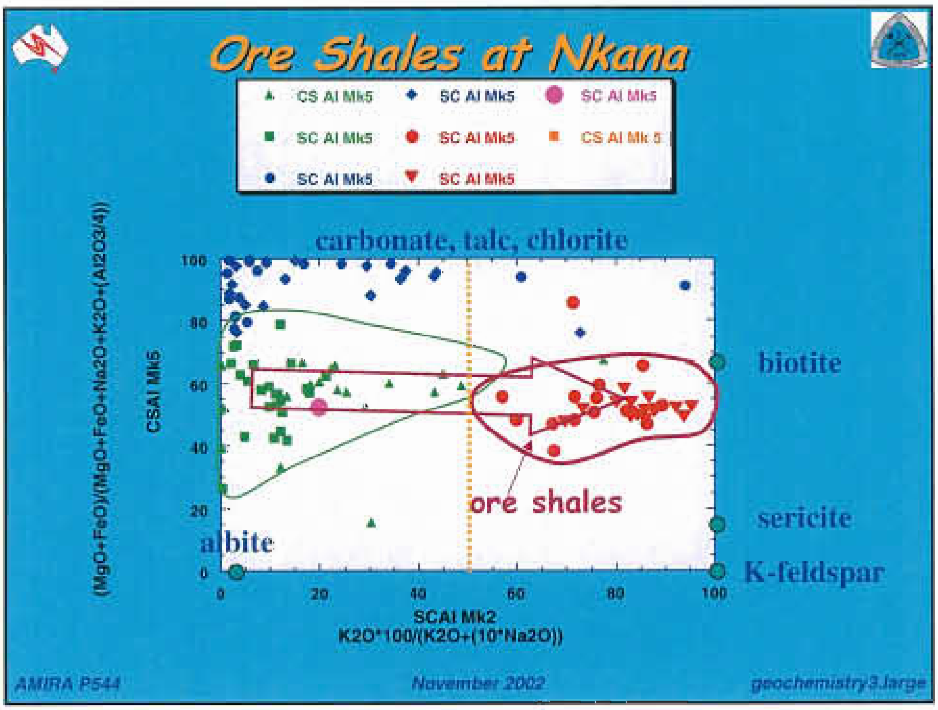
37.


Ore Shales at Nkana
CS Al Mk5
SC Al Mk5
SC Al Mk5
SC Al Mk5
SC Al Mk5
CS Al Mk 5
SC Al Mk5
SC Al Mk5
carbonate, talc, chlorite
(MgO+FeO)/(MgO+FeO+Na2O+K2O+(Al2O3/4))
CSAI Mk5
biotite
ore shales
sericite
albite
K-feldspar
SCAI Mk2
K2O*100/(K2O+(10*Na2O))
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38.

Feldspar is the Key

- Roan silciclastics 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

$$NaAlSi_3O_8 + K^+ = KAlSi_3O_8 + Na^+$$

- 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

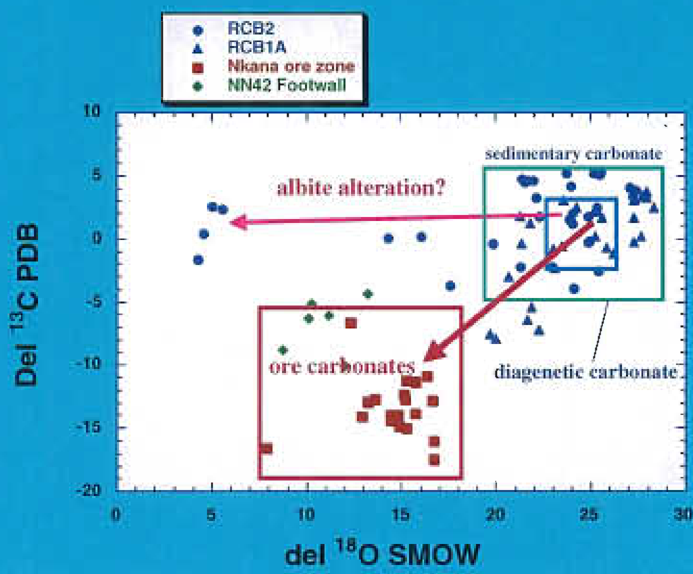
39.

Preliminary Conclusions

- Immobile element ratios (Ti/Zr) can assist stratigraphic correlations
- The ore shale at Nkana has a unique Ti/Zr ratio
- There may be a hangingwall halo to ore, defined by K_2O/Al_2O_3, Co and Zn in the siliclastics
- There appears to be a clear C-O isotope depletion halo in the carbonates surrounding ore
- C and O isotopes in carbonates may provide a useful vector to ore

40.

C-O isotope relationships

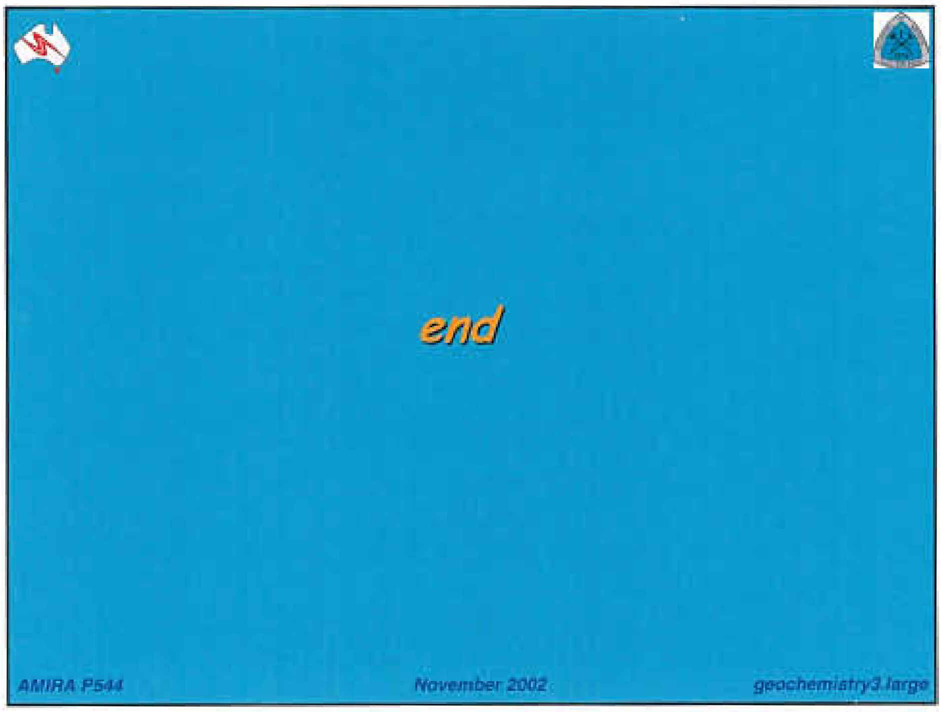


41.

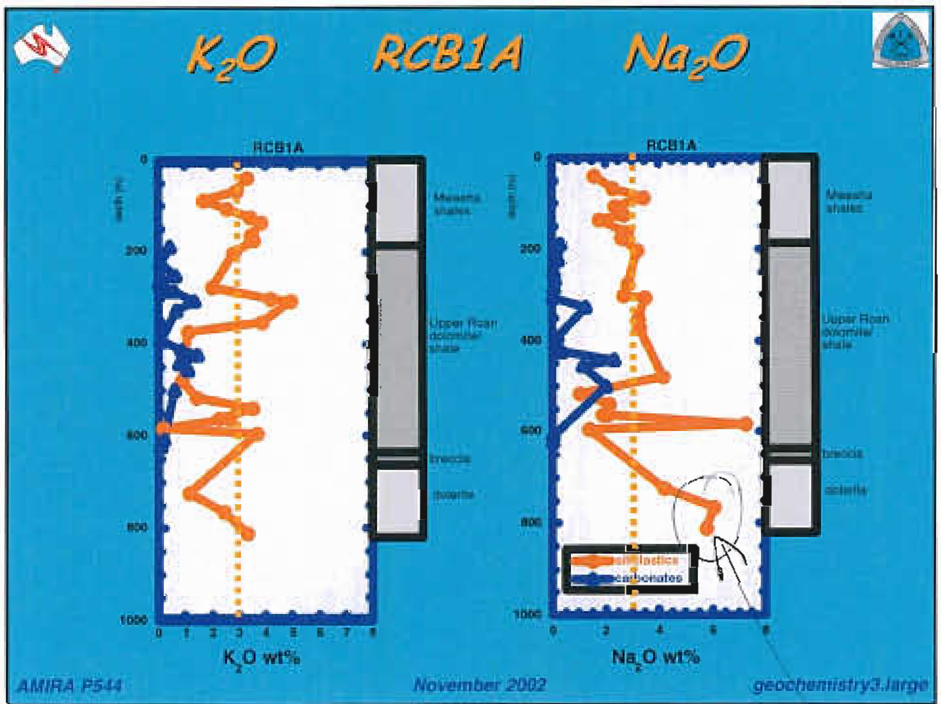
Preliminary Conclusions

- At least two different alteration fluids have effected 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

42.



43.



44.

Need to measure C/O
isotopes of carbonate alt in
[illegible] ??

Comment on Na_2O and K_2O

- In the uppermost Roan and Mwasha intersected in RCB1A, the siliclastics average 3.1% Na_2O and 2.7% K_2O
- The stratigraphically lower siliclastics in the Roan (RCB2), closer to the ores, contain a lower mean Na_2O (2.2%) and higher mean K_2O (4.2%) content

 45.

Nkana-Mindola Deposit, Zambia.

Carbon and Oxygen Isotopic Signature - Update

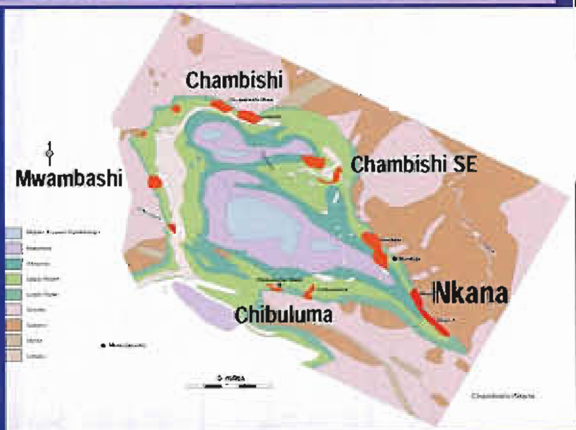
Mawson Croaker
PhD Student

NKANA-MINDOLA OREBODY

Ore Shale hosted - dolomitic Argillites, carbonaceous shale

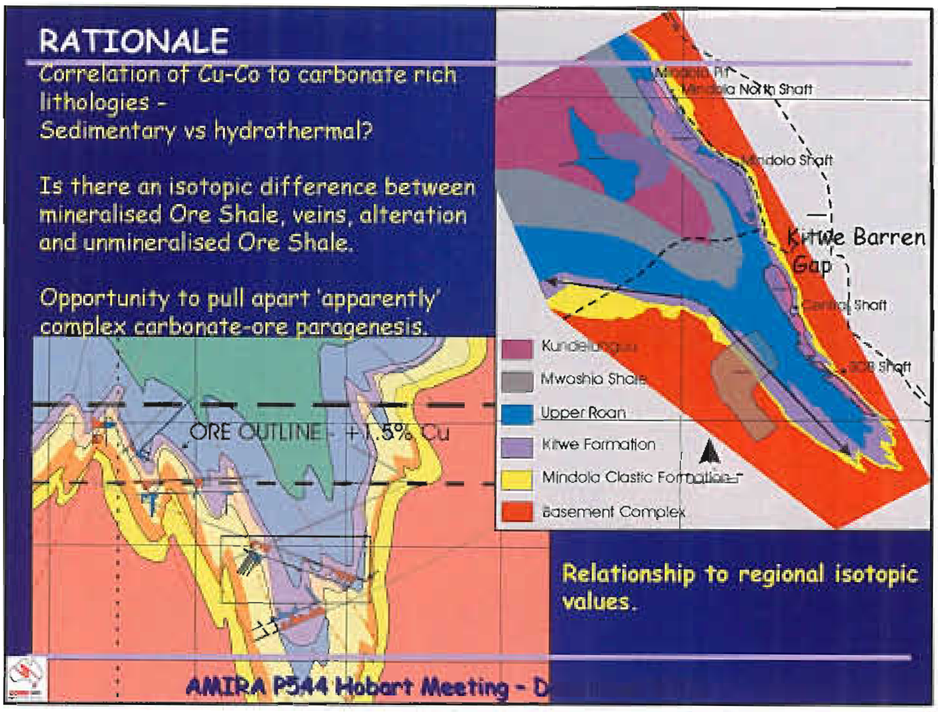
Cpy-bn-py.

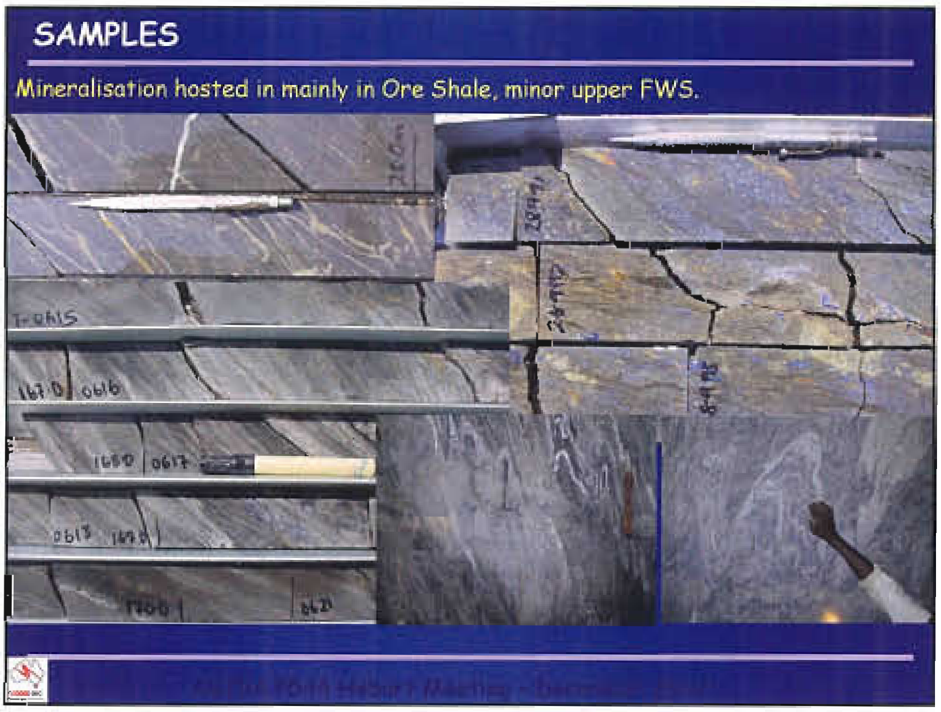
NE Limb of Syncline

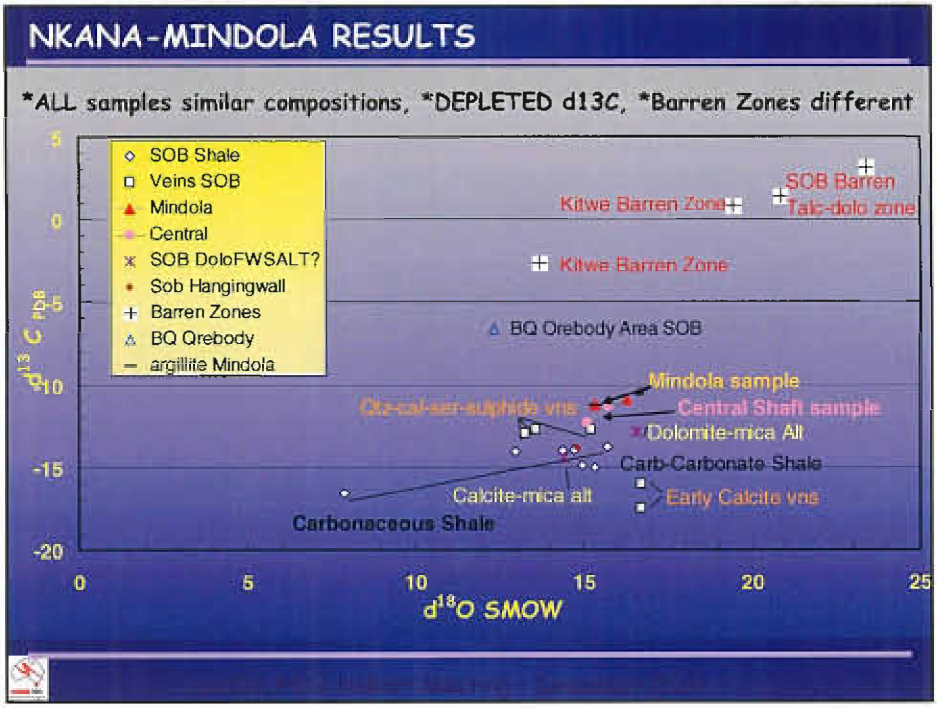


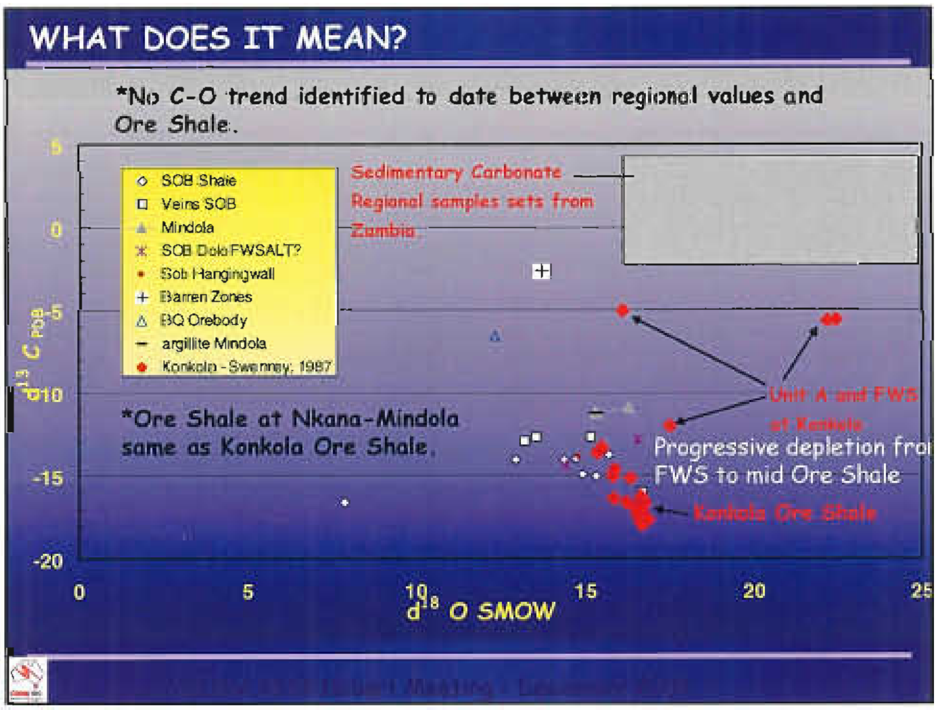
Mining depth to ~5000 ft through use of 4 shafts

Nkana Synclinorium Project Area alone is - 90Mt @ 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.
ORE OUTLINE - +1.5% Cu
Mindola North Shaft
Mindola Shaft
Kitwe Barren Gap
Central Shaft
Mwashia Shale
Upper Roan
Kitwe Formation
Mindola Clastic Formation
Basement Complex
Relationship to regional isotopic values.
AMIRA P544 Hobart Meeting -


SAMPLES
Mineralisation hosted in mainly in Ore Shale, minor upper FWS.


NKANA-MINDOLA RESULTS
*ALL samples similar compositions, *DEPLETED d13C, *Barren Zones different
SOB Shale
Veins SOB
Mindola
Central
SOB DoloFWSALT?
Sob Hangingwall
Barren Zones
BQ Orebody
argillite Mindola
SOB Barren
Talc-dolo zone
Kitwe Barren Zone
Kitwe Barren Zone
BQ Orebody Area SOB
Mindola sample
Central Shaft sample
Qtz-cal-ser-sulphide vns
Dolomite-mica Alt
Carb-Carbonate Shale
Calcite-mica alt
Early Calcite vns
Carbonaceous Shale
d^{13} C PDB
5
0
-5
-10
-15
-20
0
5
10
15
20
25
d^{18}O SMOW


WHAT DOES IT MEAN?
*No C-O trend identified to date between regional values and Ore Shale.
SOB Shale
Veins SOB
Mindola
SOB DoloFWSALT?
Sob Hangingwall
Barren Zones
BQ Orebody
argillite Mindola
Konkola - Sweeney; 1987
Sedimentary Carbonate
Regional samples sets from Zambia
*Ore Shale at Nkana-Mindola same as Konkola Ore Shale.
Unit A and FWS at Konkola
Progressive depletion fro
FWS to mid Ore Shale
Konkola Ore Shale
d^{13} C PDB
5
0
-5
-10
-15
-20
0
5
10
15
20
25
d^{18} O SMOW

FUTURE DIRECTION

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

Barren Zones plot within sedimentary carbonate field.

Same C-O values as Konkola 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

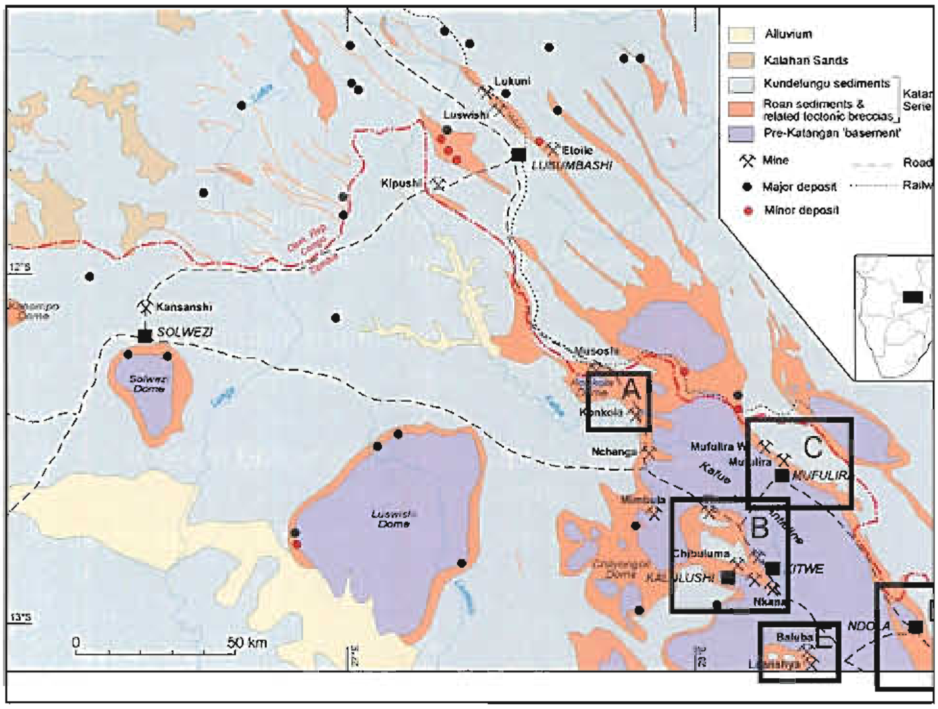
(PhD student)
Centre for Global Metallogeny,
University of Western Australia

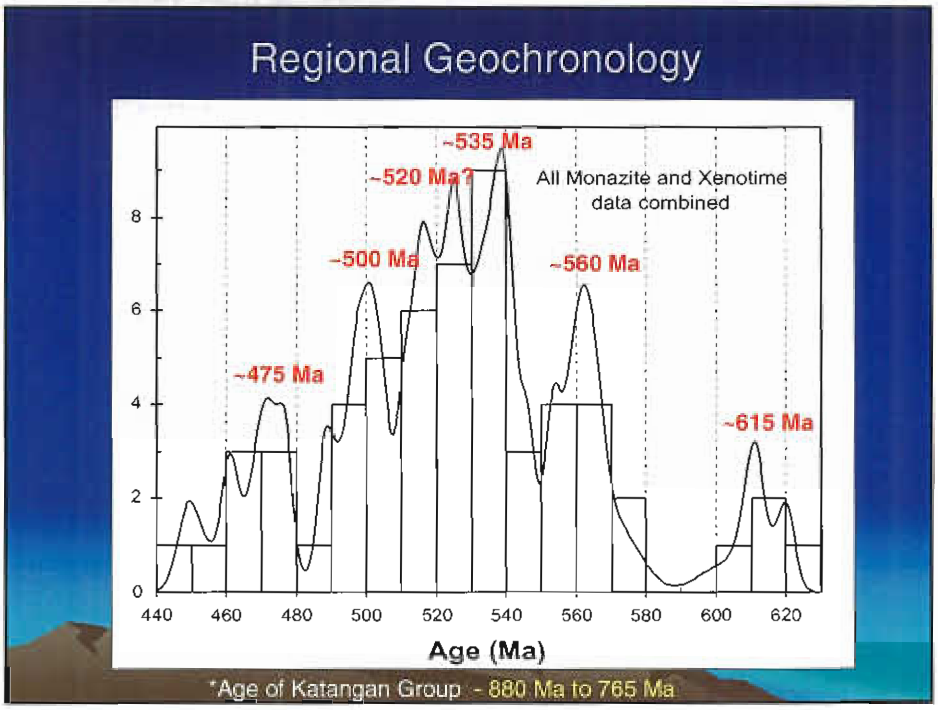
Aims of study

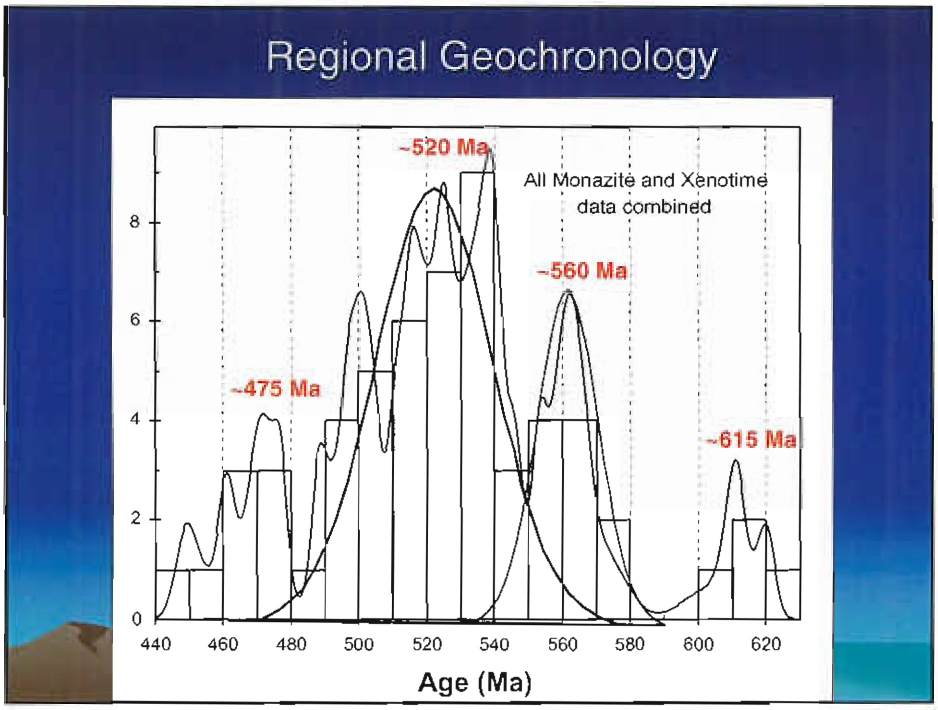
- Identify and characterise post-sedimentation phosphate minerals which can be isotopically dated
  - i.e. xenotime and monazite
- Determine the U-Pb age of phosphate minerals to "best precision" using SHRIMP – (Sensitive High Resolution Ion Microprobe)
- Relate phosphate age data, petrography and mineral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

Important considerations

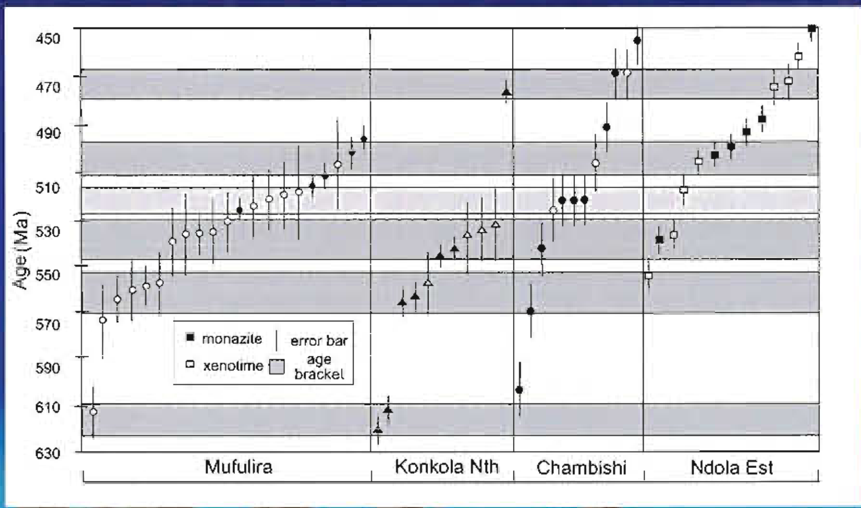
- Geochronology presented here were obtained from 4 SHRIMP sessions
  - Still in data collection stage of project (4-6 more sessions?)
  - Limited data collected from high-grade ore samples
- SHRIMP ages are preliminary provisional results only
  - Matrix corrections are still to be made to data
  - 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
~535 Ma
~520 Ma?
All Monazite and Xenotime data combined
~500 Ma
~560 Ma
~475 Ma
~615 Ma
0
2
4
6
8
440 460 480 500 520 540 560 580 600 620
Age (Ma)
*Age of Katangan Group - 880 Ma to 765 Ma


Regional Geochronology
~520 Ma
All Monazite and Xenotime data combined
~560 Ma
~475 Ma
~615 Ma
0
2
4
6
8
440 460 480 500 520 540 560 580 600 620
Age (Ma)

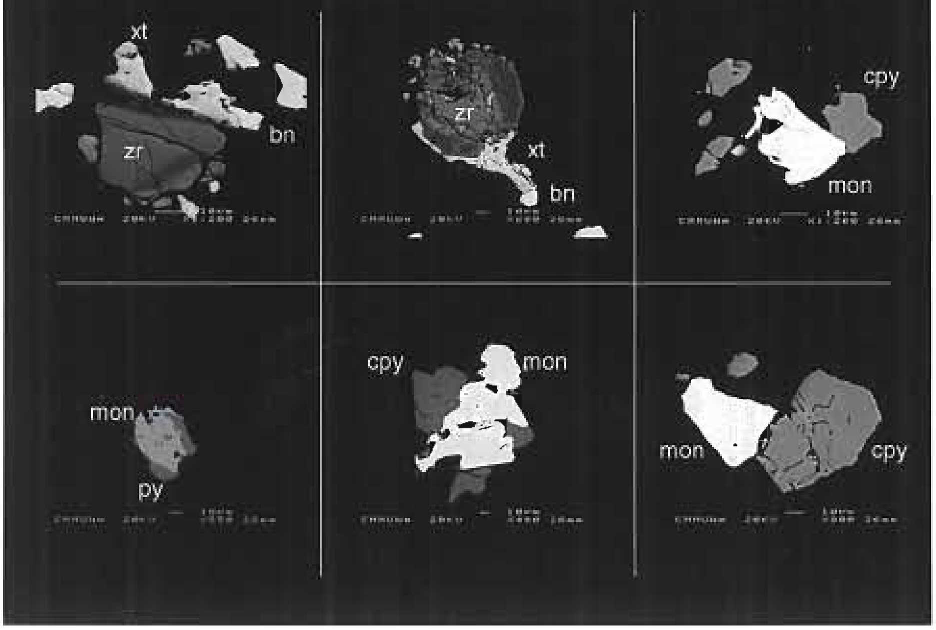
Regional Geochronology



Association of trace phosphates to mineralisation

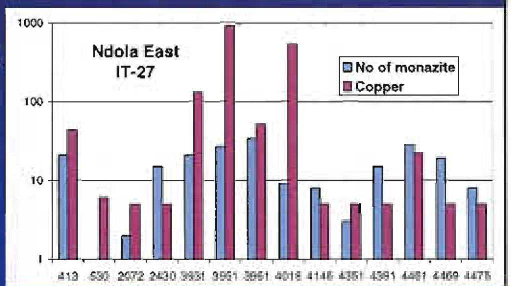
- Things to consider…
  - Is there textural evidence for an association between trace phosphates and copper?
  - Is there a correlation between trace phosphate abundance and copper content?
  - Does this imply that the minerals are coeval and that dating trace phosphates will date mineralisation?
  -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

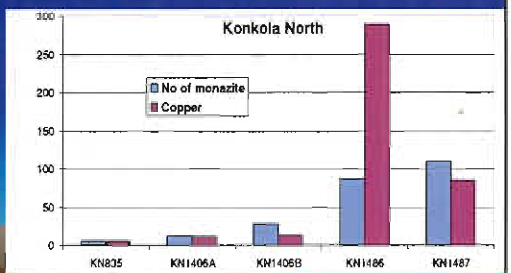
Textural evidence



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

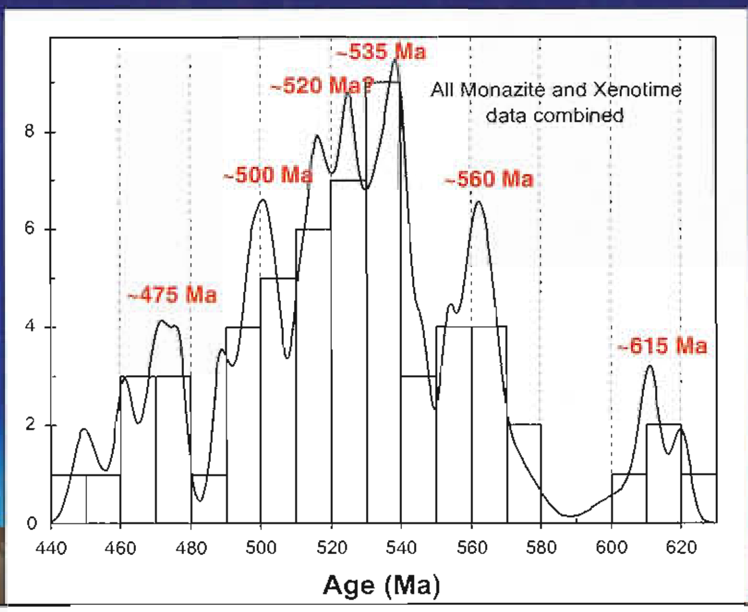




Trace phosphate abundance vs copper

- 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

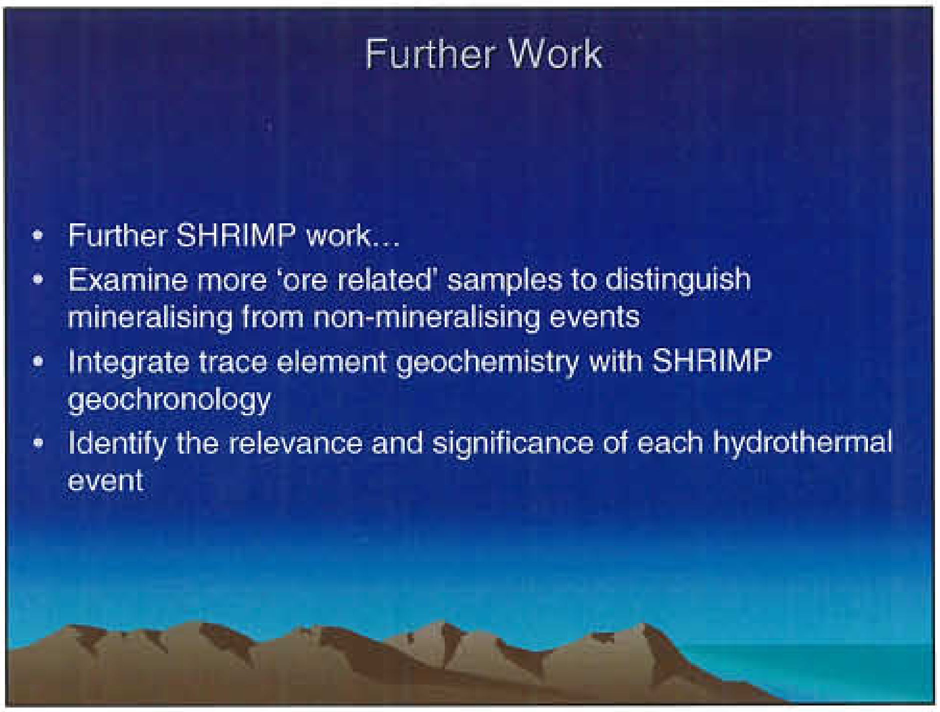


Event	Age (Ma)	Sample location	Cu mineral in assoc.
500 Ma	496+/-4	Mufulira	cpy
	501+/-4	Ndola East	py
	501+/-5	Mufulira	cpy
	*502+/-2	Kansanshi	cpy
	511+/-4	Mufulira	cpy
	*511+/-11	Kansanshi	cpy
	*512+/-2	Kansanshi	cpy
	515+/-4	Mufulira	cpy
	517+/-16	Mufulira	cpy
535 Ma	525+/-4	Mufulira	cpy
	535+/14	Mufulira	bn
	539+/-12	Mufulira	bn
560 Ma	560+/-11	Mufulira	bn

*Re-Os and U-Pb ages taken from Hitzman et al. (2000)

Preliminary Conclusions

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


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

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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?

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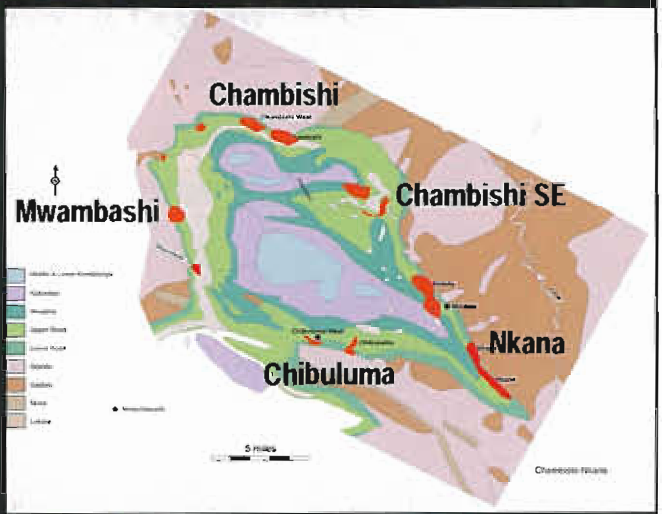
Chambishi Basin

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



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Chibuluma West (Strat)

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FW Thickness

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

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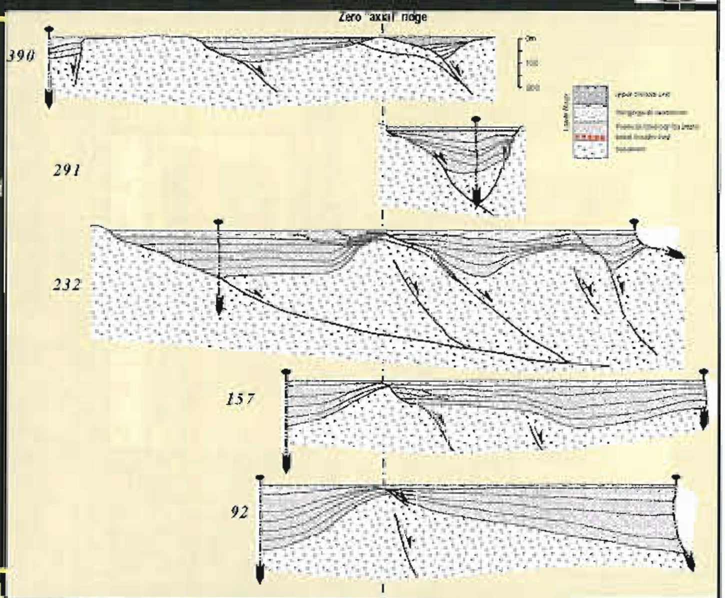
Restored Basin

faults propagate to surface in western portion, leading to compartmentalised basin system

physical hydrocarbon trap



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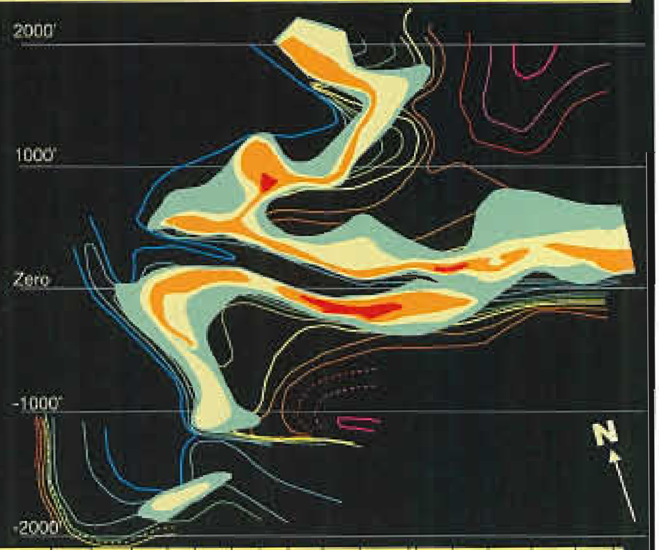
Basin Geometry

- Ore located at periphery of basement ridges
  - FW pinchouts



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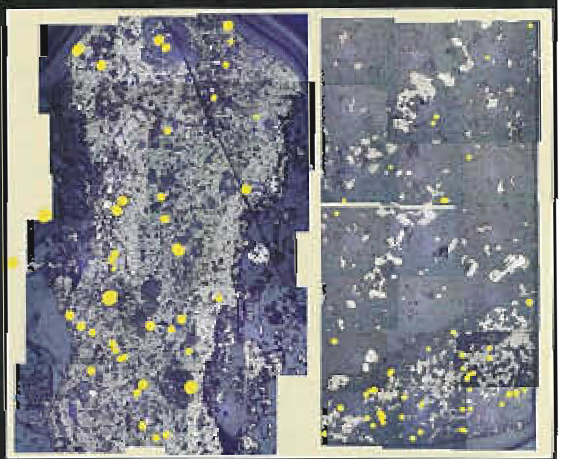
Sulfide-"Heavy Mineral" Association

- 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



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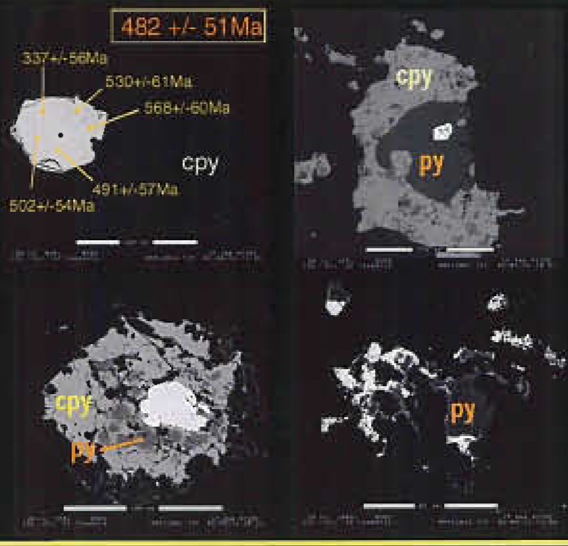
Sulfide-"Heavy Mineral" Association

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



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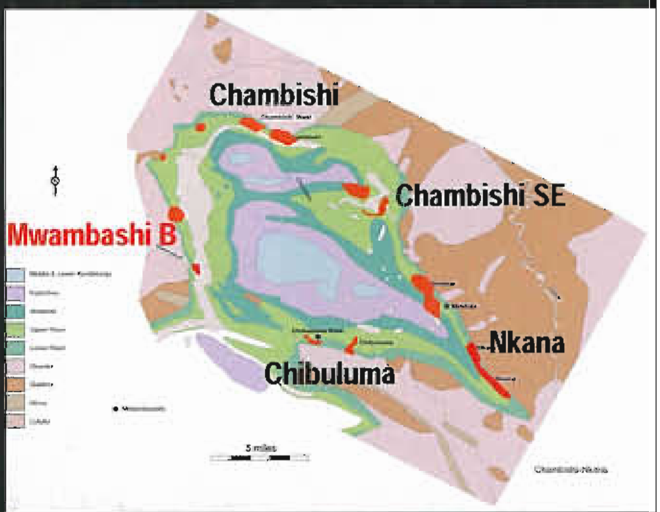
Mwambashi B

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



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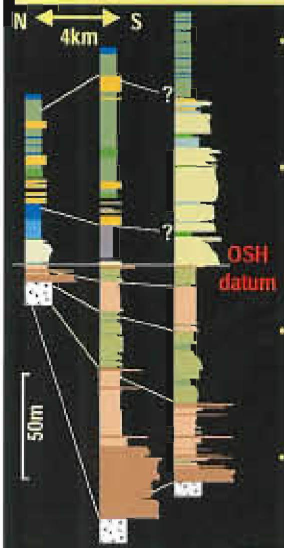
Stratigraphy and facies types



- 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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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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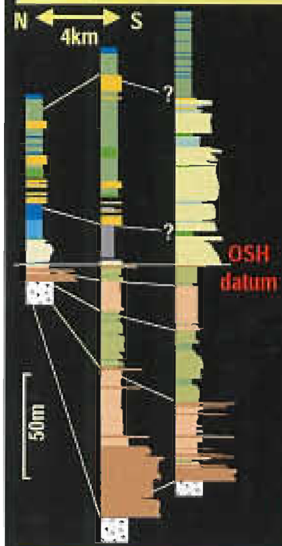
Lower Siliciclastic Package



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

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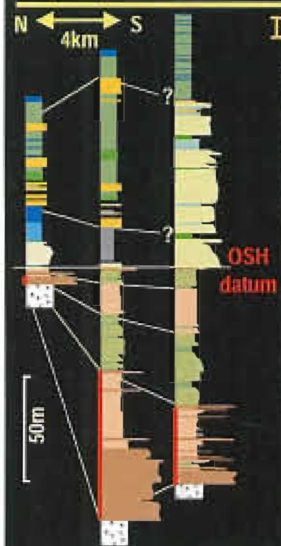
Basal alluvial-fluvial sequence



Inner-mid fan / fluvial facies association

Talus

- angular granitic fragments
- matrix poor
- patchy feldspathic alt

- Stratified heavy mineral bearing sub-arkose
- intercalated sandy debris flows
- typically feldspar-calcite altered, locally pitted

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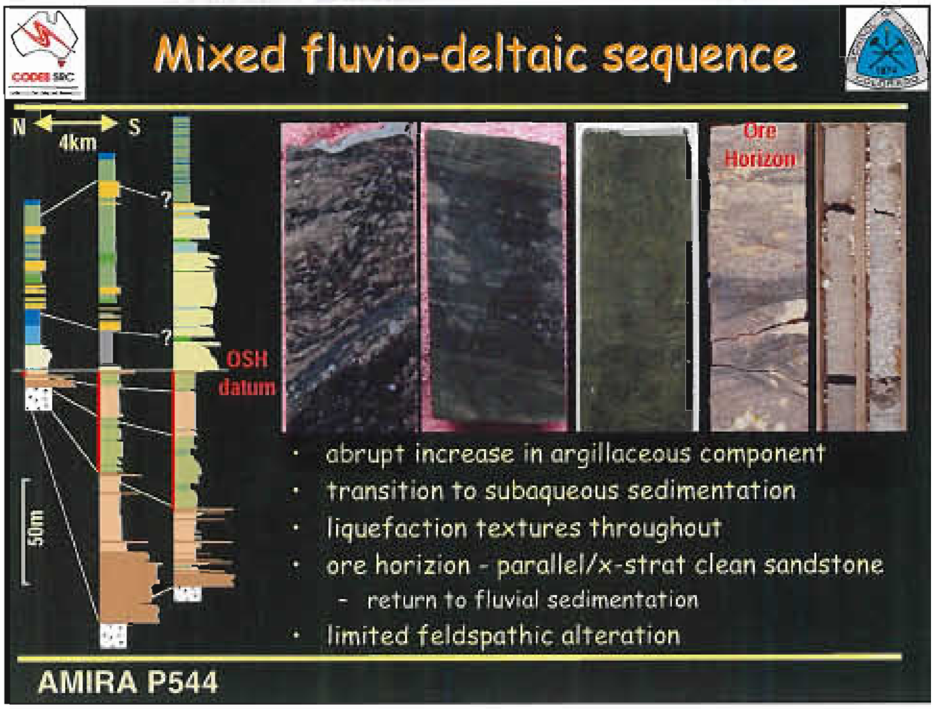
Mixed fluvio-deltaic sequence
N
4km
S
OSH
datum
50m
Ore
Horizon
• abrupt increase in argillaceous component
• transition to subaqueous sedimentation
• liquefaction textures throughout
• ore horizion - parallel/x-strat clean sandstone
– return to fluvial sedimentation
• limited feldspathic alteration
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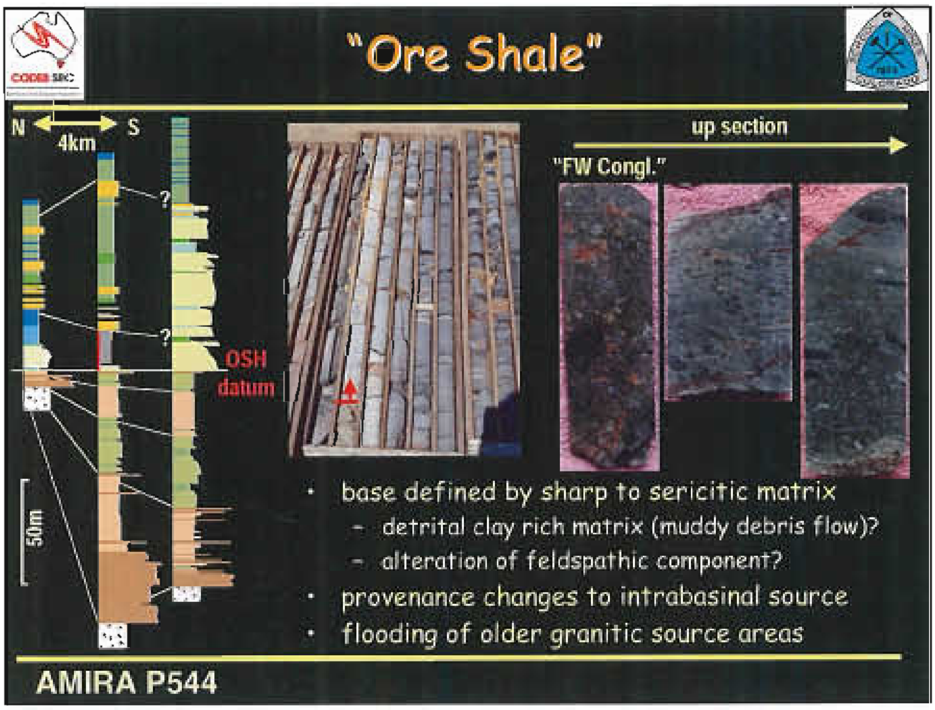
"Ore Shale"
N
4km
S
OSH
datum
50m
up section
"FW Congl."
• base defined by sharp to sericitic matrix
– detrital clay rich matrix (muddy debris flow)?
– alteration of feldspathic component?
• provenance changes to intrabasinal source
• flooding of older granitic source areas
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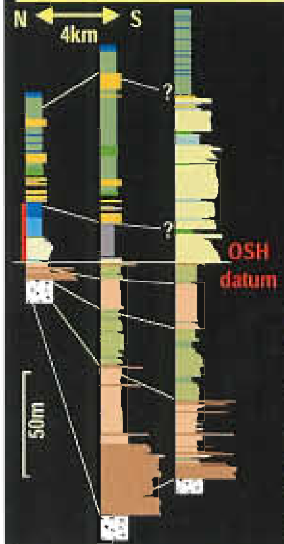
"Ore Shale" - "dolomitic facies"



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

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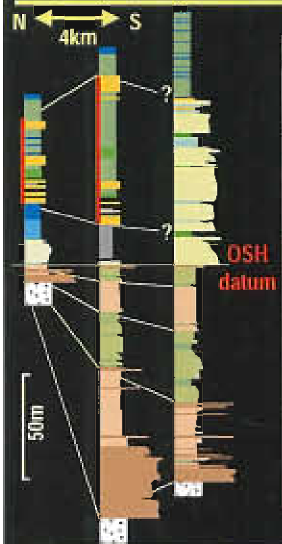
"Hangingwall" siliciclastics



- 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

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Breccia Facies
N
4km
S
?
?
OSH
datum
50m
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
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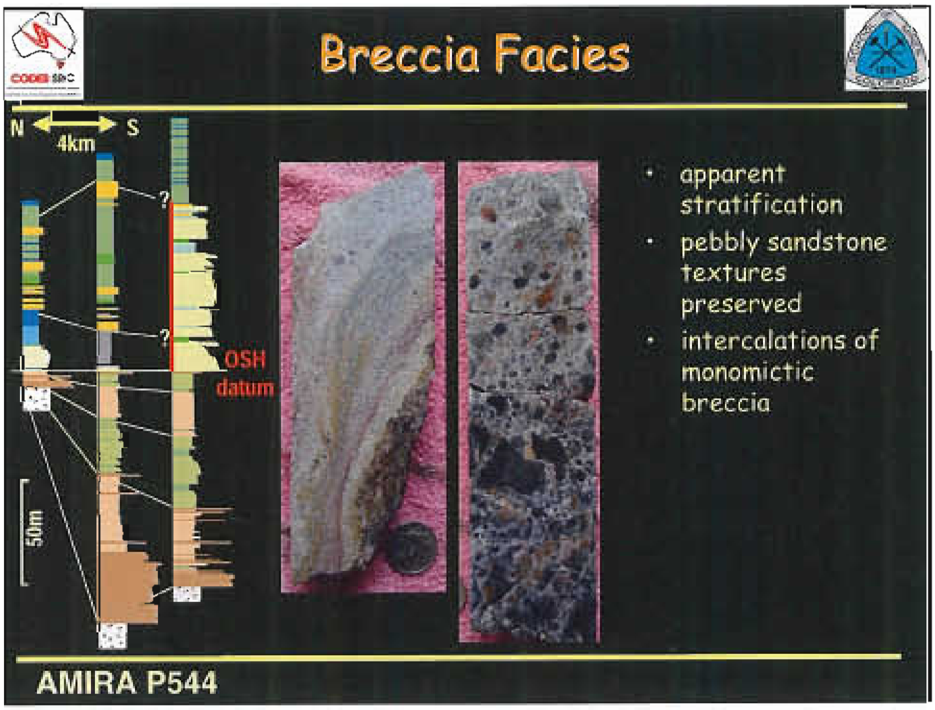
Breccia Facies
N
4km
S
?
?
OSH
datum
50m
apparent stratification
pebbly sandstone textures preserved
intercalations of monomictic breccia
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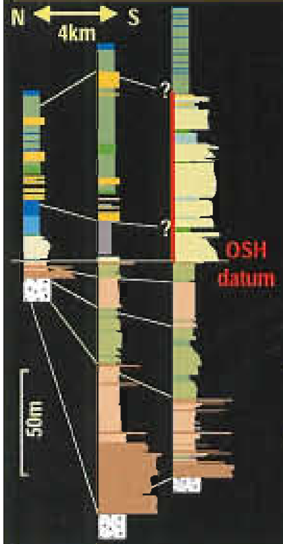
Breccia Facies - upper contact



- halite casts preserved at top of "upward fining sequence"
- breccia fabrics and scapolite throughout ?Upper Roan dolomitic and chloritic shales

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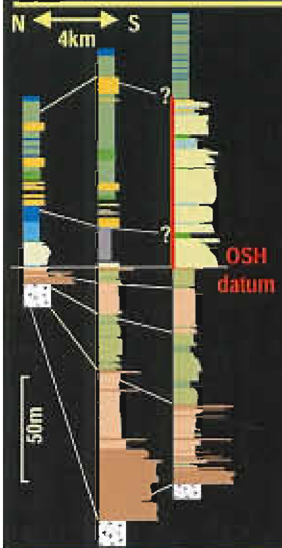
Breccia Facies - Origin?



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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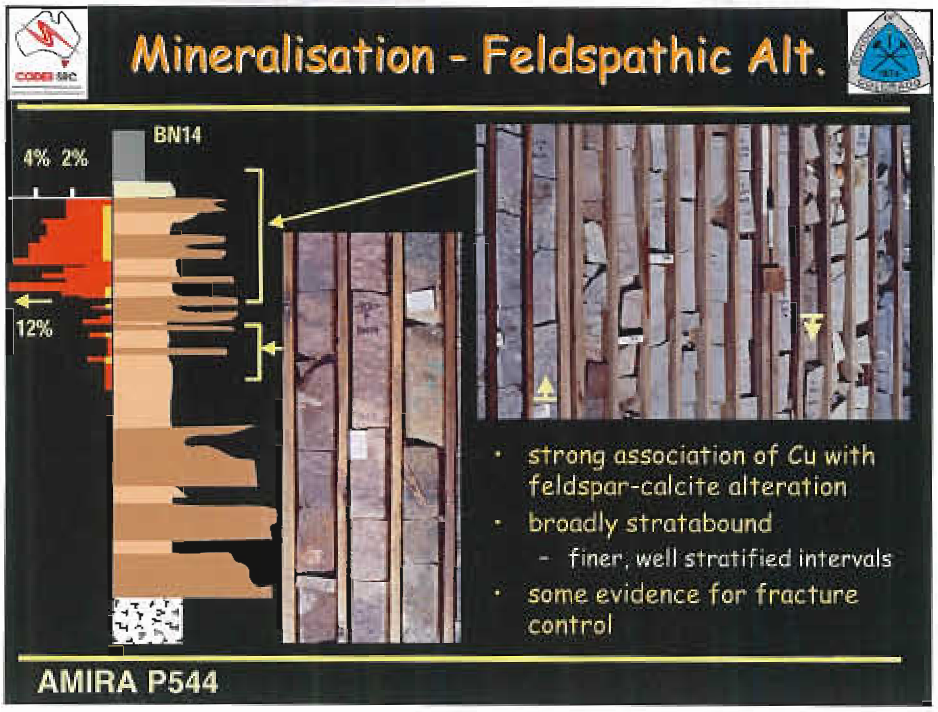
Mineralisation - Feldspathic Alt.
BN14
4% 2%
12%
• strong association of Cu with feldspar-calcite alteration
• broadly stratabound
– finer, well stratified intervals
• some evidence for fracture control
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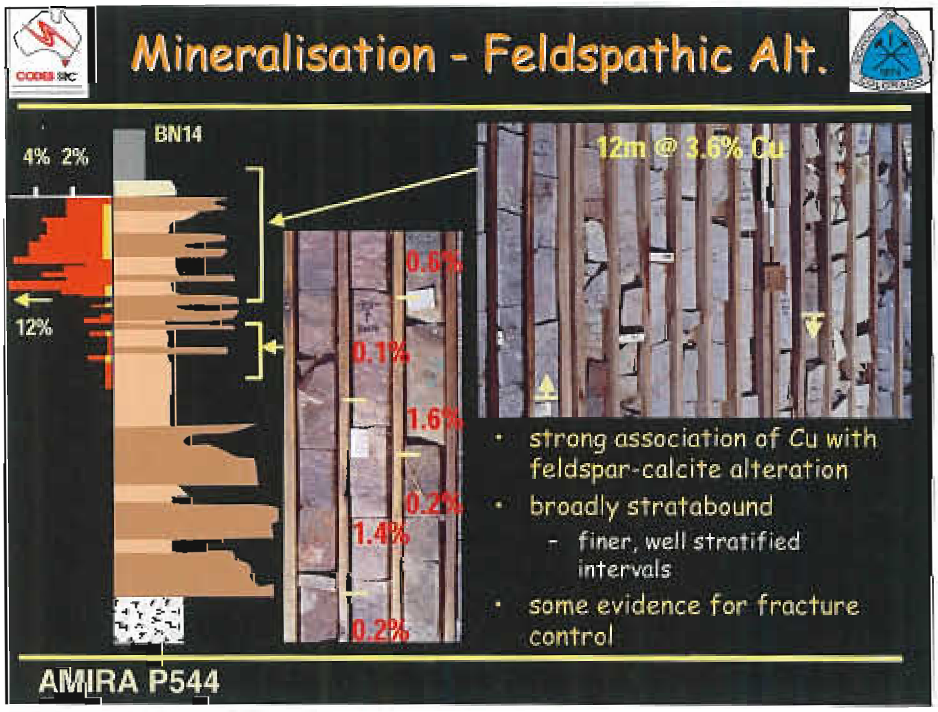
Mineralisation - Feldspathic Alt.
BN14
4% 2%
12%
12m @ 3.6% Cu
0.6%
0.1%
1.6%
0.2%
1.4%
0.2%
• strong association of Cu with feldspar-calcite alteration
• broadly stratabound
– finer, well stratified intervals
• some evidence for fracture control
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Mineralisation - Feldspathic Alt.

Cu

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

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Alteration at periphery of ore

BN50

'Ore Horizon'

- 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

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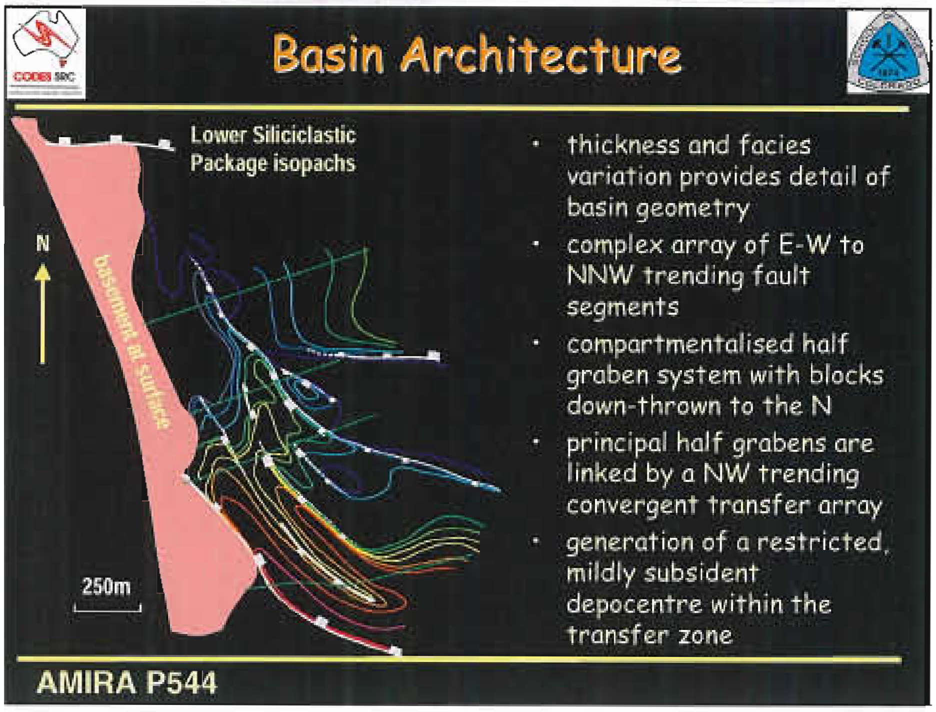
Basin Architecture
Lower Siliciclastic Package isopachs
N
basement at surface
250m
thickness and facies variation provides detail of basin geometry
complex array of E-W to NNW trending fault segments
compartmentalised half graben system with blocks down-thrown to the N
principal half grabens are linked by a NW trending convergent transfer array
generation of a restricted, mildly subsident depocentre within the transfer zone
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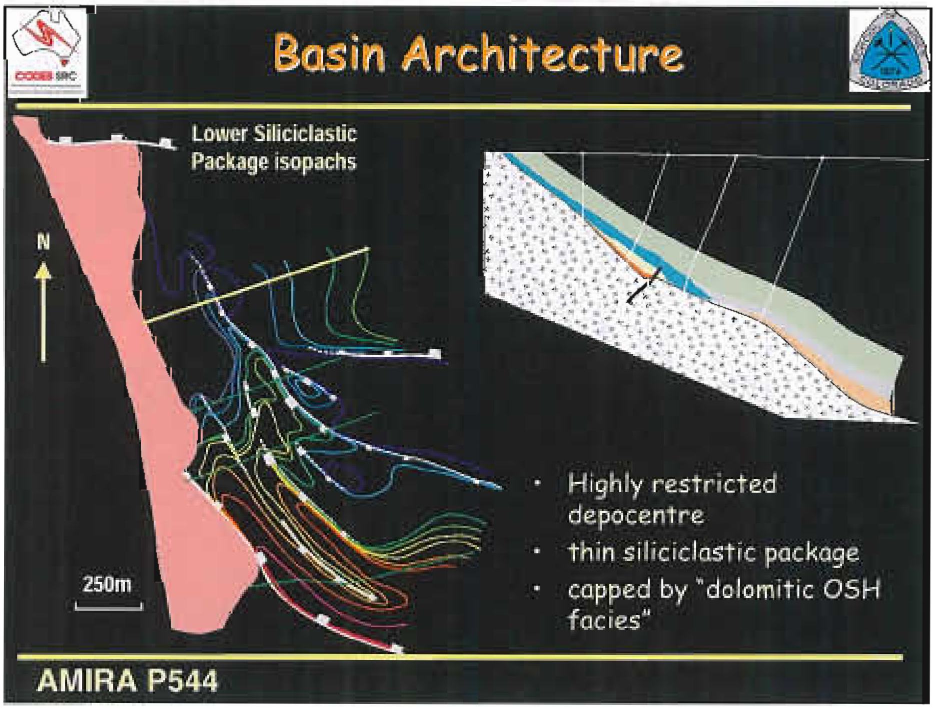
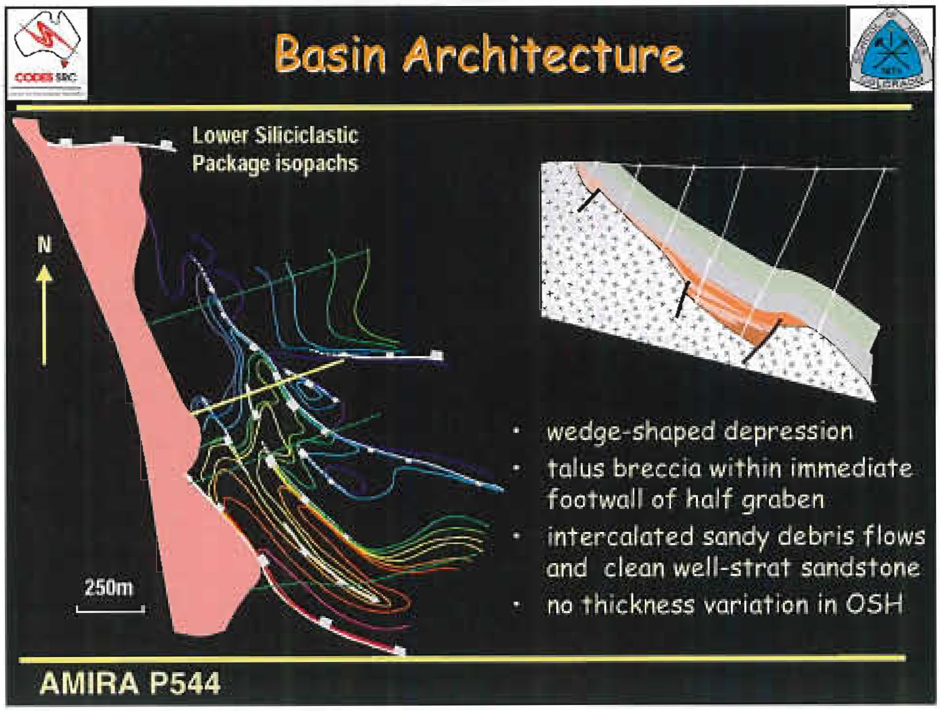

Basin Architecture
Lower Siliciclastic Package isopachs
N
250m
Highly restricted depocentre
thin siliciclastic package
capped by "dolomitic OSH facies"
AMIRA P544


CODES SRC
Basin Architecture
Lower Siliciclastic Package isopachs
N
250m
• wedge-shaped depression
• talus breccia within immediate footwall of half graben
• intercalated sandy debris flows and clean well-strat sandstone
• no thickness variation in OSH
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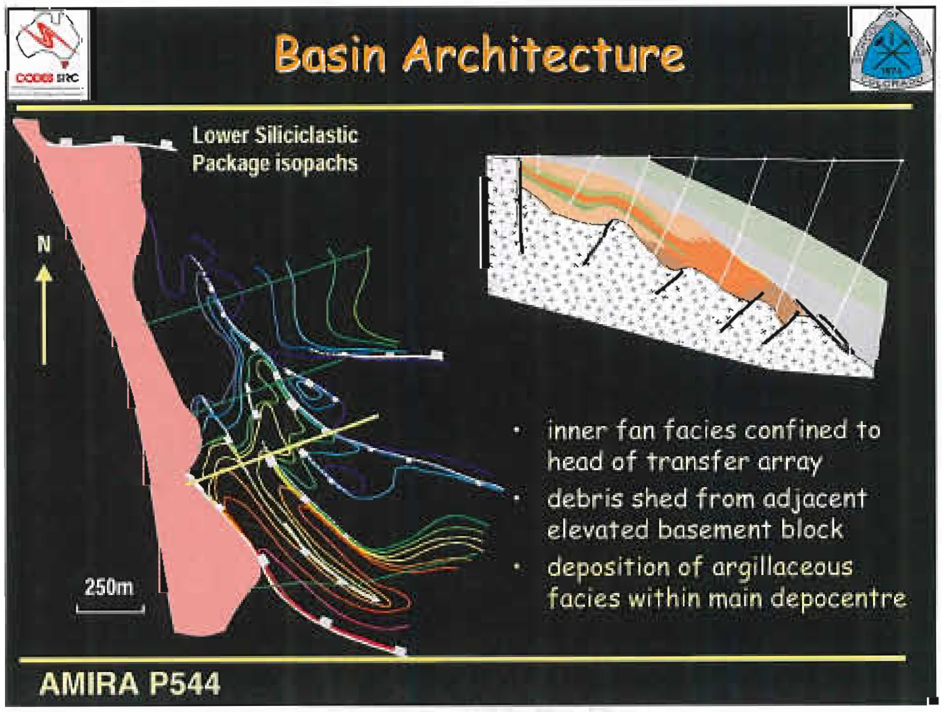
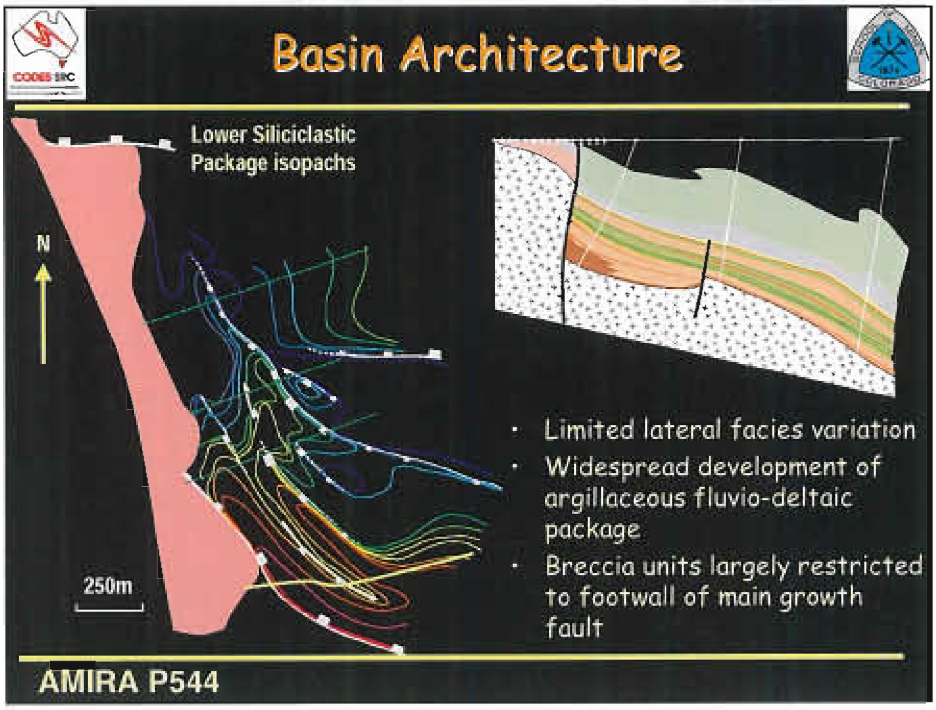
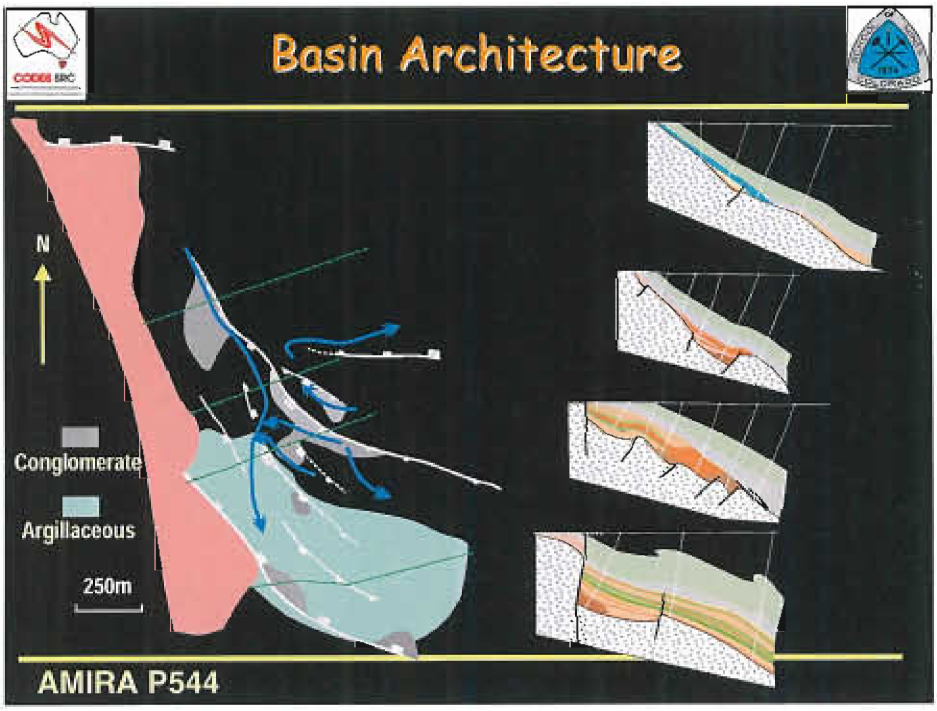
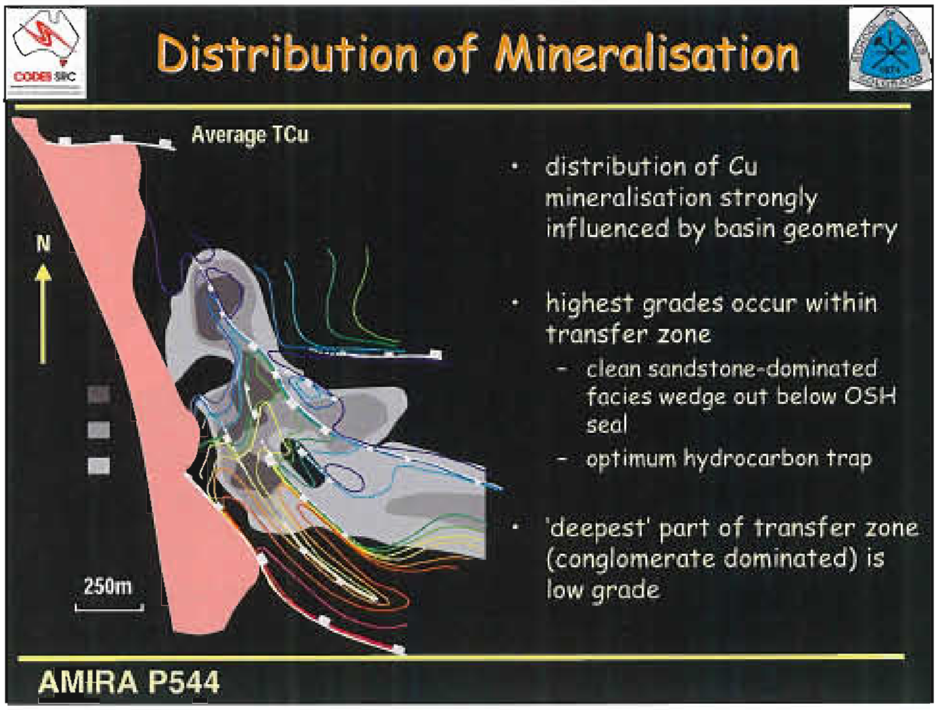
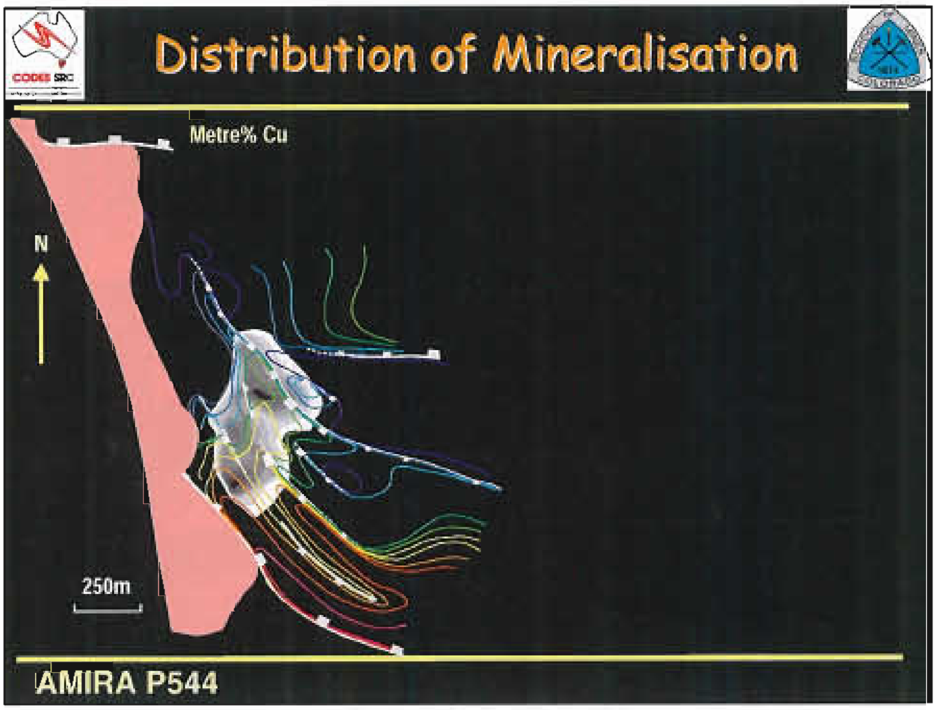
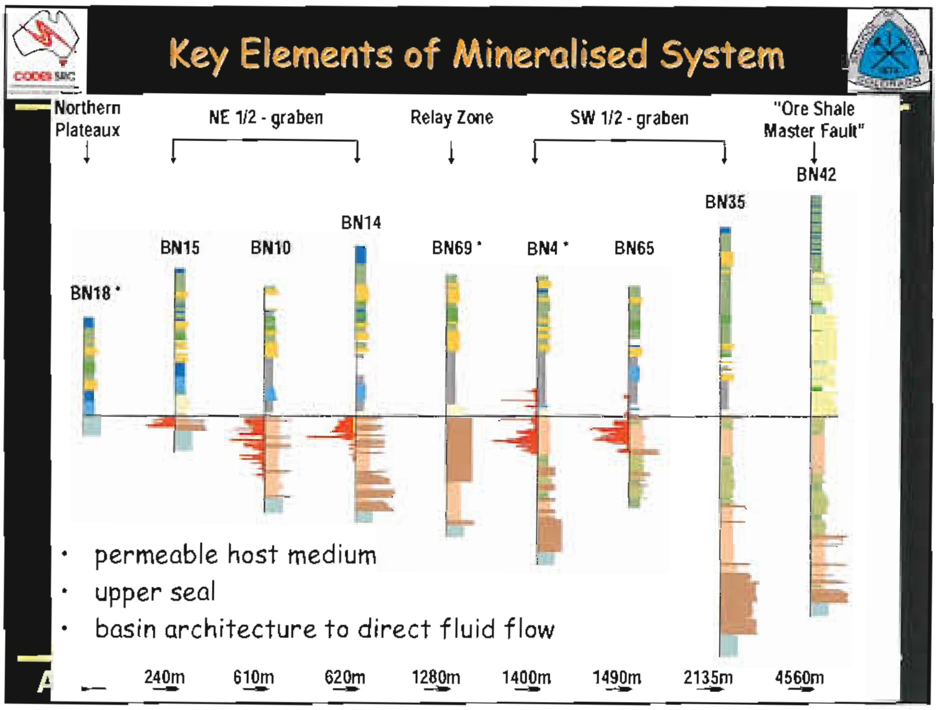

CODES SRC
Basin Architecture
Lower Siliciclastic Package isopachs
N
250m
• inner fan facies confined to head of transfer array
• debris shed from adjacent elevated basement block
• deposition of argillaceous facies within main depocentre
AMIRA P544


Basin Architecture
CODES SRC
Lower Siliciclastic
Package isopachs
N
250m
• Limited lateral facies variation
• Widespread development of argillaceous fluvio-deltaic package
• Breccia units largely restricted to footwall of main growth fault
AMIRA P544

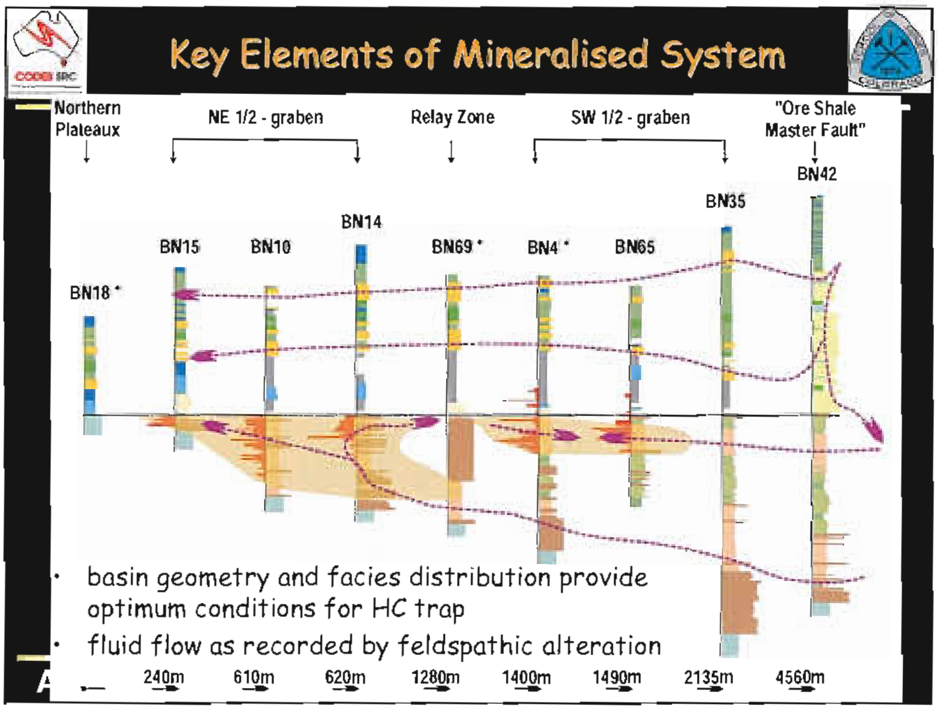

Basin Architecture
CODES SRC
N
Conglomerate
Argillaceous
250m
AMIRA P544


Distribution of Mineralisation
CODES SRC
Average TCu
N
250m
• 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
AMIRA P544


Distribution of Mineralisation
CODES SRC
Metre% Cu
N
250m
AMIRA P544



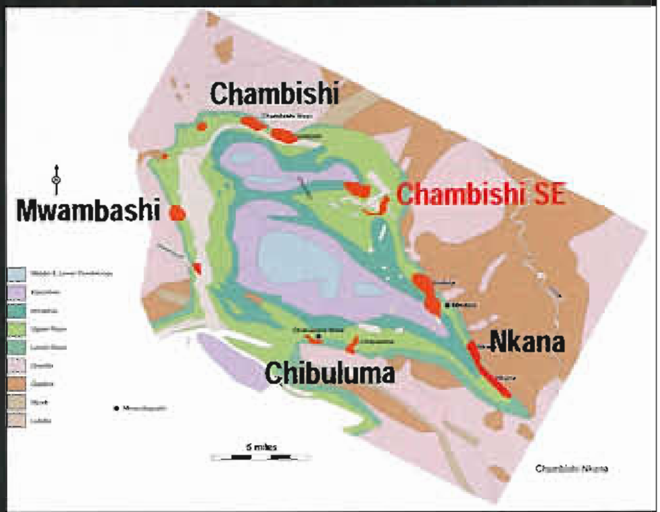
Key Elements of Mineralised System
Northern Plateaux
NE 1/2 - graben
Relay Zone
SW 1/2 - graben
"Ore Shale Master Fault"
BN42
BN35
BN14
BN15
BN10
BN69 *
BN4 *
BN65
BN18 *
• permeable host medium
• upper seal
• basin architecture to direct fluid flow
240m
610m
620m
1280m
1400m
1490m
2135m
4560m



Key Elements of Mineralised System
Northern Plateaux
NE 1/2 - graben
Relay Zone
SW 1/2 - graben
"Ore Shale Master Fault"
BN42
BN35
BN14
BN15
BN10
BN69 *
BN4 *
BN65
BN18 *
• basin geometry and facies distribution provide optimum conditions for HC trap
• fluid flow as recorded by feldspathic alteration
240m
610m
620m
1280m
1400m
1490m
2135m
4560m

Chambishi SE

- Ore Shale hosted mineralisation
- ore is situated at fringes of "biohermal facies"
- additional spatial association of ore with footwall pinch outs



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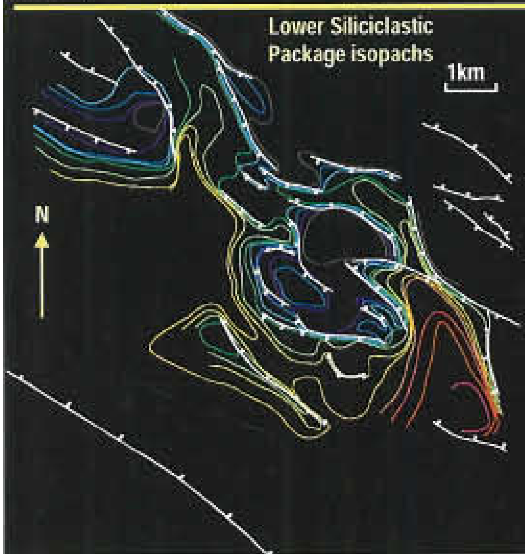
Chambishi SE



- 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

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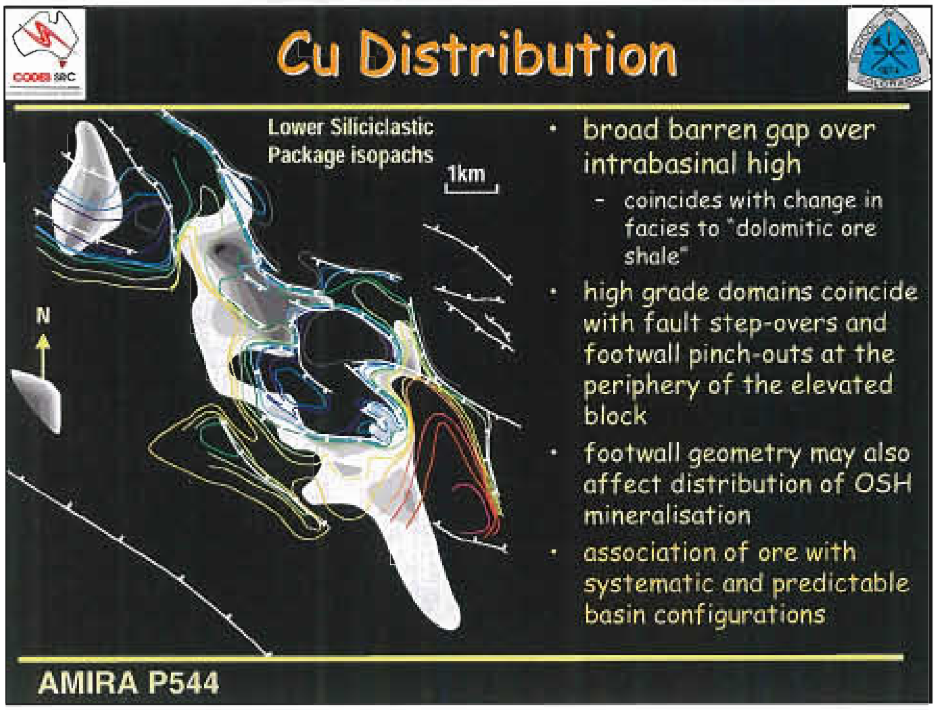
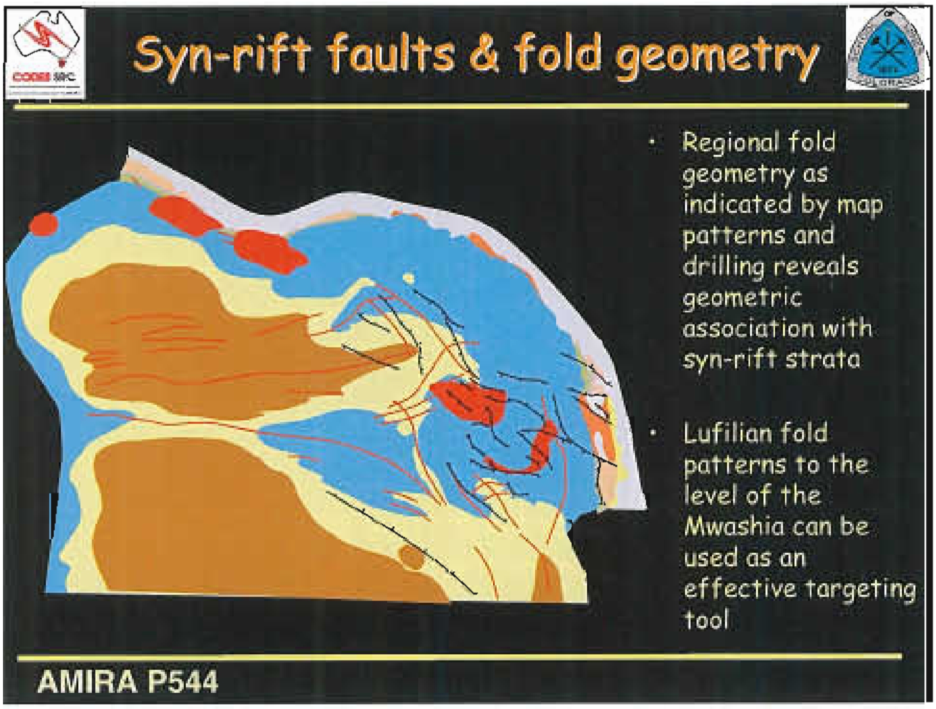

Cu Distribution
Lower Siliciclastic
Package isopachs
1km
N
• broad barren gap over intrabasinal high
– coincides with change in facies to "dolomitic ore shale"
• high grade domains coincide with fault step-overs and footwall pinch-outs at the periphery of the elevated block
• footwall geometry may also affect distribution of OSH mineralisation
• association of ore with systematic and predictable basin configurations
AMIRA P544


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
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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 *ie.* 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 -

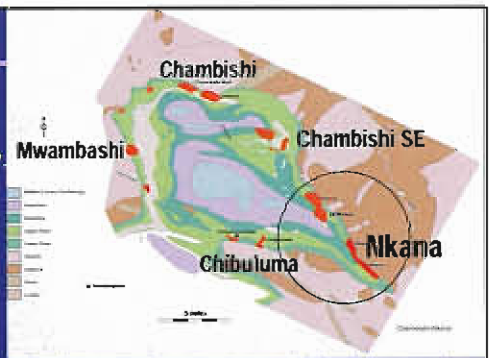
At Mindola and Mindola North poor control from data available on depth to Basement / SOB high deformed, work ongoing.
Limited old drill core from surface drilling exists.
Underground exposure predominantly limited to immediate footwall or has been whitewashed.

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.



Orebodies 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

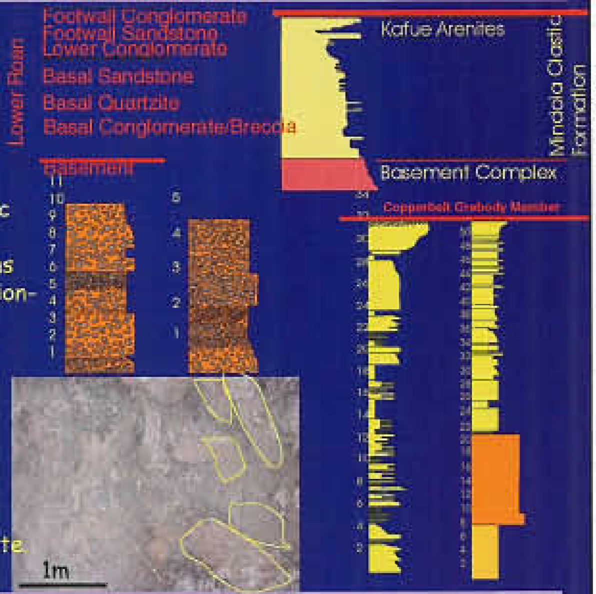
Since May 2002 - developing better understanding and controls on relationship of basement to Lower Roan deposition.

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.

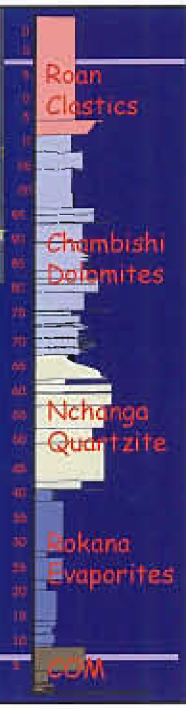
Laterally continuous fine grained units.

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 depostional environment Fluvial-deltaic, Shallow marine, Carbonates, limited evaporites.



BASEMENT CONTROL

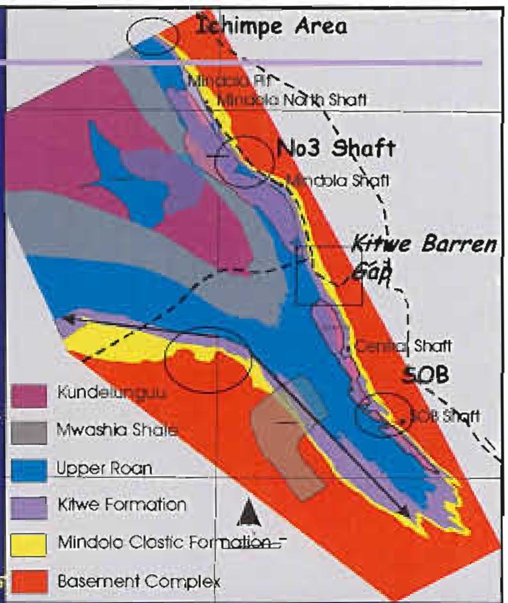
Basement-Lower Roan contact map geometry very useful for areas of potential early basin margins.

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 BUT 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 Roan.

Also clearly recognised by Selley at Chibuluma, 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?

ACKNOWLEDGEMENTS

- MOPANI COPPER MINES - Gavin Ferguson, Dave Armstrong, Wellington Mukumba, Giddy Mwale and ALL underground workers
- FIRST QUANTUM MINERALS, ZAMBIA - Hugh Carruthers and Mike Stuart.
- ZAMANGLO. Peter Mann and staff.
- AMIRA SPONSORS, CODES STAFF AND CSM.
- JUNE PONGRATZ.

Stratigraphy, Regional Alteration and Mineralization Patterns of the Zambian Copperbelt

David Broughton
Colorado School of Mines

AMIRA P544 November 2002

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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

-progression 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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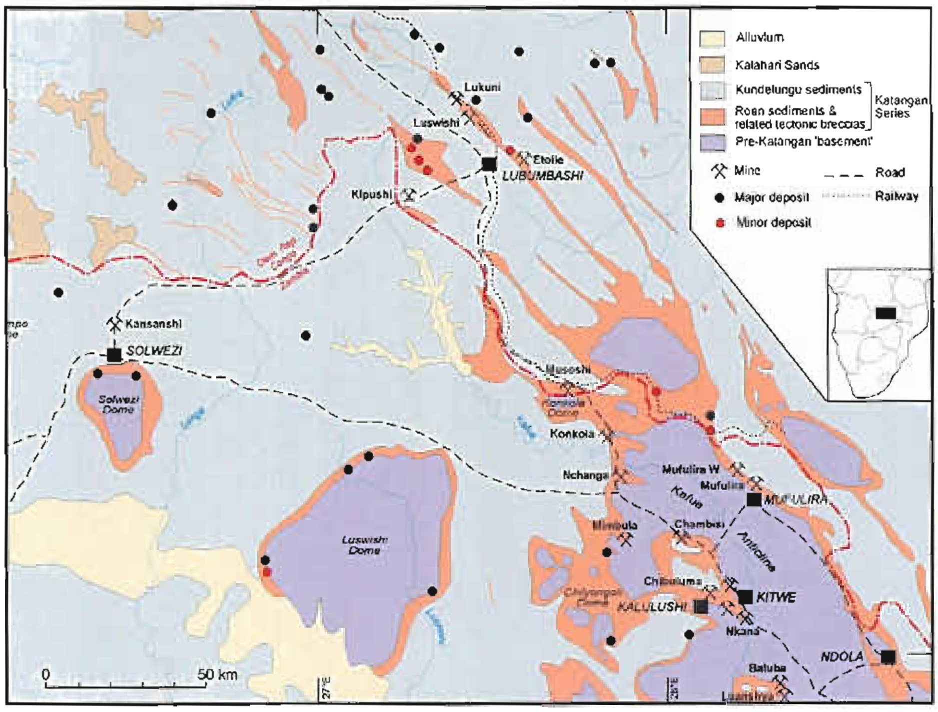
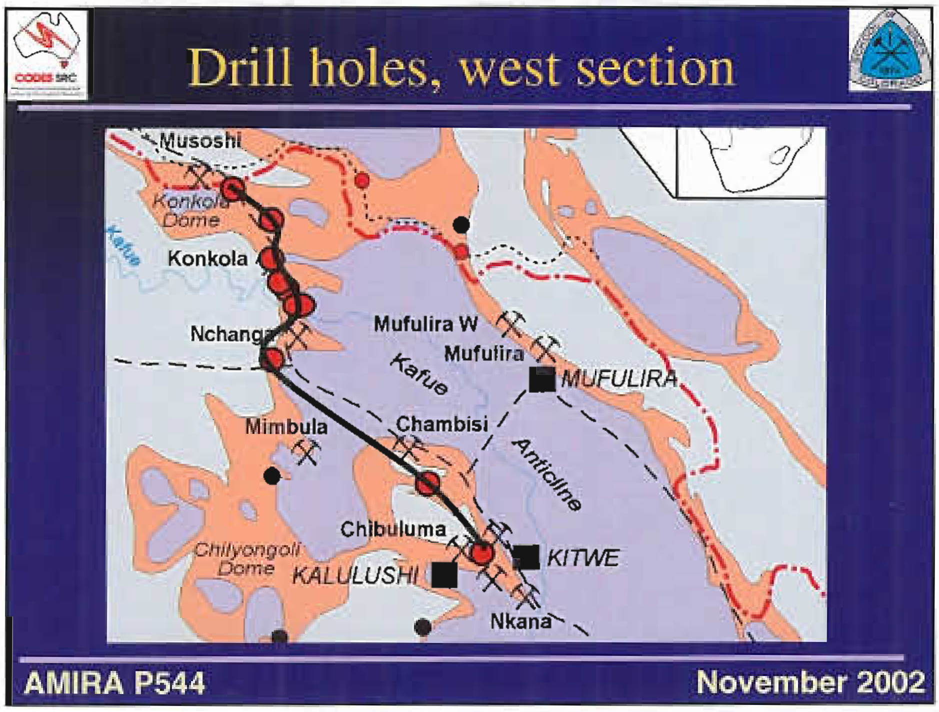

Alluvium
Kalahari Sands
Kundelungu sediments
Roan sediments & related tectonic breccias
Katangan Series
Pre-Katangan 'basement'
Mine
Major deposit
Minor deposit
Road
Railway
Lukuni
Luswishi
Etoile
LUBUMBASHI
Kipushi
Kansanshi
SOLWEZI
Solwezi Dome
Musoshi
Konkola Dome
Konkola
Nchanga
Mufulira W
Mufulira
MUFULIRA
Kafue
Chambishi
Anticline
Mimbula
Luswishi Dome
Chilyongoli Dome
Chibuluma
KITWE
KALULUSHI
Nkana
NDOLA
Baluba
Luanshya
0
50 km
27°E
28°E


Drill holes, west section
Musoshi
Konkola Dome
Kafue
Konkola
Nchanga
Mufulira W
Mufulira
MUFULIRA
Kafue
Mimbula
Chambisi
Anticline
Chibuluma
Chilyongoli Dome
KALULUSHI
KITWE
Nkana
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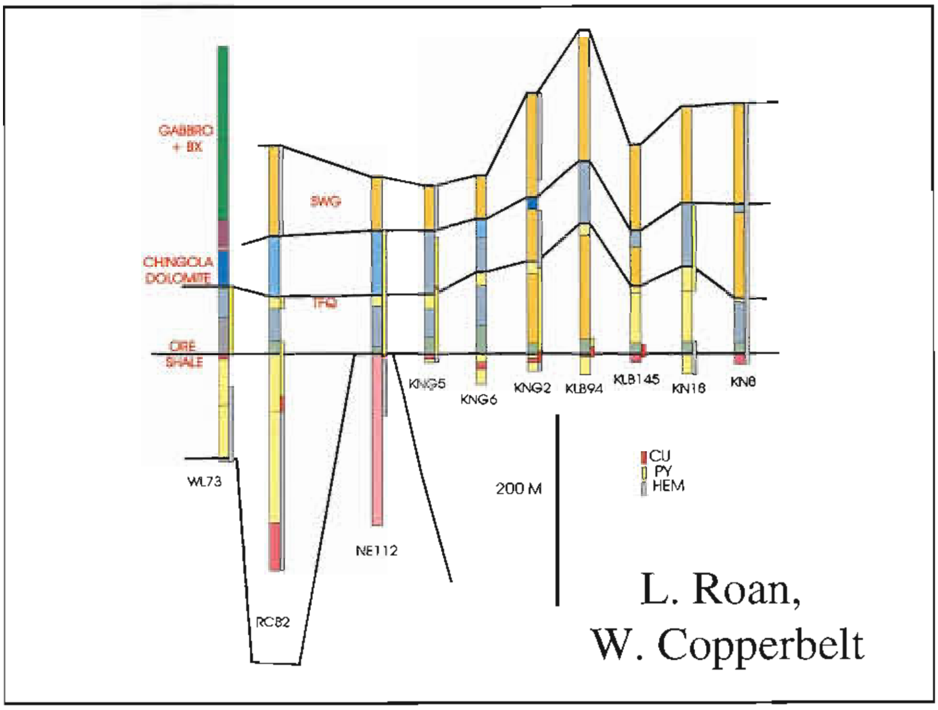
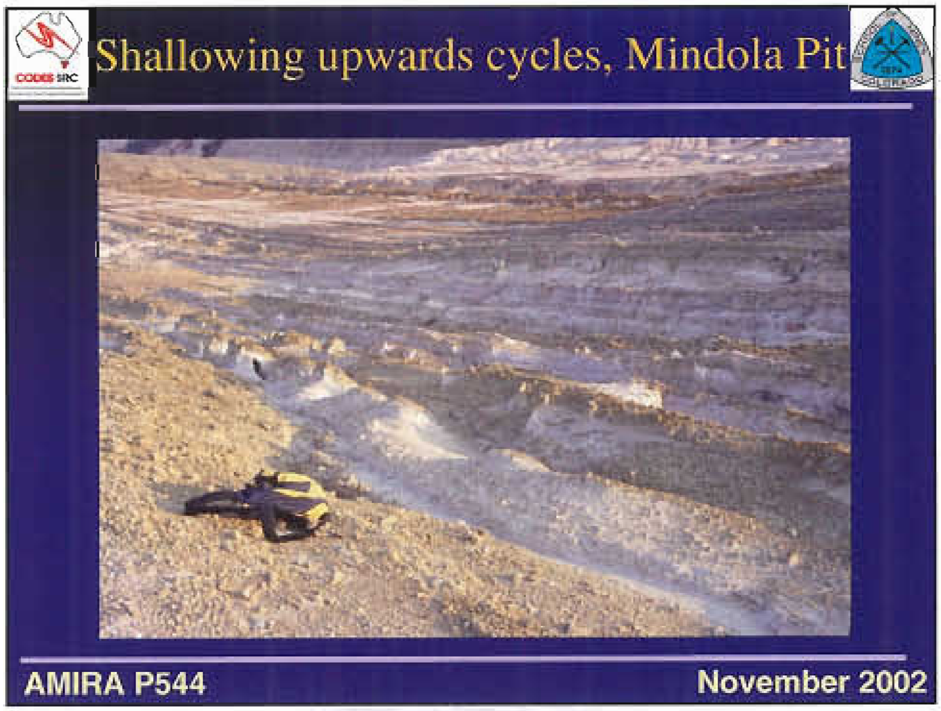

GABBRO + BX
SWG
CHINGOLA DOLOMITE
TFQ
ORE SHALE
WL73
RC82
NE112
KNG5
KNG6
KNG2
KLB94
KLB145
KN18
KN8
200 M
CU
PY
HEM
L. Roan,
W. Copperbelt


CODES SRC
Shallowing upwards cycles, Mindola Pit
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Bedding-plane salt crusts, Mindola Pit

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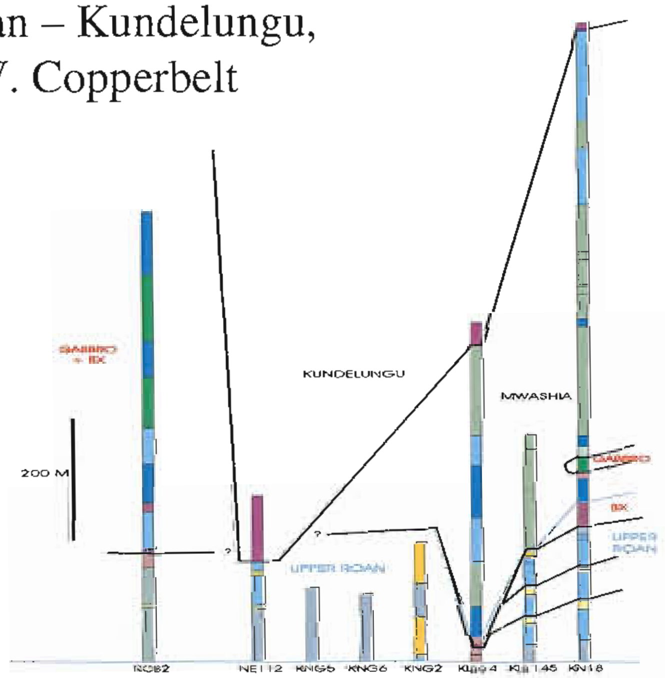
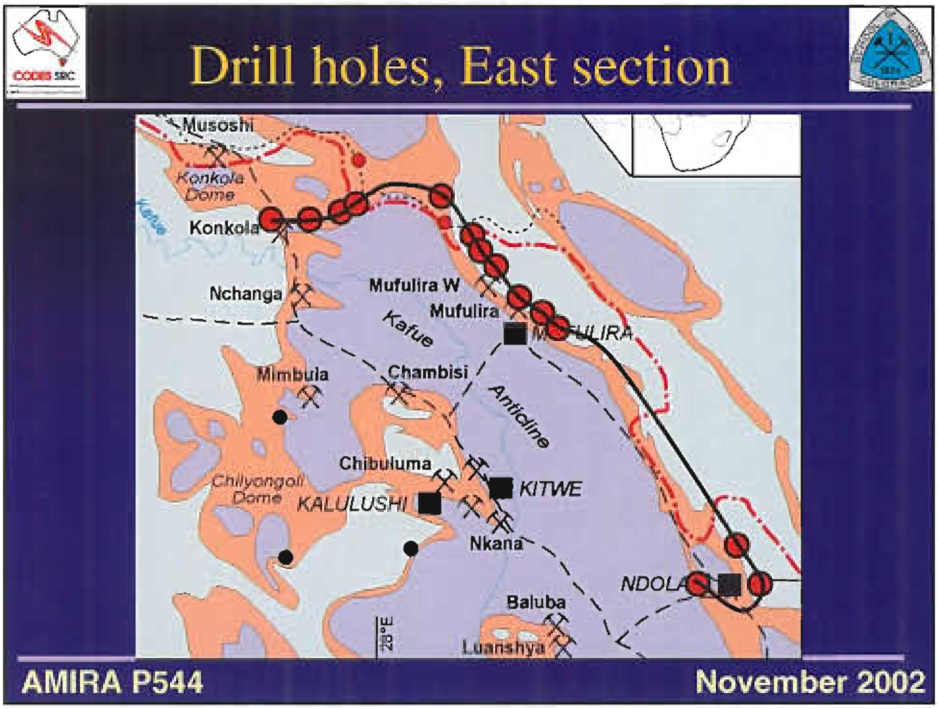
U. Roan – Kundelungu, W. Copperbelt




Drill holes, East section
CODES SRC
Musoshi
Konkola Dome
Kafue
Konkola
Nchanga
Mufulira W
Mufulira
Kafue
MUFULIRA
Mimbula
Chambisi
Anticline
Chibuluma
Chilyongoli Dome
KALULUSHI
KITWE
Nkana
NDOLA
Baluba
28°E
Luanshya
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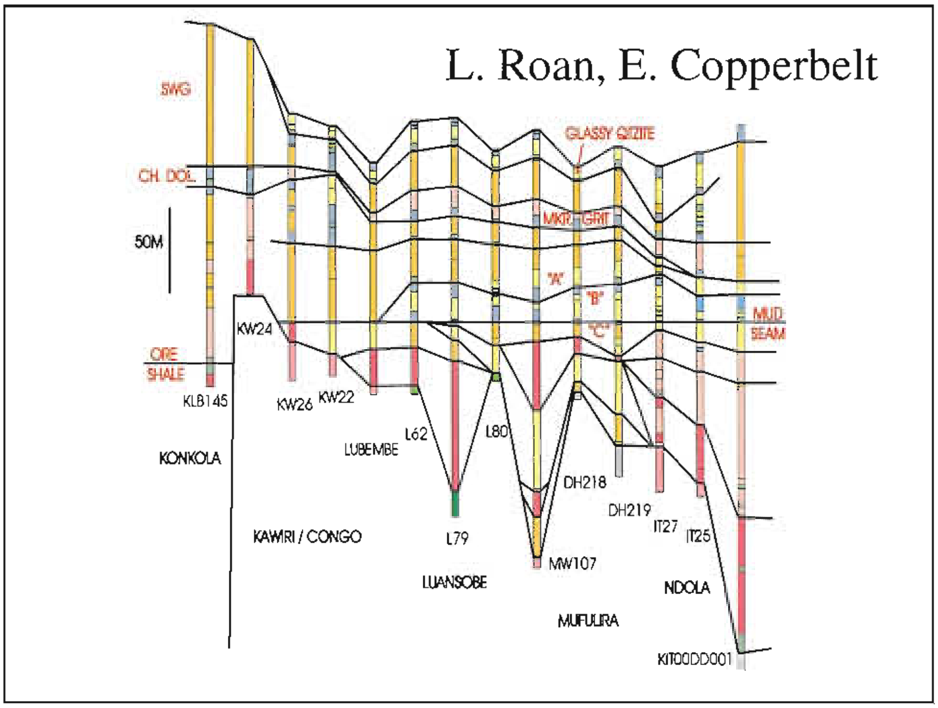
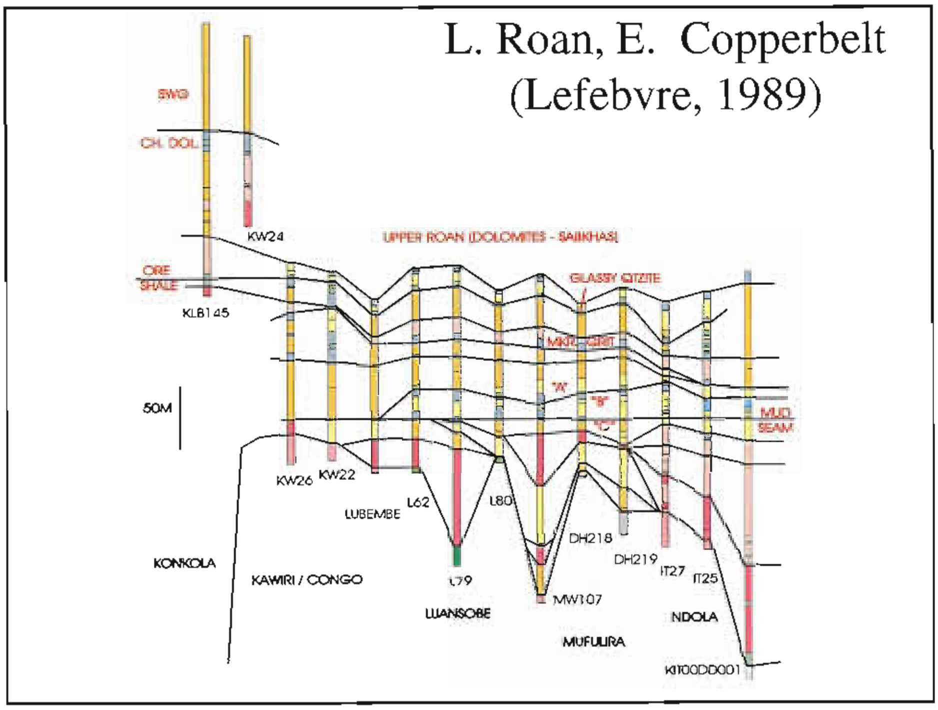
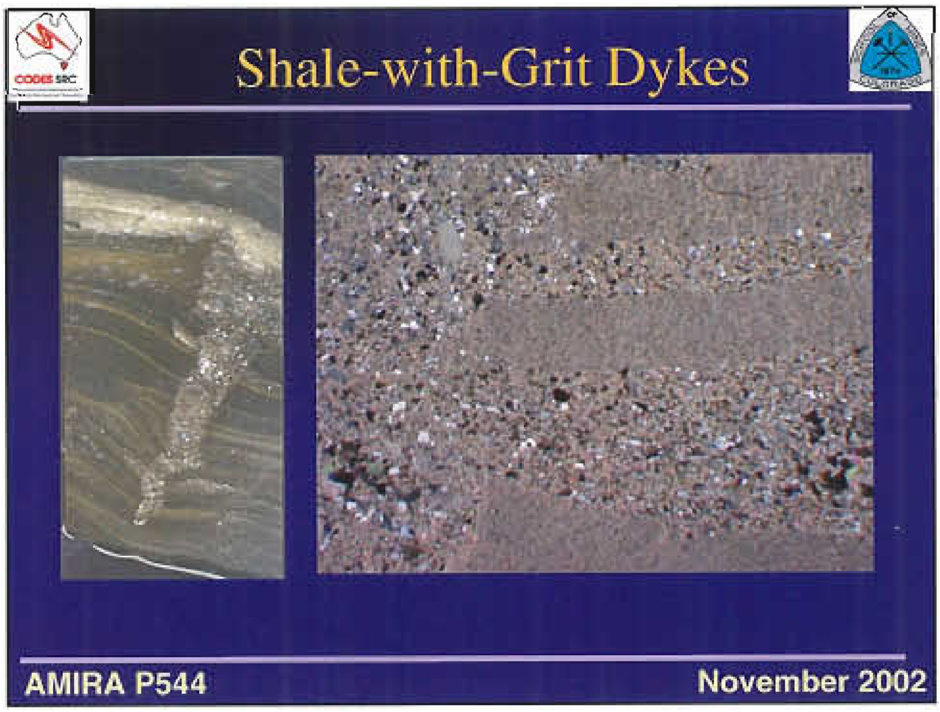
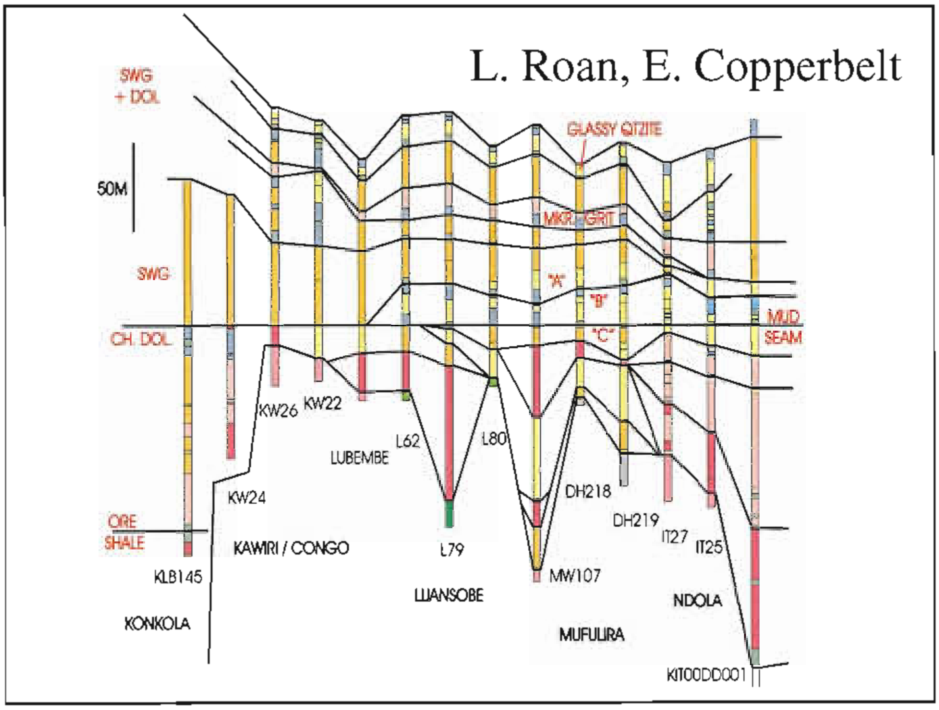
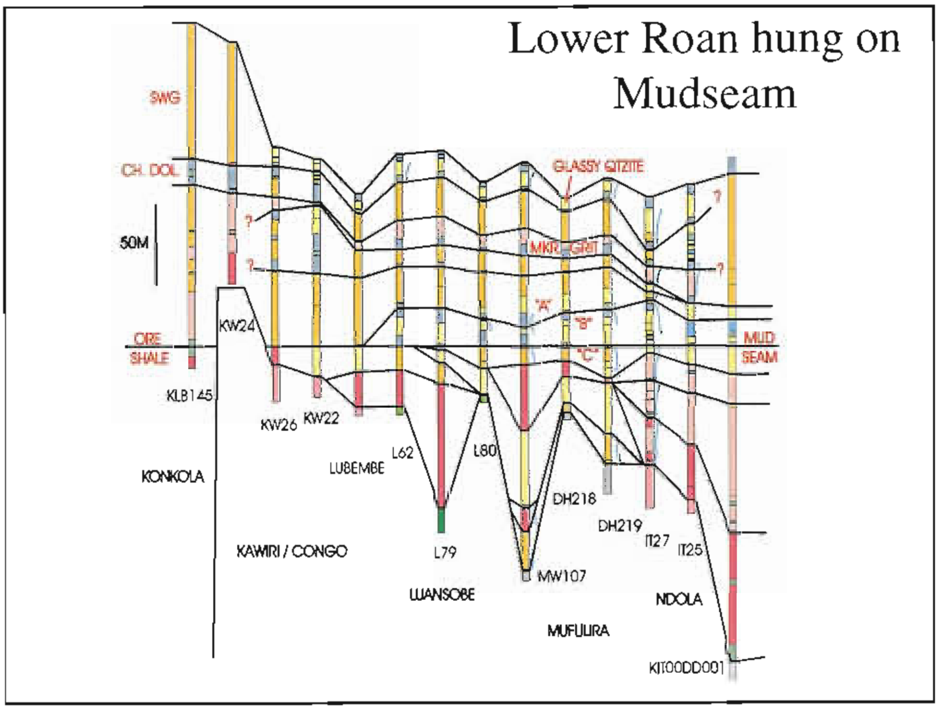

L. Roan, E. Copperbelt
SWG
CH. DOL.
50M
ORE SHALE
GLASSY QTZITE
MKR. GRIT
"A"
"B"
"C"
MUD SEAM
KLB145
KW24
KW26
KW22
L62
L80
LUBEMBE
KONKOLA
KAWIRI / CONGO
L79
LUANSOBE
DH218
DH219
MW107
IT27
IT25
NDOLA
MUFULIRA
KIT00DD001

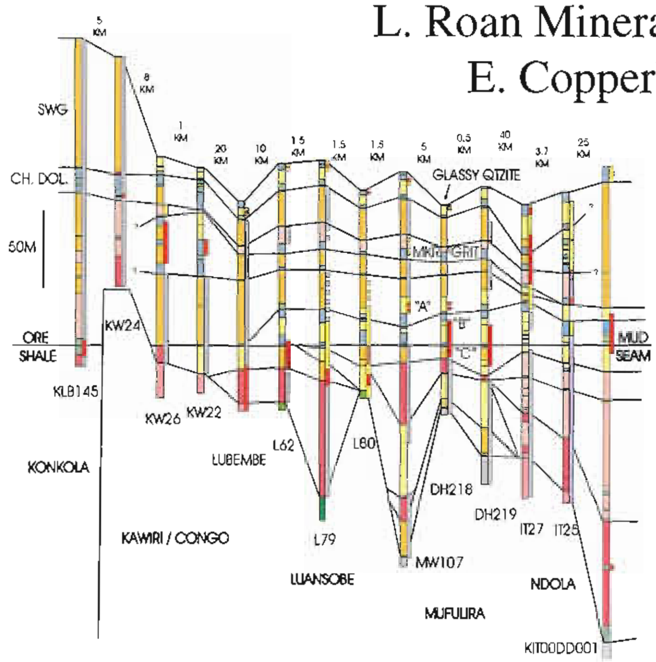

L. Roan, E. Copperbelt
(Lefebvre, 1989)
SWG
CH. DOL.
KW24
UPPER ROAN (DOLOMITES - SABKHAS)
ORE SHALE
KLB145
GLASSY QTZITE
50M
MUD SEAM
KW26
KW22
LUBEMBE
L62
L80
DH218
DH219
IT27
IT25
KONKOLA
KAWIRI / CONGO
L79
MW107
LUANSOBE
NDOLA
MUFULIRA
KII00DD001


CODES SRC
Shale-with-Grit Dykes
AMIRA P544
November 2002


L. Roan, E. Copperbelt
SWG + DOL
50M
SWG
CH. DOL
ORE SHALE
GLASSY QTZITE
MKR. GRIT
"A"
"B"
"C"
MUD SEAM
KW26
KW22
KW24
L62
L80
LUBEMBE
DH218
DH219
IT27
IT25
L79
MW107
KLB145
KAWIRI / CONGO
LUANSOBE
NDOLA
KONKOLA
MUFULIRA
KIT00DD001

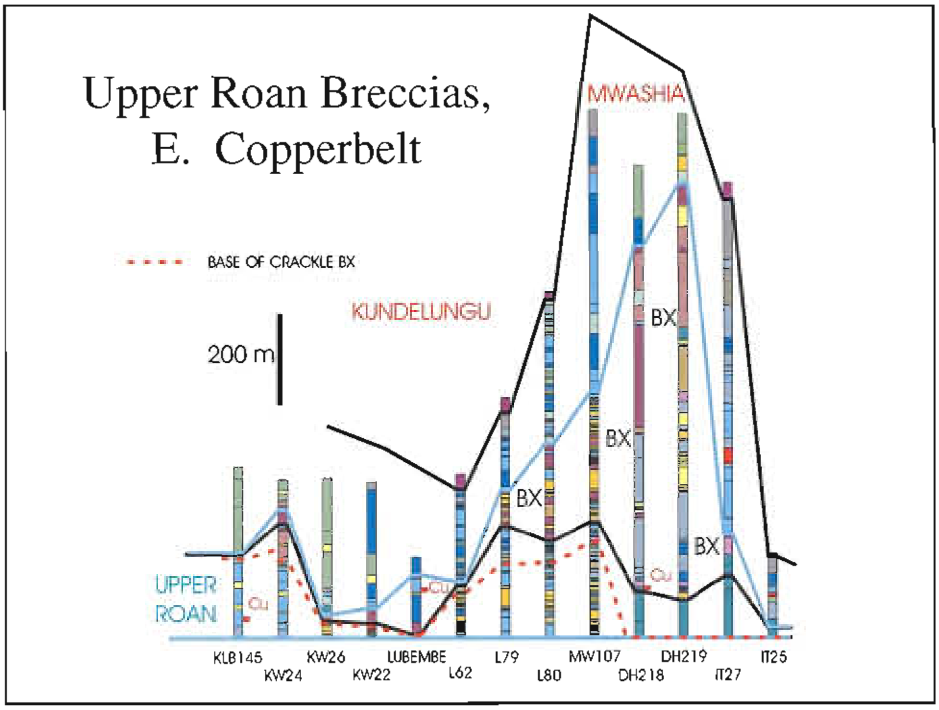

Lower Roan hung on Mudseam
SWG
CH. DOL
50M
ORE SHALE
GLASSY QTZITE
MKR. GRIT
"A"
"B"
"C"
MUD SEAM
KW24
KLB145
KW26
KW22
L62
L80
LUBEMBE
KONKOLA
DH218
DH219
IT27
IT25
KAWIRI / CONGO
L79
MW107
LUANSOBE
NDOLA
MUFULIRA
KIT00DD001

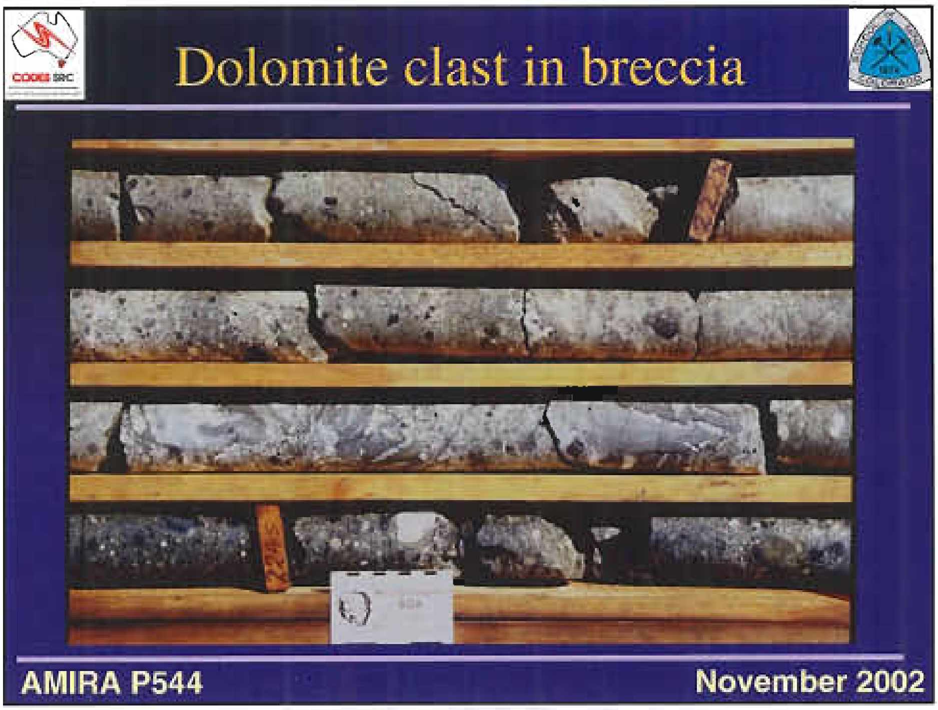
L. Roan Mineralization, E. Copperbelt



Sabkha textures, Upper Roan

Enterolithic "chicken wire" texture, anhydrite-dolomite-pyrite


Upper Roan Breccias,
E. Copperbelt
BASE OF CRACKLE BX
KUNDELUNGU
MWASHIA
200 m
UPPER
ROAN
Cu
Cu
Cu
BX
BX
BX
BX
KLB145
KW24
KW26
KW22
LUBEMBE
L62
L79
L80
MW107
DH218
DH219
IT27
IT25


Dolomite clast in breccia
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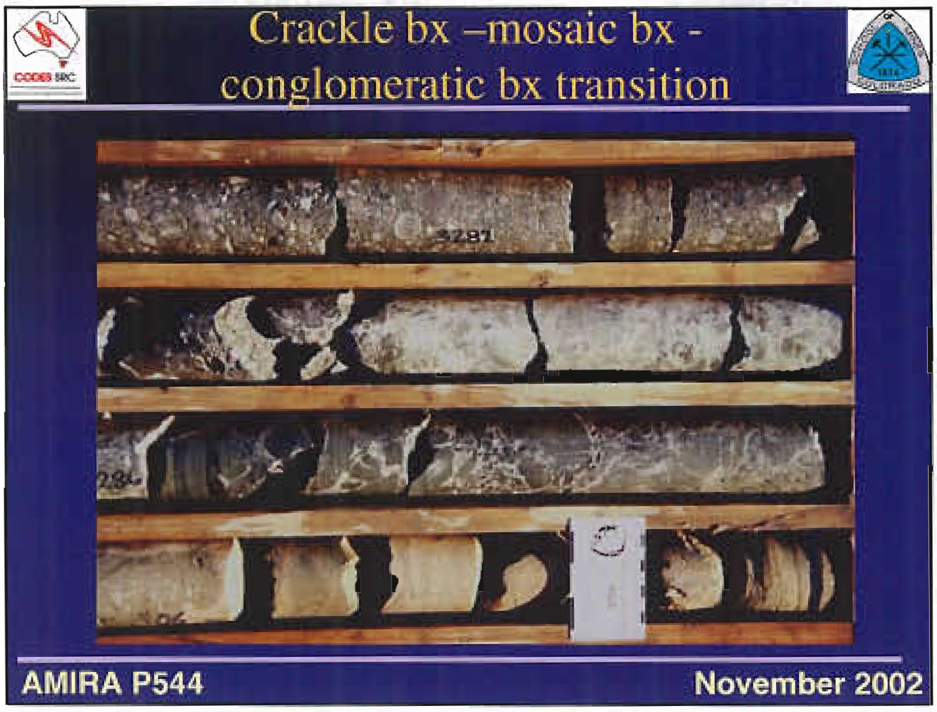
Crackle bx –mosaic bx -
conglomeratic bx transition
AMIRA P544
November 2002


Brecciated clast in breccia
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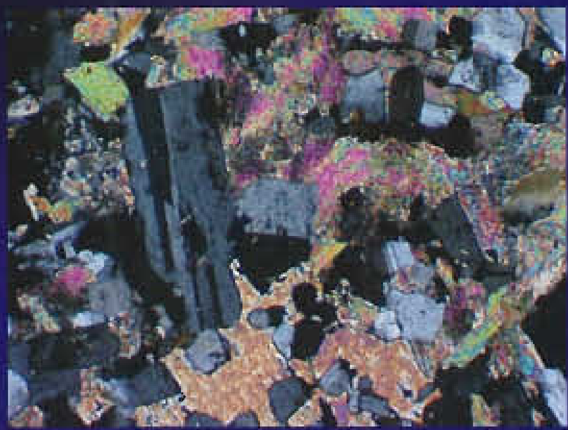
Plagioclase-Dolomite-Biotite Matrix in Breccia



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K feldspar alteration, L.Roan

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Congolese "Mines Group" mineralization in Upper Roan, Mufulira

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Mwashia sandstone and feldspathic alteration

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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)

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

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

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

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

Murray W. Hitzman
Colorado School of Mines

AMIRA P544 November 2002

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.

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Sedimentary Architecture and Structure

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Sedimentary Architecture / 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.**

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Sedimentary Architecture / Structure

- First-order, NW-trending faults (Konkola, Nchanga sycline, 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.

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Sedimentary Architecture / Structure

- The Upper Roan is a mixed carbonate-siliciclastic sequence with punctuated extensional tectonic phases recognized by coarse siliciclastic layers.

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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 3km.
- 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 diamictites and turbidites (indicating tectonically active basin conditions?).

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Sedimentary Architecture / Structure (cont.)

- 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).

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Sedimentary Architecture / Structure (cont.)

- Zambian Copperbelt does NOT occupy a major basin.

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Alteration and Mineralization

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Alteration and Lithogeochemistry

- Alteration is recognized in the Katangan sequence from at least the basal portion of the Mwashia down into the basement.
- Both potassic and sodic styles of alteration are observed.

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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 sands, 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.

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Mineralization

- Zambian Copperbelt mineralization is fundamentally controlled by oxidation change.

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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 reducants. These reducants were in physical traps.

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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."

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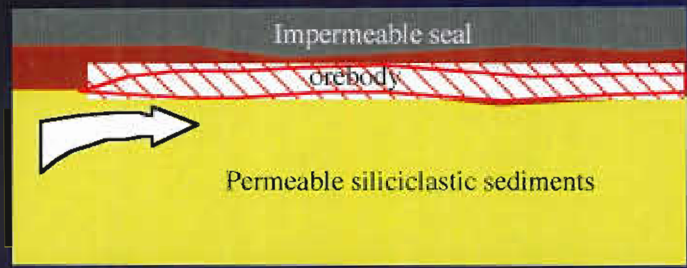
Mineralization - Ore Shale Orebodies



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

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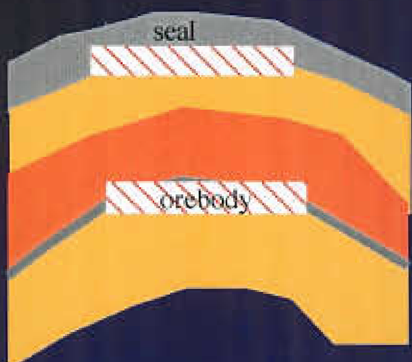
Mineralization - Arenaceous Orebodies



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

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Genetic Model for the Zambian Copperbelt

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Key Ages

870 Ma	Nchanga Granite (basement)
765	Volcanic rocks in Mwashia
765 - 740	Gabbros
735	Volcanic rocks in Grand Conglomerate (Sturtian glaciation)
650	Initial metamorphism of Katangan sequence
670 - 620	Shinkolobwe U deposit
645	Albite-Cu veins at Musoshi
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

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Lower Roan Sedimentation
877 Ma
• Extensional environment (post 870 Ma) leads to complex fluvial/alluvial basal section (lower Roan) dominated by basement derived arkose.
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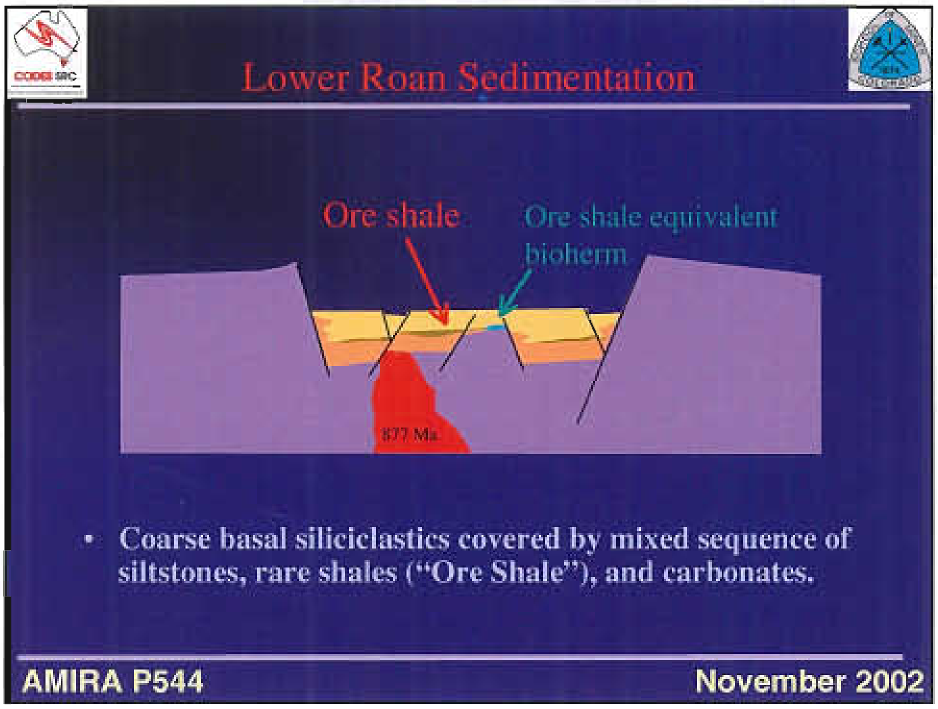
Lower Roan Sedimentation
Ore shale
Ore shale equivalent bioherm
877 Ma
• Coarse basal siliciclastics covered by mixed sequence of siltstones, rare shales ("Ore Shale"), and carbonates.
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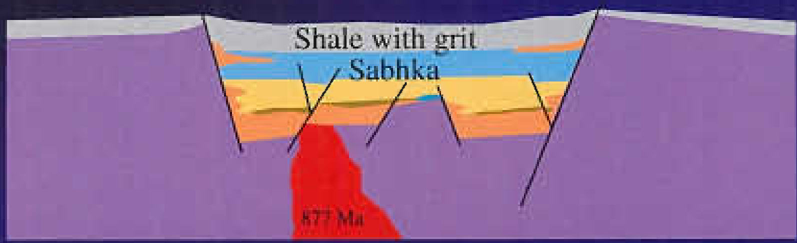
Lower - Upper Roan Sedimentation



- 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.

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Upper Roan Sedimentation

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

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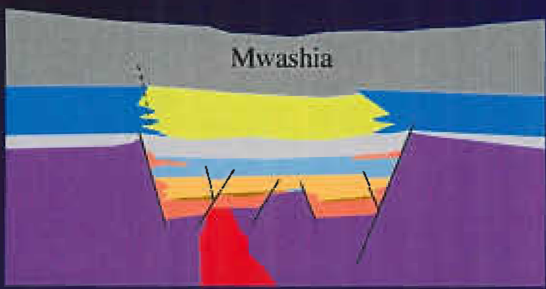
Mwashia Sedimentation



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

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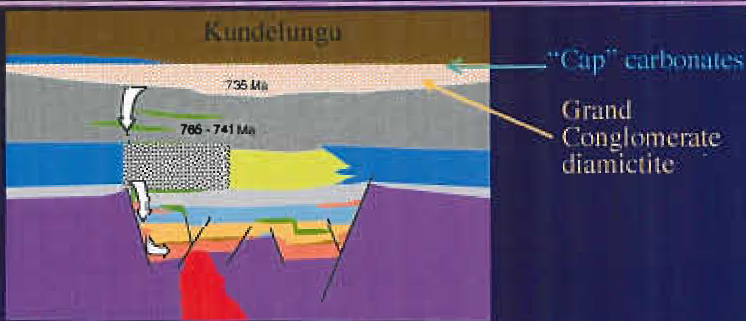
Lowermost Kundelungu + Gabbros



- Extensional event (765-740 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.

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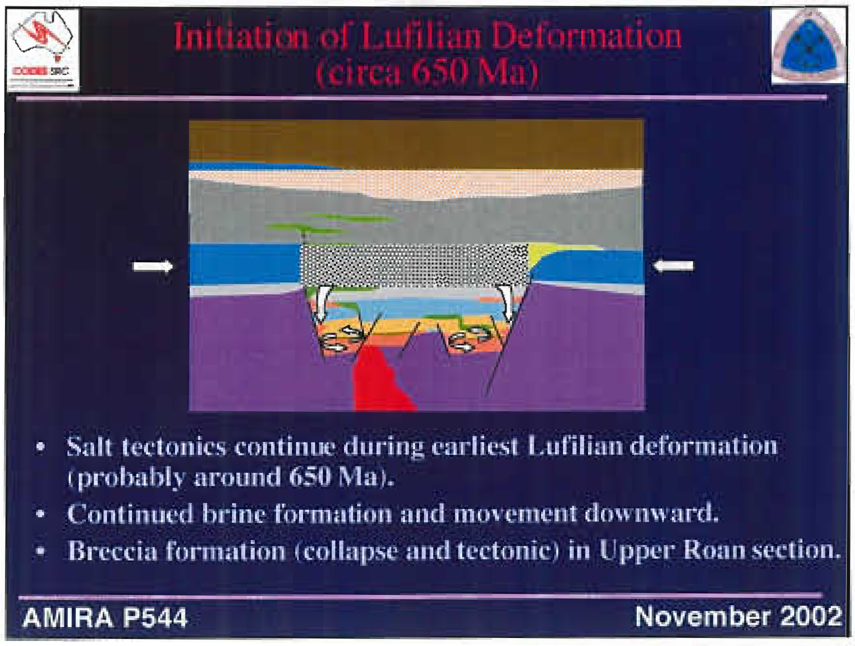
Initiation of Lufilian Deformation (circa 650 Ma)
• Salt tectonics continue during earliest Lufilian deformation (probably around 650 Ma).
• Continued brine formation and movement downward.
• Breccia formation (collapse and tectonic) in Upper Roan section.
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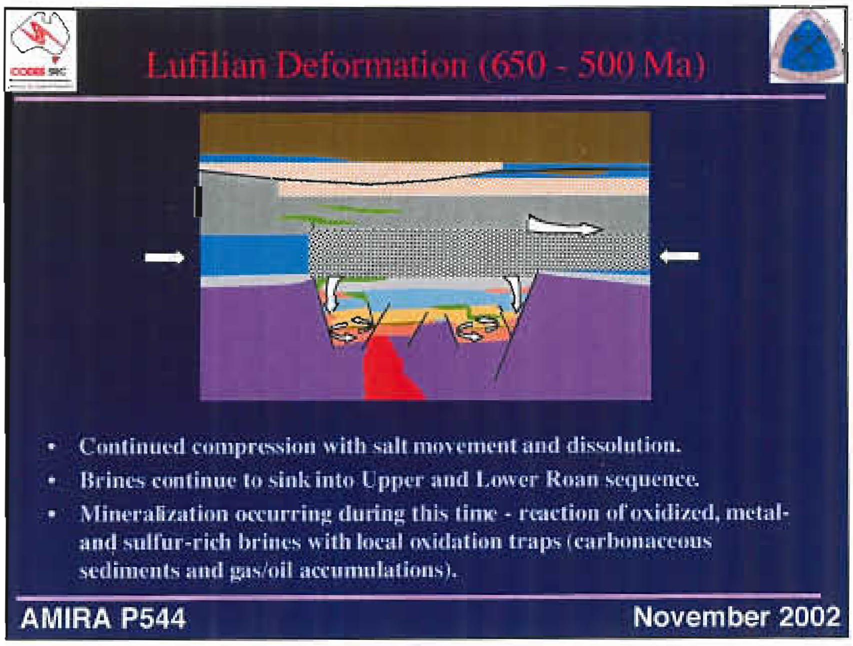
Lufilian Deformation (650 - 500 Ma)
• Continued compression with salt movement and dissolution.
• Brines continue to sink into Upper and Lower Roan sequence.
• Mineralization occurring during this time - reaction of oxidized, metal- and sulfur-rich brines with local oxidation traps (carbonaceous sediments and gas/oil accumulations).
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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 recumbent folds and low-angle (thrust) faults.
• Deformation provides energy for renewed brine movement and escape in basement and overlying rocks.
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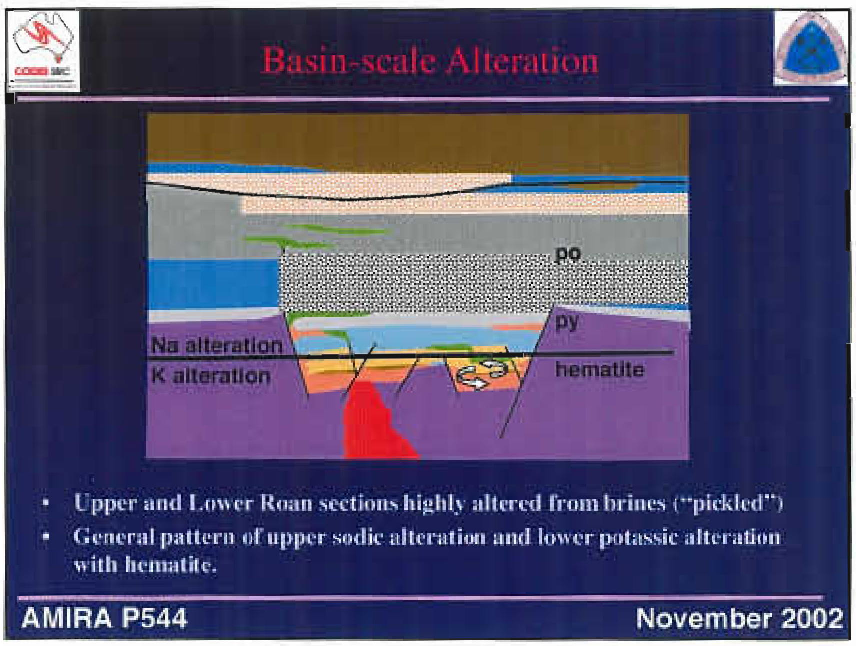
Basin-scale Alteration
po
py
Na alteration
K alteration
hematite
• Upper and Lower Roan sections highly altered from brines ("pickled")
• General pattern of upper sodic alteration and lower potassic alteration with hematite.
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Implications of the Model

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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).

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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.

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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

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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**

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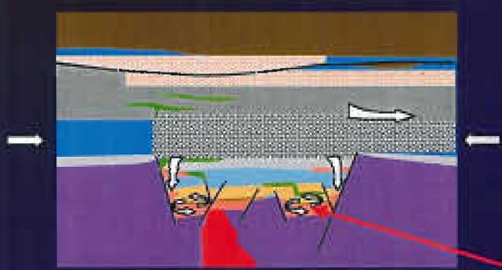
Implications of the Model (cont.)



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

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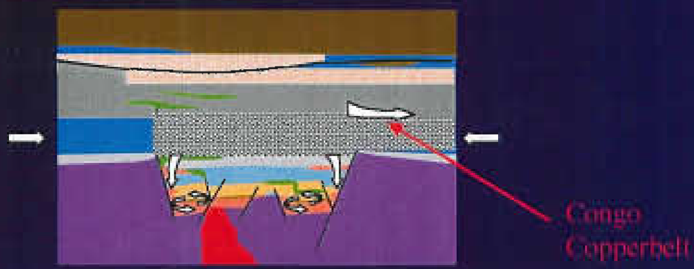
Implications of the Model (cont.)



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

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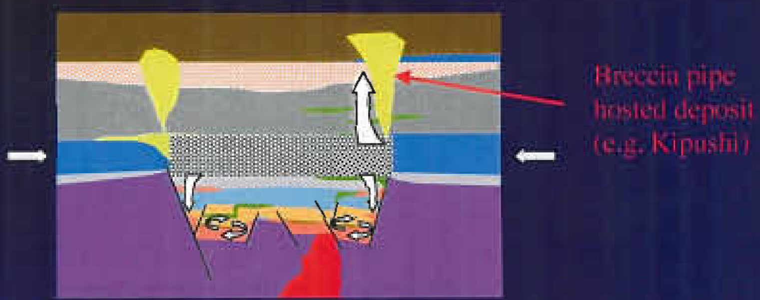
Implications of the Model (cont.)



- Southern Congo / Namibia —
  Ore deposits in cross stratal breccia pipes (paleo salt domes) charged with gas/oil cutting Mwashia and Kundelungu sequence.

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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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Implications of the Model (cont.)

- **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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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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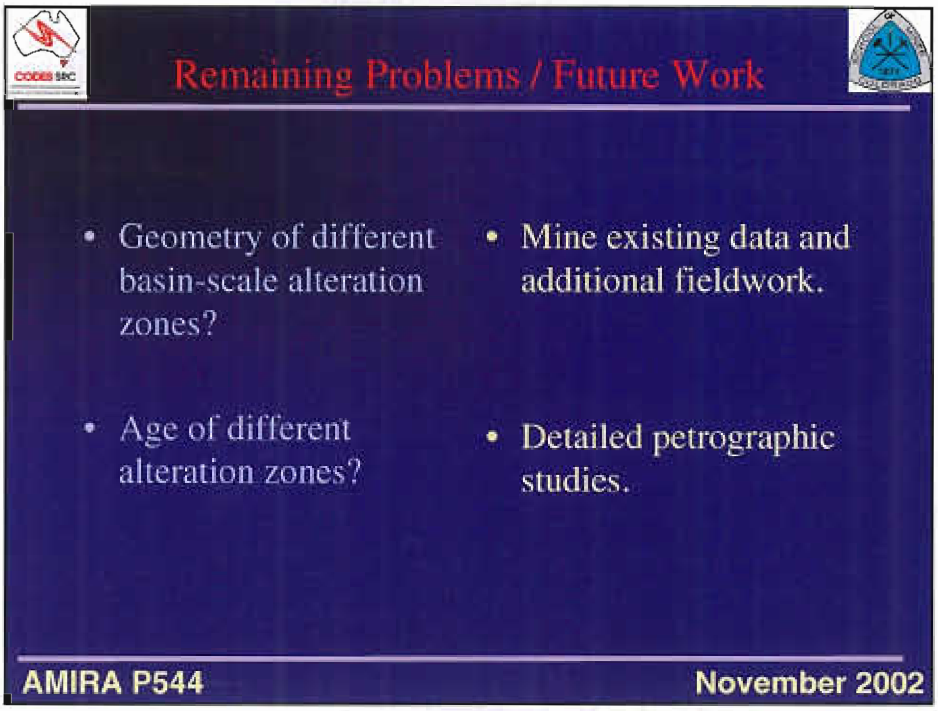
Remaining Problems / Future Work
• Geometry of different basin-scale alteration zones?
• Mine existing data and additional fieldwork.
• Age of different alteration zones?
• Detailed petrographic studies.
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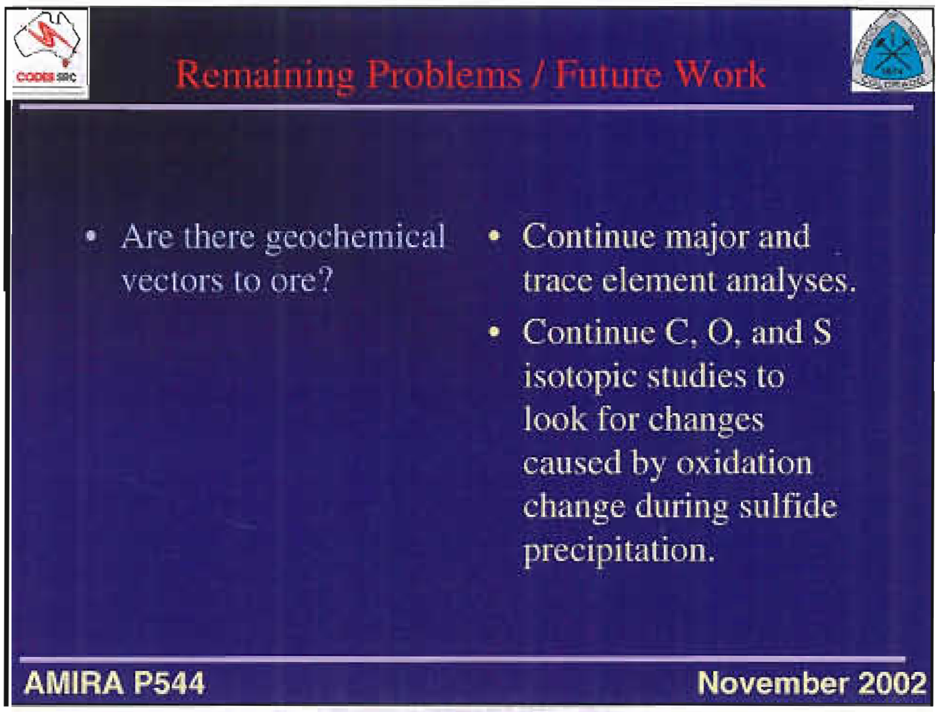
Remaining Problems / Future Work
• Are there geochemical vectors to ore?
• Continue major and trace element analyses.
• Continue C, O, and S isotopic studies to look for changes caused by oxidation change during sulfide precipitation.
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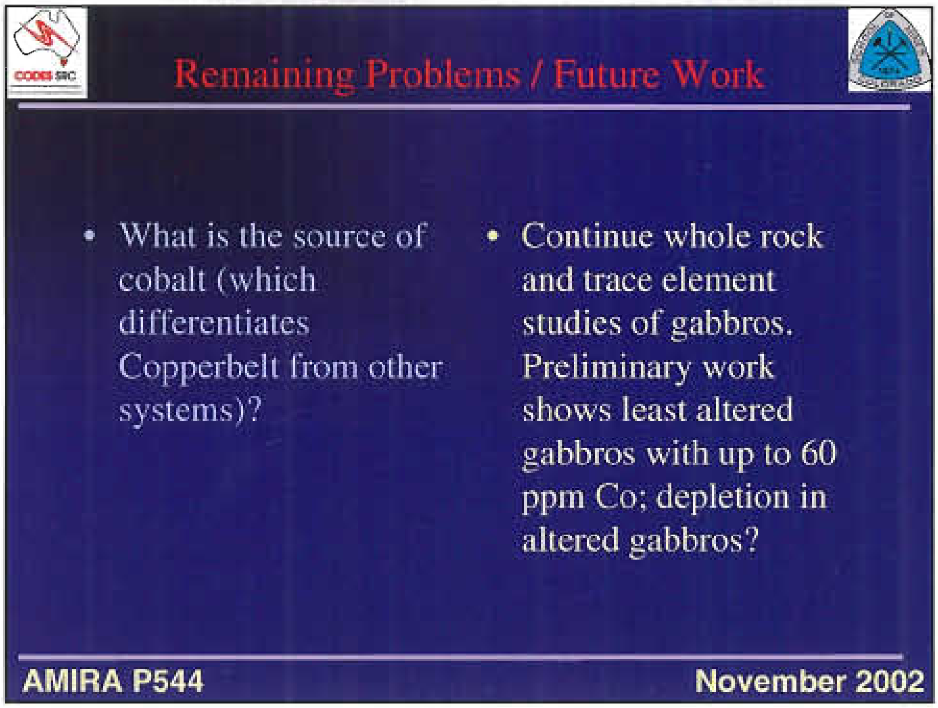
Remaining Problems / Future Work
• What is the source of cobalt (which differentiates Copperbelt from other systems)?
• Continue whole rock and trace element studies of gabbros. Preliminary work shows least altered gabbros with up to 60 ppm Co; depletion in altered gabbros?
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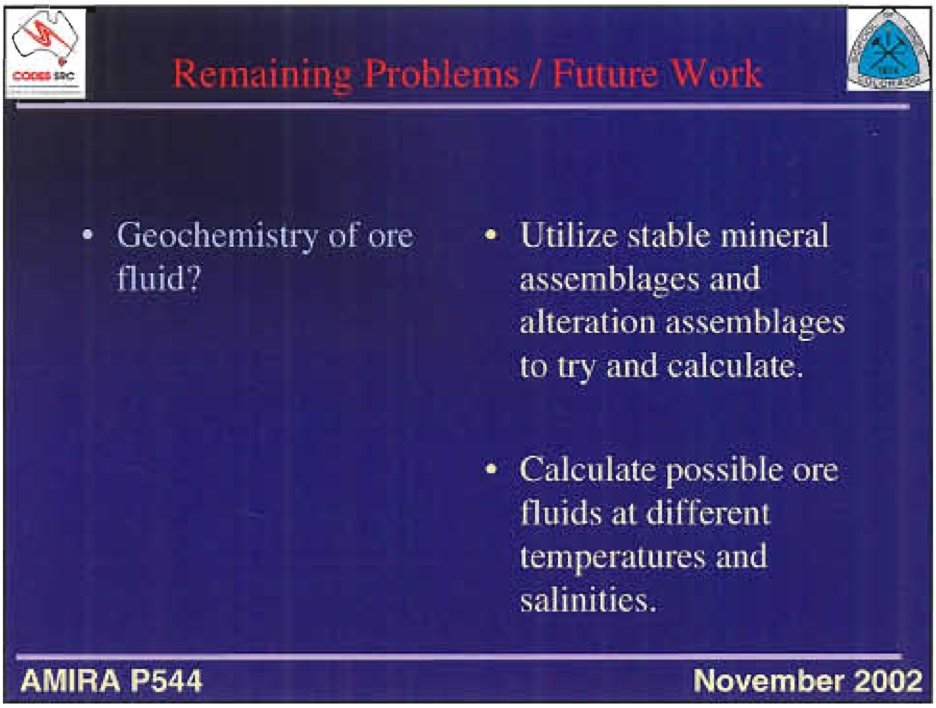
Remaining Problems / Future Work
• Geochemistry of ore fluid?
• Utilize stable mineral assemblages and alteration assemblages to try and calculate.
• Calculate possible ore fluids at different temperatures and salinities.
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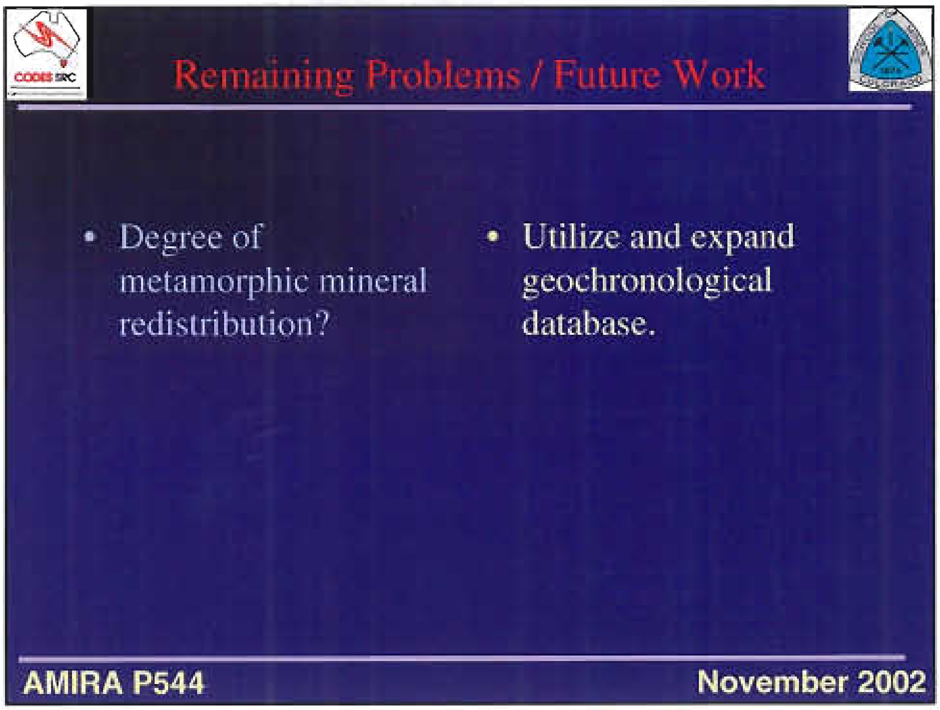
Remaining Problems / Future Work
CODES SRC
• Degree of metamorphic mineral redistribution?
• Utilize and expand geochronological database.
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November 2002

Ndola West Update

Setting and genesis of sandstone-hosted deposits east of the Kafue Anticline

Robert Scott

Centre for Ore Deposit Research

CODES / CSM AMIRA PROJECT P544 — NOVEMBER MEETING, 2002

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)

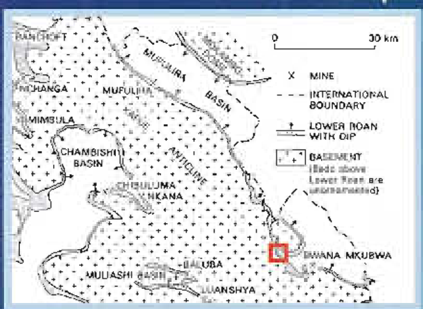
Summary of Key Findings (cont...)

- 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.

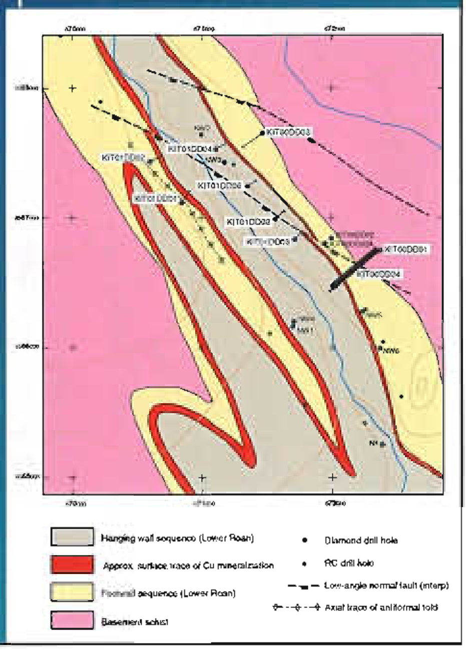
Ndola West prospect – location



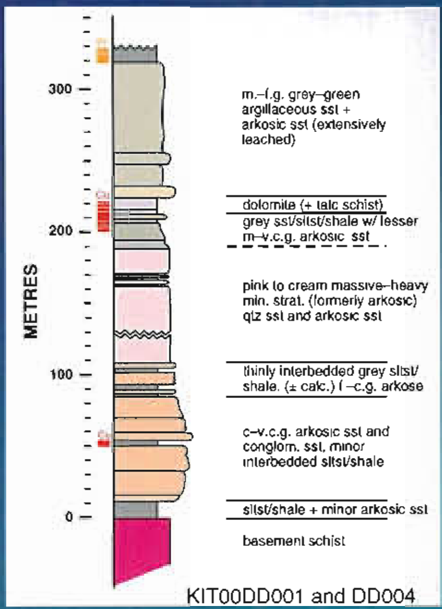
Data sources:

2001: KIT00DD1,DD4, DD4 defl. 1 & 2 (NE limb of Ndola West syncline)

2002: KIT01DD1–6 (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)

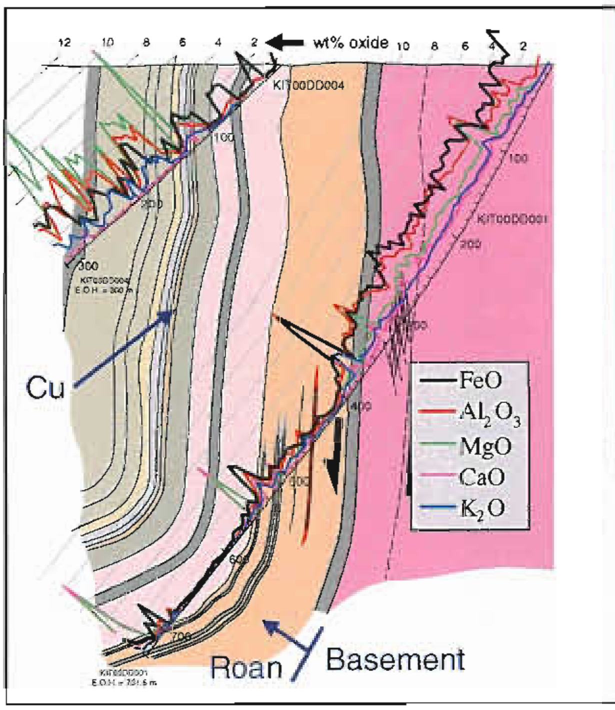
Hanging wall

"Ore formation"

Footwall

Basement

After Scott (May 2002)



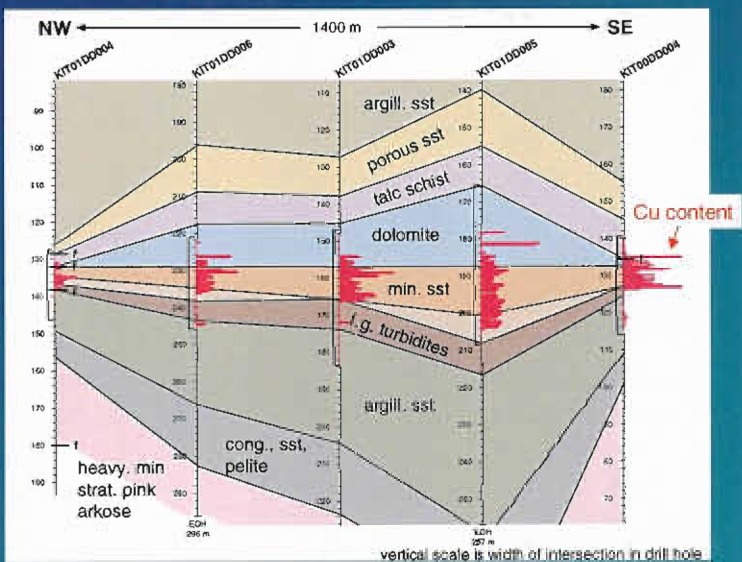
Major element geochemistry

- 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

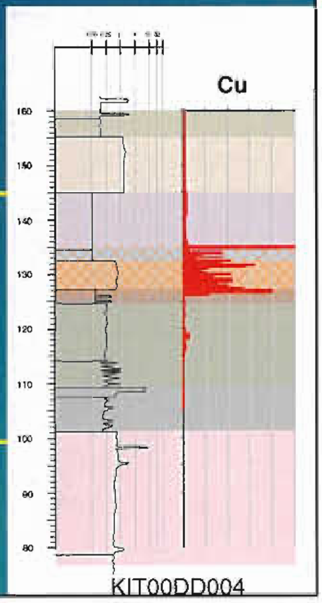
- NE limb of Ndola West synform
  - Excellent lateral continuity of units within stratigraphic interval tested by drilling (distance of ~1400m along strike)
- SW limb of Ndola West synform
  - Equivalent stratigraphic interval *not fully tested* due to unforseen structural complexities
  - Hanging wall 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)	marine transgression
Ore formation (Lower Roan)	regression
	marine transgression
Footwall formation (Lower Roan)	fluvial



"Footwall formation"

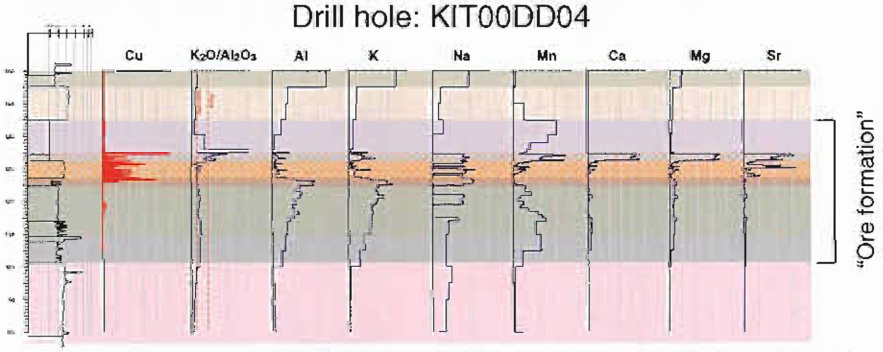
- dominated by relatively clean medium–coarse grained and pebbly arkosic sandstone
- deposited in braided fluvial system
- limited data indicate significant facies/thickness variations within the Lower Roan from SW to NE
- sedimentation patterns strongly influenced by *local* topography, consistent with 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* (2^{ndry}) >> 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 Konkola

Main Geochemical trends within Ore Formation

Drill hole: KIT00DD04



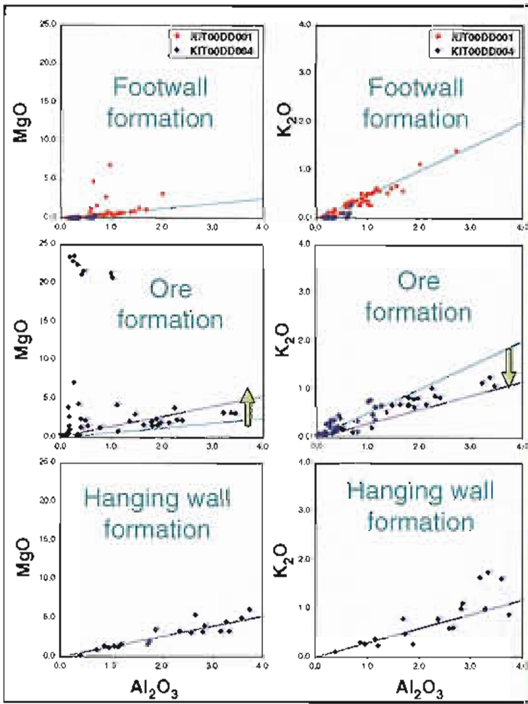
Anglo America geochemical data (NB. incomplete digestion of silicates)

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 / Al_2O_3 ratio of mica
  - decrease in K_2O / Al_2O_3 ratio of mica
  - hanging wall sediments originally more dolomitic

Whole rock geochemical data provided by Anglo America. N.B. 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

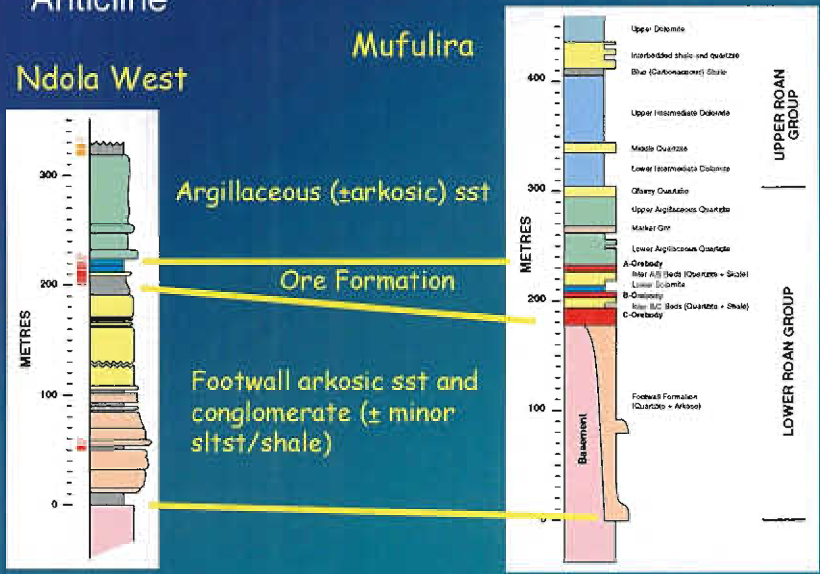
- associated with coarse xtalline to fibrous qtz+alb veins
- overprints disseminated Cu-sulfides
- predates cleavage (folding)
  - *within mineralised zone*
    - albite+tremolite clots in bleached alteration haloes around veins
    - veins may contain Cu-sulfides, but earlier dissem. Cu-sulfides depleted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

KIT01DD05

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 sltst/shale dominated turbidites, well sorted clean ±heavy mineral stratified sst (major host to Cu-ores), massive dolomite

Stratigraphic correlation NE of Kafue Anticline



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 Lufilian 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
  - Lufilian 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-sulfides 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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