Introduction

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- Aims to compare and contrast Proterozoic sediment-hosted copper deposits in Australia and Zambia
  - Study Areas: Zambia, South Australia, Queensland?, Yeneena Basin?
- The level of basic information and description is low in Zambia (much better in Australia)
- Much previous Zambian work has been model driven

Proposed P554 Framework

- **Basin Architecture**
  - structure
  - sedimentology
  - stratigraphy
  - geophysics
  - fluid flow

- **Deposit Studies**
  - morphology
  - structure
  - sedimentology
  - metal zoning
  - fluid chemistry

- **Deposit models and exploration guidelines**

- **Geochemical Studies**
  - lithogeochemistry
  - alteration
  - isotopes
  - deposit halos

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Zambia - Introduction

- What is basin vs what is basement?
- In the Roan, what is sedimentary vs structural (vs alteration vs metamorphic) in origin?
- What do the mineral assemblages tell us about alteration, metamorphism and mineralisation?
- What types of fluids have existed in the basin at different times in its history?
- What traps copper?

Zambian Project: Stage 1

David Broughton
- PhD
- regional 'strat.'
- and structure

Stuart Bull
- local and
- regional
- sedimentology
- stratigraphy
- Area 2

David Selley
- local and
- regional
- structure
- Area 2

Peter McGoldrick
- alteration
- lithochemistry
- deposits/haloes

Murray Hitzman
- metamorphic
- petrology
- dating
- isotopes
- Chem stratigraphy

2 PhDs
- Nkana-Mingola?
- Mufwila?
- Konkola?

Rose Lepsic
- carbon and
- oxygen isotope
- chem stratigraphy

PHD project
- nature of
- 'basement'

Basin architecture
and
Mineralization framework
BASEMENT COMPLEX

Lufubu Schists
- Palaeoproterozoic calc-alkaline metavolcanics

Granitoids
- 2.0 Ga granodiorites
- 1.8 Ga granites
- 880 Ma Nchanga Rod Granite

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Katangan

Muva metasediments
- Mesoproterozoic coarse & medium grained clastics

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Muva Metasediments

detrital zircons:
1990 Ma
2190 Ma
2390 ma
& older

pan-African ‘event’ c. 500 Ma
Lufilian orogeny c. 650 Ma
Lusakan orogeny c. 840 Ma
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Basement Complex: schists

- predominantly qtz - musc - biot - chl - (epid) schists
- blue opalescent quartz
- overprinted by feldspathic alteration
- gradational contacts with deformed grey granite
- gradational / indistinct contacts with L.Roan sandstones
- 1970 +/- 10 Ma (Muf)

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Basement Complex: granites

- zoned: grey core grades to pink/red margin
- opalescent quartz in grey and red granites is probable source for detrital quartz in Roan
- grey granites dated ~1960-1990 Ma
- Nchanga red granite ~ 880 Ma, brackets age of Katangan sedimentation
- potassic metasomatism affects the NRG
- potassic-metasomatized arkoses may be misidentified as NRG

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Lower Roan

- crude fining-upwards coarse clastic sequence, dominantly oxidized
- ~100 to >1000m thick, variance in basal section
- volumetrically minor dolomite
- broken detrital undeformed opalescent quartz, feldspar
- often poorly bedded & sorted
- pre-lithification / dewatering structures suggest sequence remain fluidized post – D1
- extensive metasomatism obscures / overprints sedimentary structures

Upper Roan

- cyclical dolomite / evaporite / clastic sequence, 200-300 m, dominantly reduced
- base marked by dolomite + evaporite breccias
- dolomites appear secondary or overprinted
- gritty sand-silt clastics, often poorly bedded & sorted, “dewatering” structures present
- opalescent & grey quartz, feldspar grit is present but some appears secondary
- feldspathic-dolomitic alteration in clastics
- correlation of units over 100’s of metres
Mwashia

- siltstones & fine sandstones, +800m thick
- lack of grit, opalescent quartz suggests different provenance from Roan
- "dewatering" structures locally present
- possible cryptalgal laminations preserved in dolomites at top of sequence in Konkola
- abundant anhydrite = former evaporite in Chambishi
- high-Mg basaltic sills/flows in Konkola

Grand Conglomerate

- carbonated conglomeratic schist
- dolomite, slst, sdst, quartz, granite clasts
- unsorted, not graded
- no sedimentary structures preserved
- tillite? uncertain origin
- gradational lower contact with Mwashia pelites and dolomites (KLB94)
- probably correlative with Kansanshi pebble schist
- is there an isotopic excursion that reflects a glaciated origin, as per the Namibian section?
Lower Kundelungu

- dolomitic marbles and phyllites / schists, >300m (~3000m in Congo)
- possible cryptalgal laminations in least-altered marbles
- difficult to distinguish marbles from Mwashia

Evaporites

- found in veins, replacive bands & matrix, pressure shadows, nodules
- apparent widespread movement of sulphates through system
- intergrown with cpy, py, carbonate, quartz
- anhydrite veins have metamorphic biotite selvages identical to carbonate veins
- qtz/carbonate "nodules", bands, breccias replacive after sulphate?
- anhydrite/gypsum present in every lithology and stratigraphic unit below Kundelungu
Metamorphism

- Biotite present throughout Konkola area, defines deformation fabrics, present in dewatering structures
- Biotite both accompanies & destroyed by hydrothermal alteration + mineralization
- Is there a distinction between metamorphic & hydrothermal biotite?
- Epidote present in basement complex (Konkola – Nchanga area)
- Nkana: epidote-stable in Lower Roan, sodic amphibole in ore zones, actinolite in unmineralized zones

K-Feldspar metasomatism

- Minor in Chambishi-Nkana area
- Usually with hematite (stained albite?)
- Vein-associated & pervasive replacement
- Kspar overgrowths
- Generally envelopes Cu zones (Konkola)
- Appears to overprint metamorphic biotite
- Kspar + cpy + bn + anhy + biot veins (Nkana)
- Widespread in L. Roan and red granites (Konkola area)
Fe Oxides

- euhedral porphyroblastic magnetite present in Mwashia, granites
- hematite replaces magnetite, forms disseminated grains, also present along bedding planes and in veins
- oxidized Mwashia + Roan = possible source beds up to 2000 metres thick

The problem of ‘basement’

- Difficulty in distinguishing between Katangan and ‘basement’ on a structural basis.
- Is it possible to distinguish Katangan from ‘basement’ on: (1) textural - (2) geometric bases?
- What is the nature of ‘basement’? ie. true crystalline basement or an earlier phase of the same ‘basin’.

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NE 112

- Complete representation of stratigraphy.
- Anomalously high strains and metamorphic grade.
- Up to 4 cleavage-forming events recorded throughout entire hole.

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Structural fabrics developed in "Kundelungu"

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Katangan Fabric Geometry:
from surface and underground exposures

- Chamblish and Konkola record inclined and upright W-plunging folds consistent with N-directed thrusting.
- Mufulira records only one cleavage which is axial planar to downward facing folds.
- Nkana SOB records 2 prominent cleavages associated with SSW-directed thrusting and upright NW folding respectively.
- Locally 3 folding events at Nkana SOB

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Fold Geometry at Mufulira

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Katangan Fabric Geometry:
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Nkana SOB Fold and Thrust Geometry

- SW-directed thrusting with complex fold geometry
- Early inclined and upright folds are generated during progressive thrust event
Muva Fabric Geometry

- Two to four cleavage forming events
- Early N-directed fold and thrust event (SM1 & 2)
- Two later phases of upright folding
- SM3 may account for dome and basin folding within Katangan

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Comparison of Katangan and Muva Fabrics

- Broad similarity between the geometry of Muva and Katangan fabrics
  - Initial thrust-related folding about roughly E-W axes
  - Late stage NW trending folds
- Local development of two thrust-related cleavages in the Muva may reflect progressive deformation associated with thrusting

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**Basin or Basement?**

- Katangan and Muva systems form part of a common fold belt

- Implications for basin development:
  
  - architecture of the Muva basin may be reflected in the Katangan
  
  - mineralising fluids may have interacted with the Muva system

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**Structural Geology**

- bedding can be transposed into S1

- Mwashia appears more deformed than underlying Roan in Konkola area

- mineralization now in tectonic structures

- WNW (D2) folds control ore shoots & deposit geometry at Konkola – generally north-verging

- NE (D3) cuspatate folds related to Konkola barren gap geometry

- breccia at base of Mwashia contains variety of differently-altered clasts and appears to cut S1 fabric

- breccia truncates early ?D1 mega-folds, but is itself folded and cut by quartz-carbonate-biotite veins

- breccia appears to remove section and may represent a thrust: equivalent to Congolese mega-breccias?
Mineralization & alteration

- mineralization occurs throughout section
- Cu (Co) sulphides associated with Fe carbonates, local albization
- bedding-parallel & oblique mineralized veins are widespread, lack depleted halos
- sandy/carbonate/evaporite-rich layers preferred fluid pathways
- Distal facies = pyrite + Fe carbonate
- Konkola barren gap is non-dolomitic, structurally controlled

Regional Correlation

- close-spaced holes at Konkola demonstrate excellent continuity of carbonate & alteration facies, and mineralized zones
- correlation between Konkola – Nchanga – Chambishi demonstrates sedimentary facies changes and/or structural complication of parts of section
- distal equivalents of ore zones are correlative
- Kawiri area- basal Roan sediments appear continuous on Muliaahi Porphyry “basement high”
- thrust breccia equivalent to Congolese mega-breccias?

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Work Plan, Jan-May 2001

- data compilation of logging to date
- petrography
- preliminary dating
- preliminary C & O isotopic characterization of carbonates in section
- preliminary S isotopic characterization of anhydrite and sulphide through section

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In the Roan, what is sedimentary vs structural (vs alteration vs metamorphism)?

Finding drillcores in key areas not straightforward

DDH NN47 from the Chambishi basin chosen as a typical example of mineralised lower Roan stratigraphy

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In the Roan, what is sedimentary vs structural (vs alteration vs metamorphism)?

Collared in the upper Roan and terminated in Basement Complex (granite/Lufubu Schist)

Opinions on nature of "ore shale" differ

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In the Roan, what is sedimentary vs structural (vs alteration vs metamorphism)?

With respect to the features you see in the Katangan rocks, two end member views:

- most are primary sedimentary features
- most are alteration and structural fabrics

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In the Roan, what is sedimentary vs structural (vs alteration vs metamorphism)?

Difficult rocks! Roan sediments are fluidised, altered/metamatised, metamorphosed and deformed.

Hard to understand:
- what we are looking at
- reconciling previous interpretations

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In the Roan, what is sedimentary vs structural (vs alteration vs metamorphism)?

NN47 indicates that care is needed in both:
- discriminating “basement” from Katangan
- interpreting stratigraphy within the Katangan

Can protolith sediments be recognised, or are many so called sediments really alteration and sedimentary structures really structural fabrics?

A - provisionally yes (no sample analysis yet) protolith can be distinguished with careful logging

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In the Roan, what is sedimentary vs structural (vs alteration vs metamorphism)?

Basal part of hole (~lower Roan) was coarse-grained sandstone overprinted by albite

+ interbedded dolomite ± anhydrite zones

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In the Roan, what is sedimentary vs structural (vs alteration vs metamorphism)?

Upper part of hole (~upper Roan) is finer-grained interbedded sand/siltstone

+ interbedded dolomite ± anhydrite zones

• Considerable destruction of primary clastic sedimentary fabrics - fluidisation?

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In the Roan, what is sedimentary vs structural (vs alteration vs metamorphism)?

Fluidisation and associated cc/anhydrite zones spatially related to fold closures and fault zones = synchronous with deformation?

Metamorphic problem - faults are defined by biotite apparently formed while sediments still partly unconsolidated?

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In the Roan, what is sedimentary vs structural (vs alteration vs metamorphism)?

Were there sedimentary carbonates/evaporites present?

A - can't prove it based on what we have seen of the lower Roan

- are suggestions of primary textures higher in the stratigraphy

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In the Roan, what is sedimentary vs structural (vs alteration vs metamorphism)?

Are there real tillites?

A - probably (based on figures in Binda 1972)

- clear from NE 112 that some units interpreted as tillites are probably not

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In the Roan, what is sedimentary vs structural (vs alteration vs metamorphism)?

A - need to be careful that there is evidence of a sedimentary origin

• e.g. a diverse clast assemblage etc.

Otherwise could be structural dismemberment of Katangan stratigraphy

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In the Roan, what is sedimentary vs structural (vs alteration vs metamorphism)?

Can we distinguish clastic from cataclastic textures?

Important issue for basin geometry and controls on mineralisation

A - yes with careful observation at a drill core and microscopic scale

Nchanga

Basal Conglomerate

Fault Breccia

L129

∀ Granité ꕿ Footwall arkose ꕿ Ore shale

• Distinguishing between sedimentary origin is critical for basin reconstruction.
• Sedimentary origin indicates considerable thinning of the footwall package and lapping onto ‘basement highs’.

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Mufulira

- Underground exposures reveal little evidence of high strain or obvious structural control on mineralisation.
- Orebodies hosted by tabular sandstone units
  - minor veining and layer-parallel shear
  - disseminated medium-grained Cu-sulphides

DH 218
- Hangingwall stratigraphy is thoroughly brecciated
- Sulphides concentrate in irregular domains of slightly finer grainsize
  - grain breakage

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Mufulira footwall sandstone

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Mufuiira A orebody

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Mufulira A orebody

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Mufliira A orebody

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Using chemical modeling to understand aspects of sediment-hosted base metal deposits

David Cooke
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Why use chemical models?

Hypothesis testing
• Source(s) of metals & ligands
• Understanding metal transport
• Depositional processes - predicting ore and gangue assemblages

Understanding fluid compositions
• Extend our understanding of known fluid compositions
• Estimate fluid compositions for environments where no other options are available

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Modelling Techniques

- Activity diagrams can be used to illustrate metal transport & deposition conditions in P-T-X space

- Programs such as EQ3/6, CHILLER, THERMODATA, HCH, GEOCHEMISTS WORKBENCH are used to simulate reaction paths and depositional processes

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Controls on Metal Solubilities

- Temperature
- Salinity
- Redox ($\log f_{O_2}$)
- pH
- Total sulfur concentrations ($\Sigma S$)
- (Pressure, $\Sigma C$ concentrations)

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Estimating fluid compositions

- Fluid inclusion data \((T, \text{ salinity}, \text{ PIXE analyses, cation ratios, } P?)\)
- Estimates based on observed equilibrium mineral assemblages \((\text{redox, } p\text{H}, \Sigma S, \Sigma C)\)
- Comparison with documented systems
- Calculated solubility relationships \((\text{metals})\)
- Geological relationships \((P, T, X)\)

P384 Modelling Outcomes

- Testing of source-transport-trap hypotheses for a variety of Pb-Zn mineralising brine compositions \((\text{Cooke & Large, 1998})\)
- An understanding of trace metal associations & their implications for brine compositions in Sed-hosted Pb-Zn deposits, resulting in a twofold classification scheme based on fluid chemistry \((\text{Cooke et al., 2000})\)
Cu Solubility Relationships

- What were the conditions favourable for Cu transport in the Zambian Copperbelt? (*low T oxidised, acidic; high T reduced, acidic?*, etc.)
- What were the transporting agents?
- What is the significance of the associated trace metals?
- What are the most effective depositional processes?

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Previous Work

- Haynes (1986a,b) & Haynes and Bloom (1987a,b) - *low T (<50°C) oxidised, near-neutral chloride brines precipitate Cu-Co-Ag ore via H₂S addition*
- Sverjensky (1989) - *Warm (50-150°C) Cu-Ag-bearing brines can be transported along redbed + anhydrite aquifers (related to Pb-Zn ores?)*
- Rose (1989) - *low T (<100°C) oxidised Cl-rich brines precipitate Cu-Co-Ag ore via reduction*

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Metal Solubilities: 150°C, 25 eq. wt %, pH = 4.5, ΣS = 0.001 m

AMIRA P544
Metal Solubilities: 150°C, 25 eq. wt %,
pH = 4.5, ΣS = 0.001 m

Results - 150°C calculations

- High Cu solubilities in oxidised 150°C brines at pH = 4.5
- Reduction promotes Cu deposition primarily as chalcocite (+ hm), followed by bn-sid, cp-sid, cp-py and bn-py
- Associated trace elements: Zn, Pb, Ag, Sb
- Au & possibly Ba (?) not present in anomalous concentrations
Forward Program

- Detailed chemical modelling to commence in 2002 (collection of field data, hypothesis generation, completion of other work commitments)
- Addition of Co & Ni thermodynamic data to chemical database
- Consideration of organometallic Cu complexes
- Other trace elements?

What types of fluids have existed in the basin at different times in its history?

Extrabasinal
- magmatic
- metamorphic

Intrabasinal
- connate water
- evaporitic brines (bitters?)
- meteoric
- metamorphic

All of the above!
What types of fluids have existed in the basin at different times in its history? (con)

Several approaches:

- understand the type of basin
- direct observation (fluid inclusions)
- chemical modelling (can use information on ore mineralogy and geochemistry to constrain this)
- hydrological modeling

What traps copper

chemical/physical (geological/hydrological)?
SA - Introduction

Main outcomes
- structural geometry and magmatic events within basement exert a strong influence on the basin history within cover
- sed-hosted Cu is diverse in terms of stratigraphic position, style & genesis

Structure of talk
- geological framework: Palaeoproterozoic - Cambrian
- styles of sed-hosted Cu

Basic stratigraphic elements

Palaeoproterozoic
- clastic-dominated sedimentary package
- deformed during Kimban Orogeny
  - 1840 - 1700 Ma
- KD3 mylonite zones
Early Mesoproterozoic

- Gawler Range volcano-plutonic event (GRVPE: 1595-1580 Ma) - Galwer Craton, Yorke Peninsula and Stuart Shelf regions
  - extension and thermal subsidence

- Olarian Orogeny - Curnamona Province
  - syn-tectonic magmatism roughly coeval with GRVPE

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Gawler Craton & Stuart Shelf

- GRVPE comprises Gawler Range Volcanics and Hiltaba Suite granites
- NE-SW to NNE-SSW directed extension

Hiltaba Suite
- two geochemical types:
  - Roxby Downs Type - oxidised haematite-magnetite series: U, Th enriched
  - Kokatha Type - less oxidised ilmenite
- two major plutonic provinces:
  - Olympic Dam & Spencer plutonic provinces

Heat Flow

- Roxby Downs type granites correspond with anomalously high heat flow
- elevated surface heat flow values extend below AG towards Mt Painter
- implications for fluid flow?
Middle Mesoproterozoic

- Pandurra Formation represents the first of a series of clastic-dominated rift basins
- rift margins are indistinct
- characterised by considerable thickness variation

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Neoproterozoic - Cambrian

- series of rift and sag phases
- records progressive breakup of Rodinia from 830 Ma to 515 Ma
- Delamarian compression 515 Ma to 480 Ma

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Structural Framework

Cu Distribution

- Cu coincides partly with margins of sub-basins and platformal shoulders

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Stuart Shelf Cu

Size and Grade

- Mt Gunson: 5.6 Mt @ 2.1% Cu
- Emmie Bluff: 24 Mt @ 1.3% Cu
- Myall Creek: up to 1.5% Cu
Stratigraphic controls on Cu

- Unconformable contact of the Pandurra Sandstone and Whyalla sandstone
- permeable horizons within the Tapley Hill Formation
  - main mineralised zone at the unconformable base
  - minor mineralisation at the top

Local structural controls

Mt Gunson
- Pernatty Upwarp - series of N-S trending horst blocks
- emergent at least by Whyalla Sandstone time
- THF-hosted mineralisation restricted to narrow NW trending 'palaeovalleys'

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Structural controls (cont.)

Myall Creek
- half-graben geometry - but no direct association with known structure
- minor N-S 'palaeovalleys'
- no association with 'basement highs'

Mineralisation

Sandstone-hosted deposits
- Cu sulphides occupy secondary porosity in brecciated upper surface of Pandurra
- Ore mineral paragenesis:
  - Fe-oxides → pyrite → Cu sulphides
- sphalerite and galena represent final mineral products in the ore paragenesis
- no evidence of hydrothermal alteration
Replacement textures

Mineralisation (Cont.)

Tapley Hill Formation Cu
- permeable sandstone/silt beds or lamellae
- vein hosted mineralisation in less permeable strata
- Fe and Ti are depleted in mineralised zones
- strong correlation of $C_{\text{organic}}$, Fe and S
- base metal sulphide introduced late
Ore Genesis

Stage 1: Recrystallised upper surface of Panduro Formation, concentration of Fe-Rich fluids and/or Fe-silicates via mechanical disruption or precipitation from solution. Pervasive I-FI derived from biotite reduction of sulfide, 

Stage 2: Reduced fluids, potentially derived from I-FI adjacent with or within Fe-oxides, leading to concentration of pyrite in upper Panduro surface. 

Stage 3: Base metal-rich fluids interact with early formed pyrite to precipitate progressively more Cu-rich Fe-Cu sulphides.

Summary

- Palaeoproterozoic - early Mesoproterozoic structures are long lived and influence:
  - Hiltaba Suite granites
  - Neoproterozoic - Cambrian basin geometry
- Spatial association of Roxby Downs type granites with:
  - surface heat flow
  - Neoproterozoic - Cambrian rift packages
  - Fe-stone and sed-hosted Cu
- Structural geometry of Delamarian Orogen is directly related to Neoproterozoic-Cambrian basin geometry
Summary (cont.)

- Sed-hosted Cu displays broad spatial association with:
  - inverted basin margin faults
  - platformal margins of major rift depocentres
  - inner arc of Delamarian thrust belt
    - syn-orogenic fluid flow and Cu mineralisation?

- Stratabound Cu mineralisation on the Stuart Shelf is low-T and lacks evidence of hydrothermal fluid
  - Cu mineralisation is late stage
  - pyrite is only truly syngentic sulphide

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Zambian Forward Program

David Broughton
- PhD
- regional "strat." and structure

Stuart Bull
- local and regional sedimentology
- stratigraphy
- Area 2

David Selley
- local and regional structure
- Area 2

2 PhDs
- Nkana-Mindola?
- Mufuira?
- Koscoka?

Peter McGoldrick
- alteration
- lithogeochemistry
- deposit halos

Murray Hitzman
- metamorphic petrology
- dating
- Sr isotope chemosratigraphy

Ross Large
- carbon and oxygen isotope chemosratigraphy

PhD project
- nature of "basement"

Basin architecture and Mineralization framework

South Australia Forward Program

Willouran Ranges Transect
- controls on minor Cu occurrences
- basis for fluid flow modelling
- field work next autumn
- construct section for fluid modelling

Emmie Bluff & Mt Gunson deposit studies
- paragenesis of sandstone & siltstone hosted Cu deposits
- geochemical signatures of Cu mineralisation
- visit Mt Gunson & review core at PIRSA library
- lithogeochemistry

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Budget Considerations

- total ARC and AMIRA income has now reached target (abt. A$1.4 million)
- however the decline in the A$ coupled with relative increase in work offshore means an overall 20% drop in the budget in real terms
- thus, two further sponsors are required to complete the proposed work and balance the 3 year budget

Future P544 meetings

- Zambian field trip late July 2001?
- End of year meeting in Denver in mid-November?
- SA field trip in mid-2002?