GSA and AIG members get registration discount
Fieldtrips / workshops open to all - no need to attend conference
5 DAY FT4 - MACQUARIE; ARC or RIFT? – Blevin and Glen

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EXPLORATION MODELS -
YOU CAN FLIRT WITH A MODEL ...
... YOU SHOULDN'T MARRY ONE

With thanks to
Aurizon ASRA Mining
for financial support

Ken Maiden
SMEDG
28 February 2019
Ore face, Klein Aub mine, Namibia

Production (1966 - 1987):
5.5 Mt at 2.0 % Cu & 50 g/t Ag
Outcropping copper band, Klein Aub
Southern African Copperbelts

- Kaoko Copperbelt
- Central African Copperbelt
- Kalahari Copperbelt
- Klein Aub
- Congo Craton
- Damara Mobile Belt
- Zimbabwewu Craton
- Kalahari Craton

Map showing the distribution of copperbelts in Southern Africa.
Kojeka prospect
Kalahari Copperbelt
Central Namibia

Garry Baglin getting excited
Bob Ilchik getting excited
Copper-bearing phyllite
Kalahari Belt Evolution, Stage 1 - Rifting

- Alluvial red beds
- Basement
- Basalt
Evolution, Stage 2 - Basin Subsidence

- Shallow marine & lacustrine sediments
Klein Aub Deposit - Observations

1. Adjacent to a basement high
2. Stratigraphy -
   - Basalt & red beds (conglomerate & quartzite)
   - Overlain by pyritic quartzite & black slate
3. Copper concentrated in black slate bands
4. Elevated copper over many kilometres of strike
1. Copper leached from hinterland
2. Transported by streams
3. Deposited in reducing environments in playa lakes

This is basically the model developed for the Zambian Copperbelt in the 1960s.
Syngenetic Model - Variations

Metal precipitation due to bacterial reduction of seawater sulphate
Syngenetic Model - Variations

- Shallow sea with restricted circulation
- Metal deposited

Exhalative model
Chalcocite in silt & fine sand bands
NOT in fine-grained (clay) bands

H₂S reduces molybdate (Mo⁴⁺) to molybdenum blue (Mo³⁺ or Mo²⁺)

Mangula Copper Paint
Hi! My name is Cupric. I am a Copper Ion.
I love Chlorina - & she loves me
Chlorina & I hang out together
(It’s a complex relationship)
But then Sulphura comes on the scene
We settle down together …

Just Married

… and live happily ever after (until a greedy mining company digs us up)
Syngenetic Model

- Copper-rich hinterland
- Copper transported in rivers
- Copper deposited in playa lakes
- Basement high
- Fluvial sediments
Syngenetic Model - Deposition

(I should show them holding hands with sulphura)
Copper should be in fine-grained bands ...
It's not. In detail, copper sulphides are in silty & sandy bands

→ Permeability control
Diagenetic Model - Basin Compaction

- Copper leached from basalt & red beds
- Driven towards basin margins
- Precipitates in sulphur-bearing reduced strata
Syngenetic vs Diagenetic Models

Does this make a difference to the exploration approach?

NOT MUCH -

• Onlap onto basement high
• Reduced strata above red beds
• Mapping & geochemistry to locate copper-bearing zones
• I.P. lines over geochem anomalies
• Drill to intersect copper beds down dip
We need to define the target concept
We need to convince the Board
We need an Exploration Permit
We need a program and a budget
And we need a team
Previous drilling
• Widely-spaced holes to 300m depth
• Drilled to intersect copper beds down dip
→ Low grade copper (generally <1% Cu)

1970s drill hole (Aquitane)
Lunch time

Time to sit & ponder
Was copper introduced much later, after lithification of host rocks?
Diagenetic Models - Unconsolidated Sediment

Fluid moves freely
Partly Consolidated Sediment
Consolidated Sediment

No fluid movement through consolidated rocks ...
... except where openings exist or are created
Ore Face, Klein Aub Mine

Chalcocite in veins & brittle fractures cutting across cleavage

Chalcocite in silt & fine sand laminae
Polished slab of ore
Field of view ~12 cm
Chalcocite in fracture fillings & quartz veins

More than 50% of the copper is in structures which cut across bedding
Polished section
Field of view ~2 mm
Pale blue mineral = chalcocite
Ore face, Klein Aub mine, Namibia

Cross-cutting veins

Bedding-parallel vein
Geological Map, Klein Aub (Handley, 1965)

Mine shafts

Klein Aub Fault

Strike-parallel reverse fault

Basement

Red beds

Reduced beds

Legend:
- Kamtsas Formation
- Doornpoort Formation
- Klein Aub Formation
- Rehoboth Inlier (basement)
- Former mine
- Fault
Structural History

$D_1$ Syn-sedimentary extension

$D_2$ compression (Damaran) ~ 530 Ma

→ Large-scale folds, regional cleavage

$D_3$ transpression (late-Damaran)

→ Reverse motion on Klein Aub Fault

→ Thrusts, faults, drag folds near Klein Aub Fault

→ All explained by dextral wrench / flower structure on Klein Aub Fault

Mine exposure of Klein Aub Fault
Mineralogy:
chalcocite → bornite → chalcopyrite → pyrite away from fault

Highest copper grades (+3%) close to fault
Late Epigenetic Model

Copper concentrations

“Flower” structure
Late Epigenetic Model: Possible Ore Niches

- Fault
- Copper zones
- Fault splay
- Reactive beds
- Bend in fault
During deformation ...

... fluid can be pumped through permeable channelways
So we find copper concentrated in ...

... brittle fractures,

... veins

... breccia zones
... dilatant sites
... and replacing reactive minerals
A Klein Aub-Style Target?

- Underground mine
- Narrow ore bands 1 - 2 m
- Production: 5.5 Mt at 2.0 % Cu & 50 g/t Ag
- Is another Klein Aub a viable target?

NO
Regional Target: Kagas Member

- Enriched in copper over 60 km strike
- Copper occurrences in limestone & dark phyllite
Is There Another Exploration Angle?

Georgette Geologiste has some bright ideas
A Couple of Ideas

Target -

• Structural thickening (e.g. in hinges of folds)
• Shallow open-cuttable deposit (→ lower mineable grade)
• Multiple closely-spaced bands (→ bulk-mineable)
• Oxide copper (→ SX-EW operation)
Soil Geochemistry

50m line spacing, 10m sample spacing
Klein Aub Area - Exploration

- Interpretation of remote sensing imagery
- Regional soil geochemical traverses
- 20 targets defined for detailed follow-up
  - ground magnetics, mapping & soil geochemistry
- 47 shallow RC holes on priority targets
Exploration Results 2012

- Most holes intersected target zone at 10 – 30m depth
- Narrow intersections of low grade copper
- Best intersection 8m at 0.41% Cu
- Highest assay 3m at 1.1% Cu

**NOT VERY EXCITING**
Company Strategy 2012

• “In summary, the company’s quite extensive exploration to date has been unsuccessful in identifying potential for a substantial near-surface copper deposit”
• “Our Kalahari Copperbelt strategy needs to be reinvigorated”
• The Board decided not to continue funding the project
• Exploration permit not renewed
Did We Miss Something?

On the positive side -

• There is an enormous amount of copper
  - copper-bearing beds extend for hundreds of kilometres

• In the Botswana segment of the Kalahari Copperbelt, there are several deposits +50 Mt at ~2% Cu with Ag credits

What else could we have done?
Lunch time

Are we relying too much on soil geochemistry?

Time to sit & ponder again
Weathering of Copper Sulphide Deposits

No outcrop
No geochem anomaly
= No drilling target

Are the better-mineralised zones more deeply weathered, so don't show as geochem targets?
Mapping & Sampling, Klein Aub Area

Is soil geochemistry effective in an area like this?
A closer look at copper-bearing beds ...

Chalcocite-bearing phyllite
In detail, the copper-bearing phyllite is more strongly deformed than adjacent rocks.
These look like sheared & altered rocks

Are these beds? Or are they bedding-parallel shear zones?
Chalcocite lenticles in carbonate

Are these carbonate beds? Or are they zones of carbonate alteration?
Possible Alteration

Likely alteration minerals -
- muscovite  quartz
- carbonate  chlorite
- albite ?

If it is alteration, how extensive is it?
We don't know - it hasn't been mapped and there's been no petrology
Small hill of outcropping oxide copper

Is it resistant to erosion due to silica alteration?
Possible enhanced thickness & metal concentration in a fold
Possible Structural Control

Down-plunge target?

Metal concentrated in fold hinge
Is This Something to Get Excited About?
Kalahari Copperbelt - Mineralisation Styles

- Disseminated grains - mainly in silty & fine sandy laminae; possibly replacing anhydrite and/or carbonate
- In cleavage-parallel lenticles
- In brittle fractures
- In quartz-carbonate veins
- In zones of tectonic breccia

How do we find a model that accounts for these different styles of mineralisation?
Kalahari Copperbelt - Conceptual Models

- Copper emplaced during basin compaction and partially remobilised during deformation & metamorphism
- Early (syngenetic or diagenetic) copper significantly upgraded by later deformation-related hydrothermal events
- Epigenetic - Copper pumped up faults & shear zones during Damaran (Cambrian) deformation events
Conceptual Models

Do conceptual models matter?

Do they change our exploration approach?
Exploration models are used ..

.. to interpret controls on ore localisation ..
.. and to design exploration programs
Conceptual Models

It's the difference between a carefully-thought-out exploration program, based on understanding controls on ore localisation ...

Mineral exploration in theory
and just charging ahead
Conceptual Models - Problem

Assume a detailed knowledge of the ore-forming process

BUT ... Our understanding might be wrong or incomplete
Exploration Targets - Syngenetic & Diagenetic Models

→ focus on stratigraphy
→ especially reduced beds near a basement high
→ identify targets based on geochemistry
→ firm up targets with I.P. lines
→ drill to intersect copper beds down-dip

RESULT:
- Lots of low grade copper intersections
- No significant ore discoveries
Exploration Targets - Epigenetic Models

- Yes, we need reactive strata
- Yes, we need lots of geochemistry
- Regional interpretation to identify possible controlling structures
- Detailed mapping to:
  (a) Understand geological structure
  (b) Understand the interplay between structure & stratigraphy
  (c) Identify zones of alteration
- Deep geophysics to identify drilling targets
- Lots of drilling

HASN'T YET BEEN DONE
Stratigraphic Controls - Exploration Heritage

Because of the former focus on stratigraphic controls (the 'favourable horizon') -

• Drilling tested along strike and down-dip; not down-structure
• Copper occurrences not in the 'favourable horizon' were not adequately tested
• Copper in veins was considered as 'minor remobilisation' rather than potentially part of the halo to a larger structurally-controlled deposit

→ Many targets remain to be explored
Implications of Epigenetic Models

- Much previous exploration poorly directed
- Many copper occurrences ignored or under-explored
- Expect deposits associated with alteration & brecciation
- May be a range of deposit styles, with differing
  - host rock types
  - geometry
  - alteration assemblages
  - structural relationships to host rocks
You can flirt with a model ...
... in fact, you should flirt with lots of models...

(The technical term is Multiple Working Hypotheses)
... but you shouldn't marry one!
Thanks to Aurizon ASRA Mining for financial support