Keynote: From little things big things grow

----

What about gold nuggets?

Frank Reith, Jeremiah Shuster, Carla M. Zammit, Gordon Southam
Gold (Au) is:
- the first element discovered
- highly prized for value storage and ornamentation
- a soft, shiny, dense, malleable, rare transition metal
- a tri/univalent complex or zero valent (metallic)
- produced in Australia (4th biggest producer)
- also used in dentistry, insulation and electronics
Currently the GOLD INDUSTRY (in AUSTRALIA) faces many CHALLENGES !!!

Labour: People’s efforts and abilities

Land: Gifts of nature not created by human effort, including mineral wealth

Capital: Tools, equipment and processes to produce goods (e.g., gold)

Entrepreneurs: People who invest money and take risks to make a profit

Governments: “Paper gold”
Productivity and employment: mining in Australia

Output per person employed, 2009/10 prices (LHS)
Employment, persons (RHS)

FORECAST

REALLY ??????
The land factor: Decline of discovery rates

Mining & discovery rates for gold

Amount of gold found and mined in the World: 1950-2010

- Discoveries
- World Production

<table>
<thead>
<tr>
<th>Outlook</th>
<th>Exploration Spend $</th>
<th>Unit Discovery Costs</th>
<th>Total Metal Found</th>
<th>Future Mine Production</th>
<th>Discovery/Prodn Ratio in 2026</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>↓</td>
<td>↑</td>
<td>↓</td>
<td>➔</td>
<td>1.5x</td>
</tr>
</tbody>
</table>

Note: Chart include minor adjustment for deposits missing from the database. Is based on discoveries > 0.1 Moz.

Sources: MinEx Consulting © Nov 2011. Production data from USGS.
The land factor: Most ‘easy’ discoveries have been made (slide: R. Schodde)

Significant mineral deposits in Australia

Estimated depth of cover

INDICATIVE DEPTH OF COVER
- Outcrop & Shallow Basement
- Basement depth < 500m
- Basement depth 500 to 1000m
- Basement depth > 1000m

Most of the deep discoveries are in established districts

Large areas of Australia have not yet been explored effectively

Industry needs to come with ways of exploring more effectively under deep cover

Note: Bubble size refers to size of deposit:
- "Moderate": >100koz Au, >10kt Ni, >100kt Cu equiv, 250kt Zn+Pb, >5kt U₃O₈
- "Major": >1Moz Au, >100kt Ni, >1Mt Cu equiv, 2.5Mt Zn+Pb, >25kt U₃O₈
- "Giant": >6Moz Au, >1Mt Ni, >5Mt Cu equiv, 12Mt Zn+Pb, >125kt U₃O₈

Sources: MinEx Consulting © November 2013
Geoscience Australia
Trend in average ore grades

Average ore grade for all primary gold discoveries >1 Moz in the World versus average head grade of ore mined

- Average grade of gold mined in USA + Canada + Australia + South Africa:
  - 7.3 g/t in 1979
  - 2.08 g/t

- Average grade of gold mined in the World:
  - 1.8 g/t in 2009

- Average grade of gold discovered in the World:
  - (3-Year rolling average for discoveries >1 Moz)
  - Modest decline in discovery grades

Note: Excludes deposits where gold is a by-product

Sources: MinEx Consulting November 2011
Mudd (2010), Fellows (2010)
### Average discovery costs: 2001-2010

(June 2011 US$/oz)

<table>
<thead>
<tr>
<th>Region</th>
<th>Greenfield</th>
<th>Brownfield</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>$35</td>
<td>$6</td>
<td>$20</td>
</tr>
<tr>
<td>USA</td>
<td>$50</td>
<td>$29</td>
<td>$42</td>
</tr>
<tr>
<td>Australia</td>
<td>$76</td>
<td>$41</td>
<td>$60</td>
</tr>
<tr>
<td>Latin America</td>
<td>$22</td>
<td>$25</td>
<td>$23</td>
</tr>
<tr>
<td>Africa</td>
<td>$23</td>
<td>$9</td>
<td>$16</td>
</tr>
<tr>
<td>Pacific/ SE Asia</td>
<td>$34</td>
<td>$162</td>
<td>$44</td>
</tr>
<tr>
<td>Europe</td>
<td>$34</td>
<td>$42</td>
<td>$35</td>
</tr>
<tr>
<td>EE + FSU + China</td>
<td>$27</td>
<td>$46</td>
<td>$31</td>
</tr>
<tr>
<td>Rest of World</td>
<td>$46</td>
<td>$17</td>
<td>$45</td>
</tr>
<tr>
<td><strong>World</strong></td>
<td><strong>$31</strong></td>
<td><strong>$17</strong></td>
<td><strong>$26</strong></td>
</tr>
</tbody>
</table>
Entrepreneurs

Ten Largest Gold Mining Companies

Gold production by year

- Newmont Mining: 5065, 5166, 7676
- Anglo Gold Fields: 4105, 4331, 3944
- Goldcorp: 2020, 2514.7, 2543.790
- Newcrest: 2,109.874, 2,285.917, 2,527.352
- Polyus: 1648, 1569, 1495
- Yamana: 1141.617, 1188.916
- Eldorado: 721.201, 1093.858, 658.652

Analysis by Seraphim Blentzas
www.northamericaninterests.ca
THERE IS A BIG NEED FOR INNOVATION!

We need better ways to find new gold deposits
We need to make more of existing mines/deposits

Microbiologists can help:

What if we could turn waste rock and tailings into a resource ????
Multiple uses of microbes - some examples

- Food production
- Provide a geologist’s favorite drinks
- Medicines, enzymes and food supplements

AND:
- Soil fertility
- Ore processing (BIOX-process)
- Environmental remediation of organic and inorganic pollutants
Work by D. Falconer on authigenic secondary gold formation in New Zealand (from 1985 on)
Work by G. Southam et al. on gold biomineralisation in bacteria (from 1990 on)
GRAIN AND -NUGGET FORMATION
Hypogene or supergene?

PRIMARY GOLD (10-50% Ag)

Detrital theory

Physical movement and de-alloying

Solubilisation

Chemical Precipitation

Accretion theory

Biological Precipitation

Nuggets (>0.5 g; alloyed core, depleted outer)

Secondary gold grains (<0.5 g; sometimes > 99% Au)
GOLD CYCLING IN THE SUPERGENE ENVIRONMENT – A novel biogeochemical element cycle CONFIRMED
How to study geomicrobial cycling of gold?

**Statistics, bioinformatics, geochemical modelling:**
GWB, PRIMER, Canoco, Mothur, Chime, R, etc.

**Fieldwork and in-field laboratory:**
Soils, plants, waters, rocks, gold grains, mapping; e.g., in Australia, New Zealand, Brazil, Finland

**Experimental microbiology:**
Microcosms, columns, batch incubation, enrichment cultures

**Proteomics:**
2D-DIGE, Maldi-TOF-TOF, HPLC

**Genetics**
Transcriptomics:
RT-PCR, deletion mutations, microarrays, transgenetics

**Community fingerprinting**
PCR-DGGE, BIOLOG, qPCR, TRLFP, GEOCHIP, PhyloChip, NGS (pyro/MISEQ)

**Visualisation:**
OM, CLSM, FEG-SEM, FIB-SEM, HR-TEM, AFM, STM

**Microanalysis:**
EPMA, EDXA, EBSD, S-μXRF, S-μXANES, EXAFS, nano-SIMS, LA-ICP-MS, PIXE

**Liquids:**
ICP-OES/AES (HPLC)-ICP-MS
Electrochemistry, biosensors
First we have to get some gold:
Fieldwork in Australia and overseas
Gold cycling happens everywhere!
With John Parsons, owner of Prophet Gold Mine, Kilkivan, Qld
With John Parsons, owner of Prophet Gold Mine, Kilkivan, Qld
FIB-SEM-EDXA/EBSD
Biofilms on gold grains
Cupriavidus metallidurans on natural gold grains
(Reith et al., 2006, Science; Reith et al., 2010, Geology)

<table>
<thead>
<tr>
<th>Representative clone</th>
<th>Phylogenetic affiliation</th>
<th>Most similar sequence in database</th>
<th>Sequenced basepairs [bp]</th>
<th>Percent identity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PGM-1</td>
<td><em>Deftia</em></td>
<td>CP000884 - <em>Deftia acidovorans</em> SPH-1</td>
<td>520/520</td>
<td>100.0</td>
</tr>
<tr>
<td>PGM-2</td>
<td>Caulobacteraceae</td>
<td>AY360981 - Uncultured Caulobacteraceae</td>
<td>460/469</td>
<td>98.1</td>
</tr>
<tr>
<td>PGM-3</td>
<td><em>Burkholderia</em></td>
<td>GQ359001 - <em>Burkholderia cappia</em></td>
<td>522/524</td>
<td>99.6</td>
</tr>
<tr>
<td>PGM-4</td>
<td><em>Alcaligenes</em></td>
<td>AJ554119 - <em>Alcaligenes xylosoxidans</em></td>
<td>518/522</td>
<td>99.2</td>
</tr>
<tr>
<td>PGM-5</td>
<td><em>Hydrogenophaga</em></td>
<td>AJ585992 - <em>Hydrogenophaga atypica</em> BSE 418T</td>
<td>517/522</td>
<td>99.0</td>
</tr>
<tr>
<td>PGM-6</td>
<td><em>Stenotrophomonas</em></td>
<td>EU034540 - <em>Stenotrophomonas maltophilia</em> DN1.1</td>
<td>528/528</td>
<td>100.0</td>
</tr>
<tr>
<td>PGM-7</td>
<td>beta-proteobacterium</td>
<td>AF351227 - Uncultured beta proteobacterium</td>
<td>453/459</td>
<td>98.7</td>
</tr>
<tr>
<td>PGM-8</td>
<td>Cupriavidus</td>
<td>Cupriavidus metallidurans strain OA</td>
<td>522/522</td>
<td>100.0</td>
</tr>
</tbody>
</table>
Transmission electron microscopy – *Cupriavidus metallidurans CH34 + Au(III)Cl₄⁻aq*
Incubation of ultraflat foils – effect of biofilms (C. metallidurans CH34 and C. violaceum) on Au and Pt surfaces
Synchrotron Spectroscopy and Transcriptomics
What happens to the Au upon contact with CH34 cells?
Synchrotron work at the APS, ESRF, SSRL and the AS
Distribution of Au on individual C. metallidurans CH34 cells amended with Au(I/III)-complexes (Reith et al., 2009, PNAS, PlosOne (in prep))
Speciation of Au on individual C. metallidurans CH34 cells amended with Au(I/III)-complexes
(Reith et al., 2009, PNAS, PlosOne (in prep))
Transcriptomics – A new microarray for CH34

A. RNA Isolation
B. cDNA Generation
C. Labeling of Probe
Reverse Transcriptase
D. Hybridization to Array
E. Imaging

Legend
(1) Metal density
(2) Au(III) 10μM - 10 min
(3) Au(III) 50μM - 10 min
(4) Au(III) 100μM - 10 min
(5) Au(III) 50μM - 30 min
(6) COG classification

Fold changes
< 0.5
0.5 - 1.5
1.5 - 2.0
2.0 - 3.0
3.0 - 4.0
4.0 - 10
10 - 20
> 20

Metals
0 metals
1 metal
2 metals
3 metals
4 metals
5 metals
6 metals
7 metals

COG-classification
J
A
K
L
B
D
Y
V
T
M
N
Z
W
U
O
C
G
E
F
H
I
P
Q
R
S
1. Gold(I/III)-complexes are highly toxic.
2. Cu ions are 1000 times less toxic.
3. Gold(I) uptake block periplasmatic Cu(I) export proteins (CupA)
4. Cu(I) concentrations increase in periplasm (cupC, glutathion)
5. Formation of Cu(0) nano-particles by Cu(I) disproportionation to Cu(0) and Cu(II)
6. Cu(0) particles reduce Au(I) to Au(0).
7. Au(0) replaces Cu(0) in the particles

THIS IS UNIQUE!!!
Making gold nuggets
C. metallidurans CH34 - Gold Biomineralisation in columns spiked with millimolar concentration of Au(I)-thiosulfate (PhD-research - L. Fairbrother)
CH34 efficiently takes Au(I) out of solution
Cells and Gold Biominerals

Cupriavidus metallidurans CH34
with gold nano-particles

pili / nanowires

Spheroidal gold micro-particles
Gold Biomineralisation – Growing large nuggets

Gold nugget grown as a result of microbial biominerlaisation after 4 weeks in a tumbler experiment (Photos, J. Shuster; G. Southam)
Detailed analyses of natural nuggets
Focussed-Ion-Beam (FIB)-SEM- EDXA (Reith et al., 2010, Geology)
Scanning electron microscopy (SEM)
Electron Backscatter Diffraction (EBSD)
The supergene gold: lower levels of base metals (V, Ni, Zn, Pb) and higher concentration of some chalcophiles (Sb, Se, Te, and Bi).
Unified Model for Gold nugget formation
(Reith,, Fairbrother, Geology, ES&T , 2010, 2013)
Large Nuggets (1 g – 8 kg): rare (Hough et al. 2008) and hypogene is this the case?
First example of large secondary gold nugget from Alexandra, NZ
Transferring our process understanding to industrial applications

1. Biosensors
2. Bioindicators

Biooxidation
On-site cyanide production
Direct bioprocessing

3. Bioprocessing via Bioconcentration
Tailings reprocessing aided by microbiota

Opportunities arising from the study of gold geomicrobiology

Mining Processes
Low-grade ore (tailings)
Concentrated gold

Microbial Involvement
Gold deposit
Gold responsive genes/proteins

Primary ore/waste rock
Gold exploration

Oxidised ore
Oxidation of sulfide ores
Fe^{2+}/RISC oxidation
Fe^{2+}/RISCs oxidising microorganisms
Thiosulphate formation
Actinomycetes
Cyanide formation
Cyanide producing microorganisms
Amino acid formation
Amino acid producing microorganisms

Oxidation and complexation of gold
Gold complexes in solution

Reduction and precipitation of gold
Detoxification
Metallophilic microorganisms
Ligand utilisation
Sulfur reducing and amino acid utilising microorganisms
Passive absorption
All microorganisms
Metabolic energy generation
Methane utilisers and hypothermophilic H₂ oxidisers
Principle of biological gold processing for waste rock and tailings sites

1. Cupriavidus metallidurans CH34 with gold nano-particles
2. Spheroidal gold micro-particles
3. Image of a biological gold processing site
Talking to the local press and the sitting federal member Warren Truss (Deputy Prime Minister)

We invite anyone interested to come to Kilkivan and have a look !!!

Discussing scientific research into the extraction of gold from mining tailings at Kilkivan yesterday were Professor Gordon Southam, Dr Frank Reith and John Parsons. The research aims to probe deeper into an understanding of the role micro-organisms play in gold formation.

Tanya Easterby
This will help the big end of town to make a resource from their tailings!!!
Acknowledgements

Joel Brugger, Allan Pring, Lintern Fairbrother, Christine Ta, Brad Opdyke, Bear McPhail, Steve Rogers, Steve Wakelin, Barbara Etschmann, Adrienne Gregg, Otto Appenzeller, David Gray, Tony Eggleton, Geoffrey Smith, Sue Welch, Andy Christy, Charlotte AllenCornelia Grosse, Dietrich Nies, Gregor Grass, Hugo Moors, Pieter Monsieurs, Rafi Benotmane, Stefan Vogt, Barry Lai, Claire Wright, Jason Kirby, Simon Apte, Mike McLaughlin, Rob Fitzpatrick, Rob Hough, Peta Clode, Lyn Waterhouse, John Terlet, Len Green, Joe Shapter, John Parsons, R. Schodde

CSIRO L&W + E&M, The University of Adelaide, The Australian National University, Flinders University, Australian Research Council (ARC), The South Australian Museum, Barrick Gold, Newmont Gold, ANUEMU, CRC LEME, APS, Adelaide Microscopy, Universitaet Halle
!!!Thank you for your attention!!!

??? QUESTIONS???