Computational Simulation as a Practical Tool for Explorationists - a Progress Report

Paul Roberts (CSIRO)

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Acknowledgements

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Peter Hornby, Bruce Hobbs, Alison Ord, Klaus Regenauer-Lieb, Robert Woodcock, Gordon German, Robert Cheung, Simon Cox, Andy Barnicoat, Yanhua Zhang, Peter Schaubs, Chongbin Zhao, Heather Sheldon, Warren Potma, Klaus Gessner, Michael Kuehn, Regan Patton, John Walshe, Frank Horowitz, Nick Fox, Greg Hall, Jon Dugdale, Chris Wilson, Tim Rawling, John Miller, Fiona Elmer, Nick Oliver, James Cleverley, Evgeniy Bastrakov, Andy Wilde and many others

OUTLINE

- How can we create value in mineral exploration
- A snapshot of some technological progress
- Recent/current application examples from one-on-ones
- Conclusions

RATIONALE

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- Let's talk a little about the "paradigm shift":
  - – Empiricism is simply looking for repeated observed patterns
  - – Process thinking can only add value when it builds on empirical geological observations (and targeting insights)

RATIONALE

- The test of the process approach is if it **actually changes** how you spend the exploration dollar
- To paraphrase Greg Hall, “acting as if it is true” **defines** the paradigm shift

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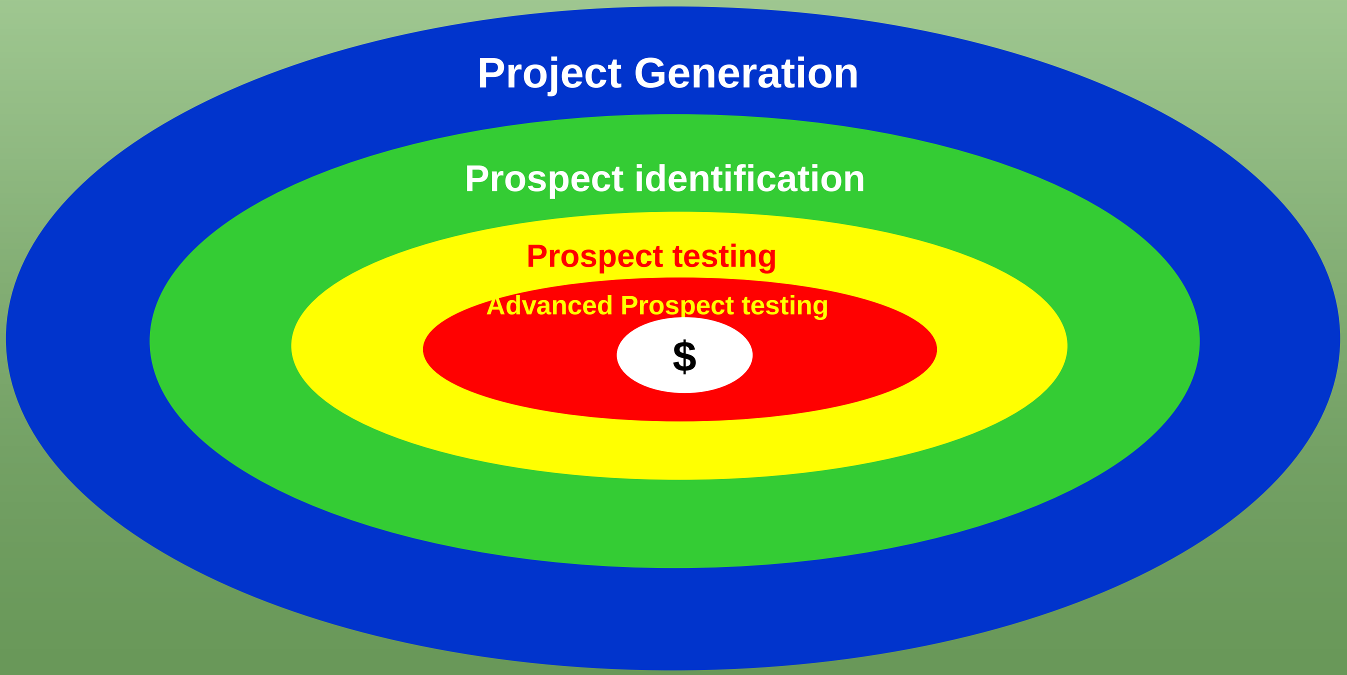
- To paraphrase Greg Hall, "acting as if it is true" **defines** the paradigm shift
- **The key question is whether such actions really add any value**

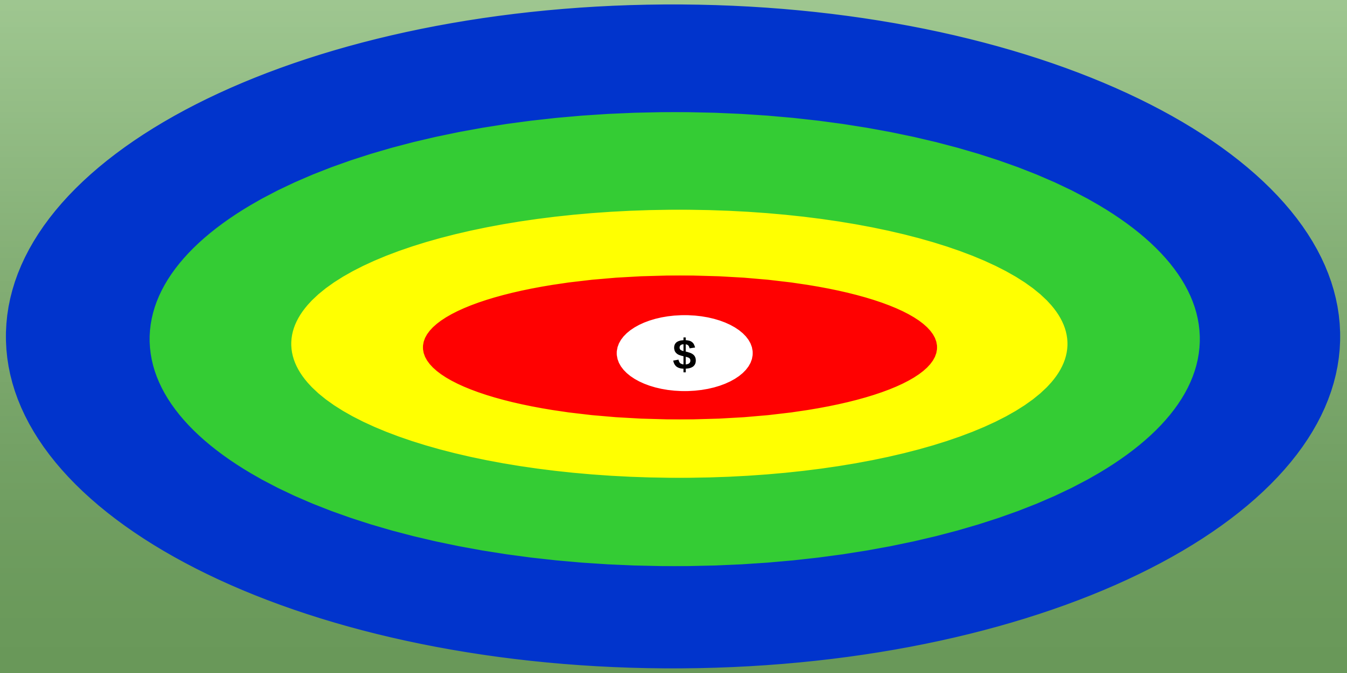
VALUE GENERATION IN MINERAL EXPLORATION

- We all know that exploration is simply about covering smaller and smaller rock volumes until we find a mine



VALUE GENERATION IN MINERAL EXPLORATION

- The tricks are:
  - To do it cheaply
  - And ensure that the mine is in the bullseye



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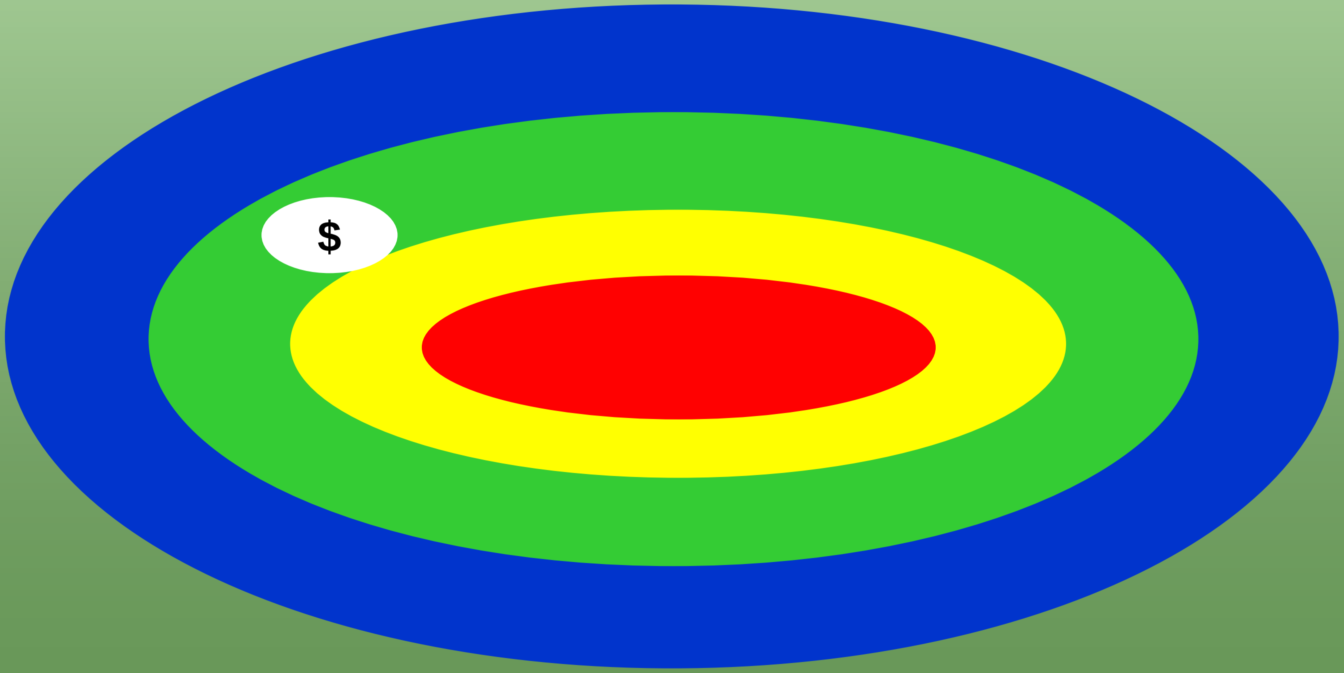

VALUE GENERATION IN MINERAL EXPLORATION

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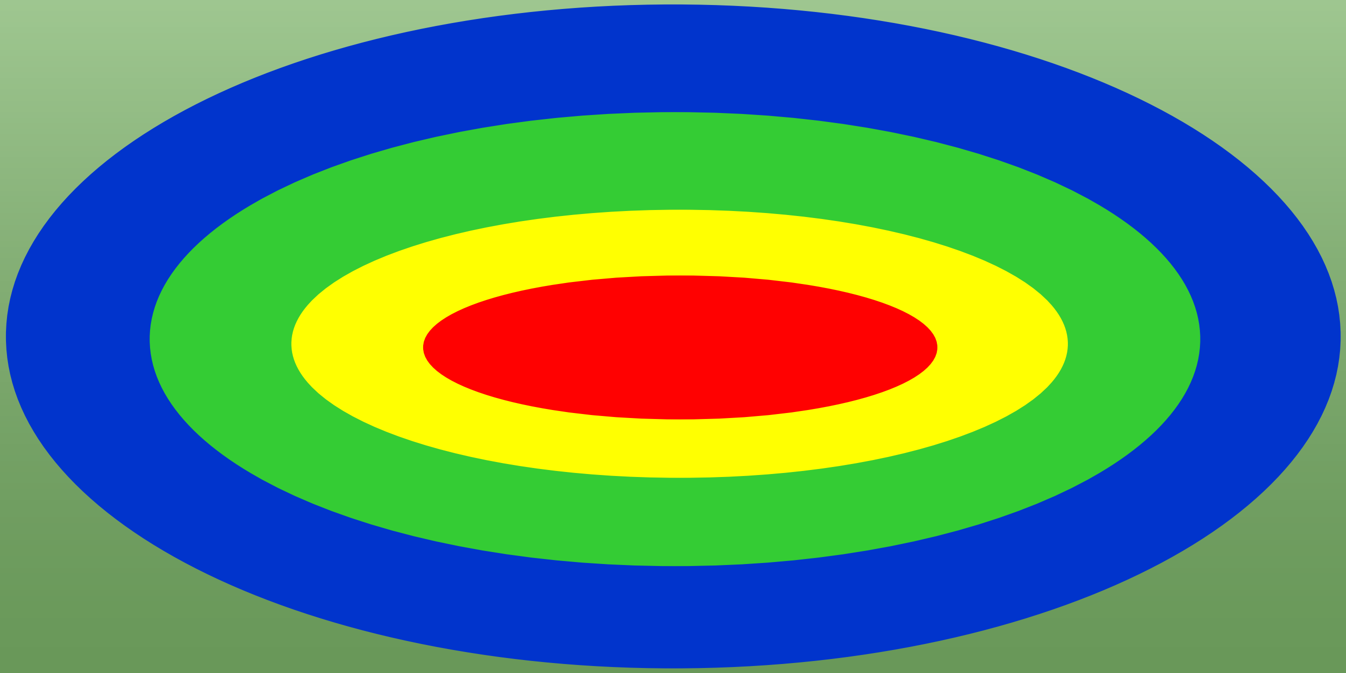
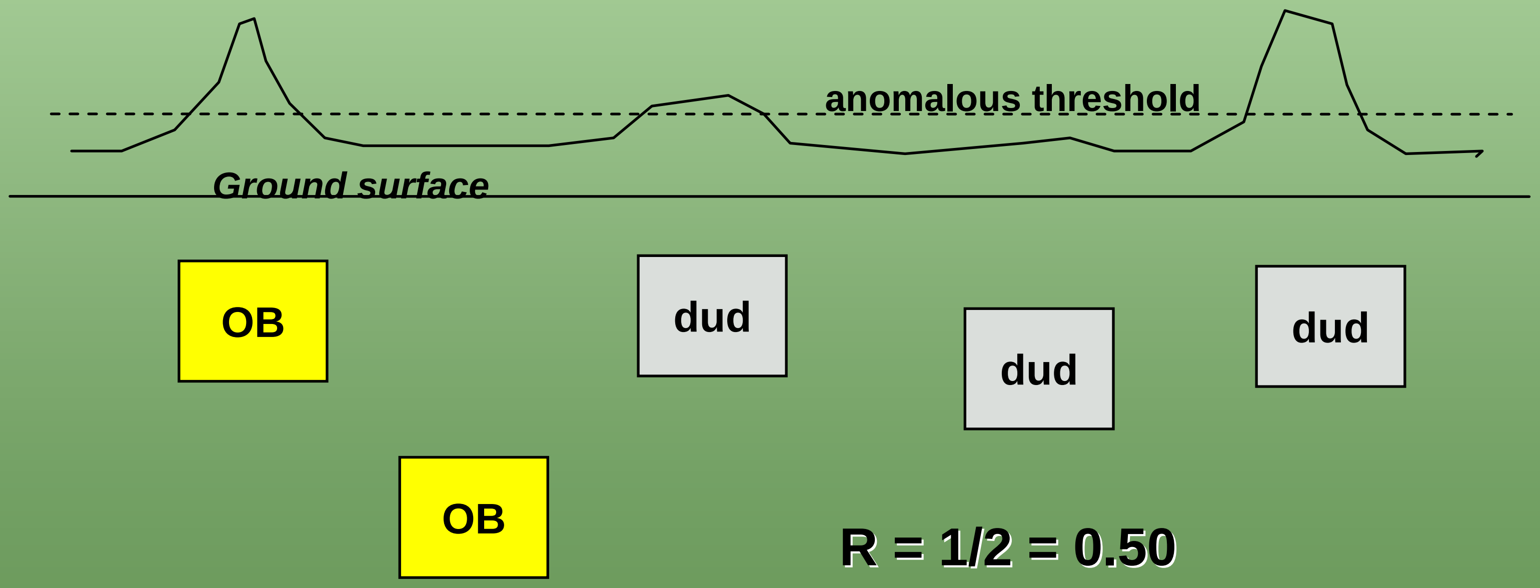


VALUE GENERATION IN MINERAL EXPLORATION

- More formally, this is about:
  - – Increasing reliability
  - – Reducing false alarm rate and unit cost



R = 1/2 = 0.50

FAR = 2/3 = 0.66

VALUE GENERATION IN MINERAL EXPLORATION

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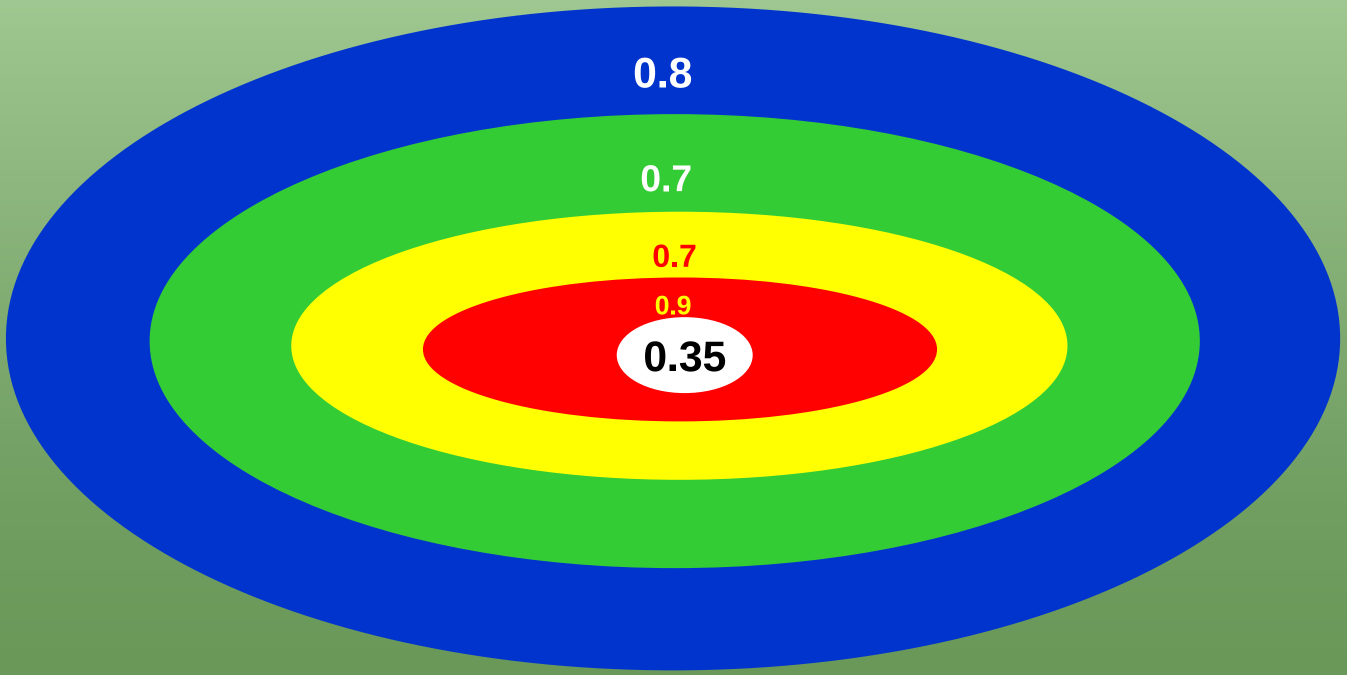
- Reliability probabilities are multiplicative:



VALUE GENERATION IN MINERAL EXPLORATION

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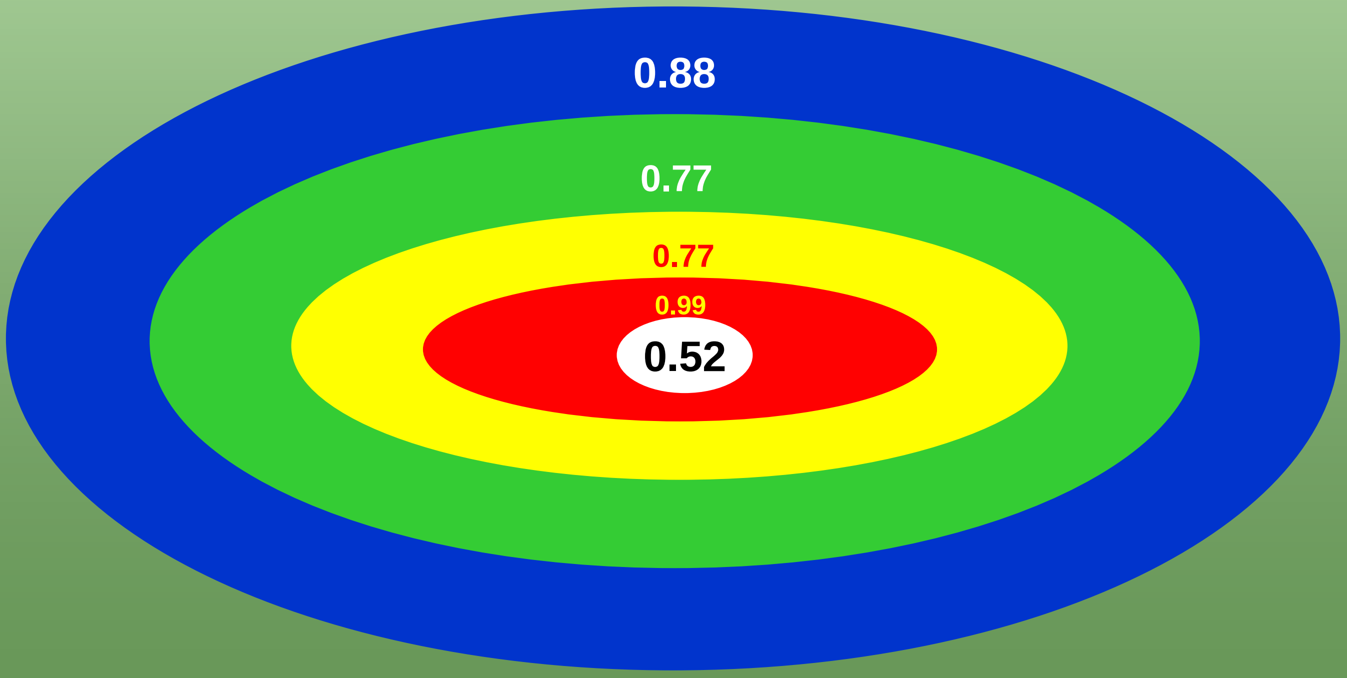
- Reliability probabilities (improved by 10%):



VALUE GENERATION IN MINERAL EXPLORATION

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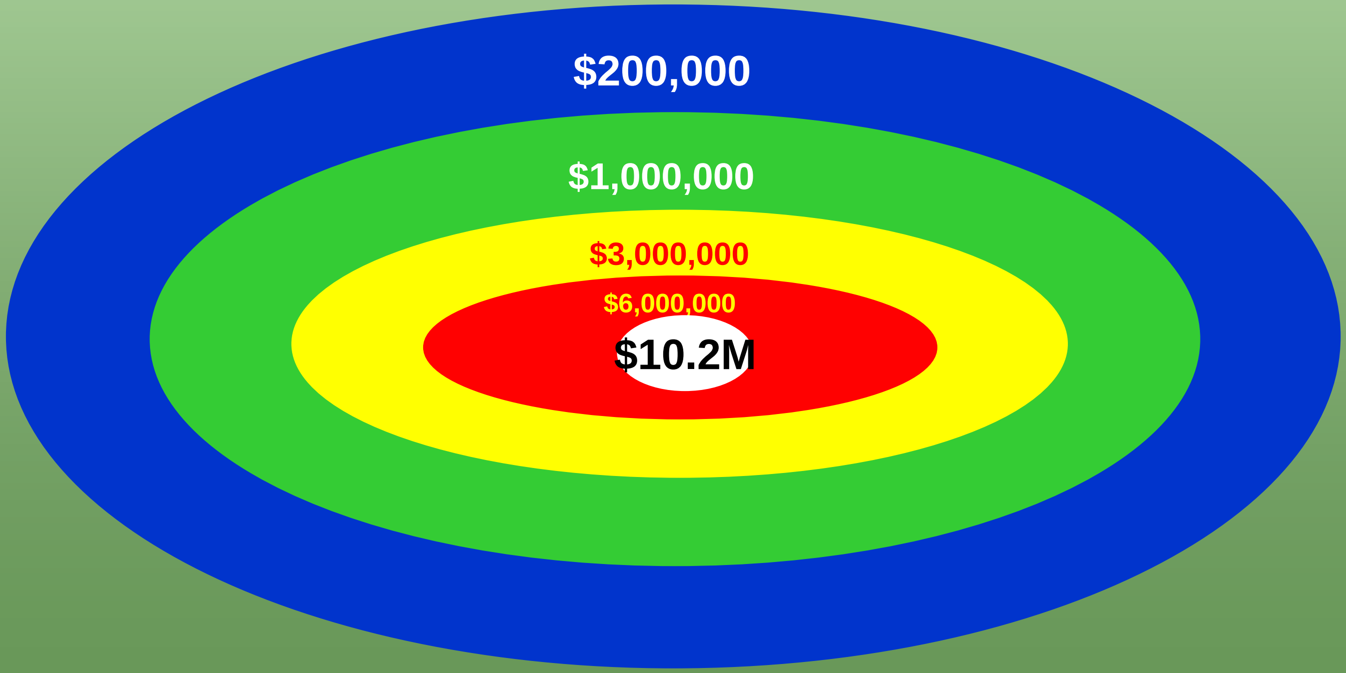
- Strategy cost (no. of false alarms multiplied by unit cost):



VALUE GENERATION IN MINERAL EXPLORATION

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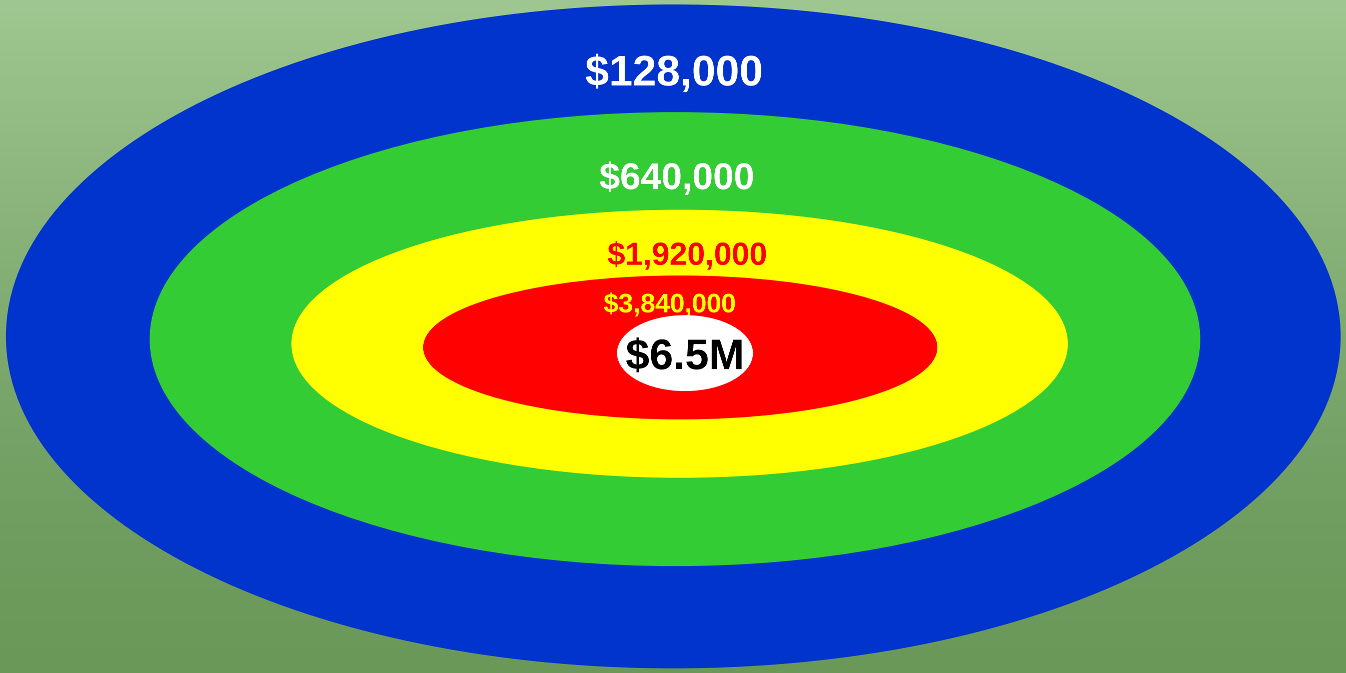
- Strategy cost (FAR and UC both improved by 20%):



RISK ADJUSTED VALUE OF DISCOVERY

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Expected Value equals:

(Probability of success x Value of success)

minus

(Probability of failure x Cost of failure)

VALUE PROPOSITION

Assume a $100M prize (NPV):

- First assumption:
  - EV = (100 x 0.35) – (10 x 0.65)
  - EV = **$28.5M**
- Incremental improvements:
  - EV = (100 x 0.52) – (6.5 x 0.48)
  - EV = **$48.9M** (72% improvement)

AND YOU HAVE AN EXTRA $3.5m TO SPEND SOMEWHERE ELSE!

HOW DOES COMPUTATIONAL SIMULATION FIT INTO THIS FRAMEWORK?

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- Firstly, the CRC is about making better targeting decisions with process (conceptual) thinking. It is not about blind application of computational simulation

HOW DOES COMPUTATIONAL SIMULATION FIT INTO THIS FRAMEWORK?

- So we advocate a process approach, and we should measure it in terms of Reliability, False Alarm Rate and Unit Cost against purely empirical approaches
- We accept that it is not a “given” that computational simulation will add value against these three measures

SO HOW CAN COMPUTATIONAL SIMULATION **ADD VALUE**?

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- Depends on:
  - The predictive value of the underlying science and the degree to which the computational tools incorporate it
  - Our ability to ask testable relevant questions
  - The efficiency of the simulation process
  - Availability of suitable spatial data to enable us to go to the “where” question (or the capacity to collect it)

WHERE CAN COMPUTATIONAL SIMULATION **ADD VALUE**?

- Brittle domain, hydrothermal ore systems – science is (largely) predictive
- Affected by scale:
  - Mine scale – agree that all mineralisation is ultimately detectable but predictive approaches can help:
    - reduce FAR and hence production cost,
    - increase discovery rate and hence asset value
  - Camp scale – improves prospect prioritisation & discovery rate
  - District scale - improves prospect prioritisation & discovery rate or speeds up walk away decision (use the $s elsewhere)
  - Terrane scale – as above but getting harder, need to consider processes below brittle/ductile transition
  - Global scale?

AND IN THE FUTURE?

The research frontier?

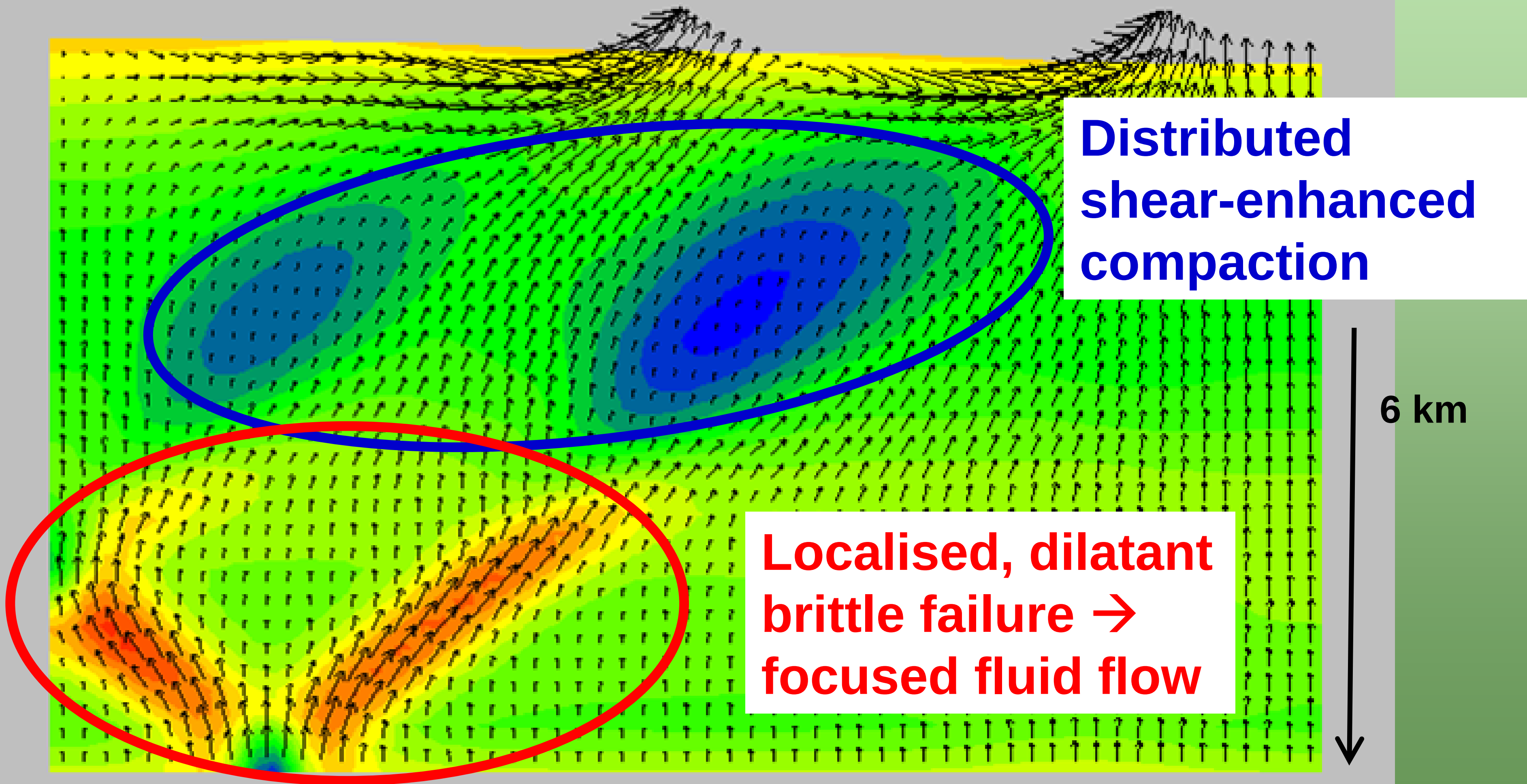
- Whole of lithosphere and all ore systems - some difficult problems:
  - Self consistent modelling of deformation (including thermal feedbacks)
  - Better understanding of permeability evolution, fluid residence and flow both in the lower crust and at the brittle-ductile transition
  - Coupling with magmatic processes and fluid evolution in the lithosphere/asthenosphere(?)

ALL THIS LEADS US TO:

- Short term objectives:
  - improve predictive value in brittle domain
  - code coupling especially with chemistry
  - efficient computation/systems and skilled people
  - ore discoveries generated by many people “acting like its true”
- Long term objectives (extending beyond CRC):
  - Self consistent, whole of lithosphere, all scales
  - Magmatic processes

PREDICTIVE BEHAVIOUR IN "BRITTLE" DOMAIN

Cam Clay example



Heather Sheldon

COUPLING DEFORMATION WITH CHEMISTRY

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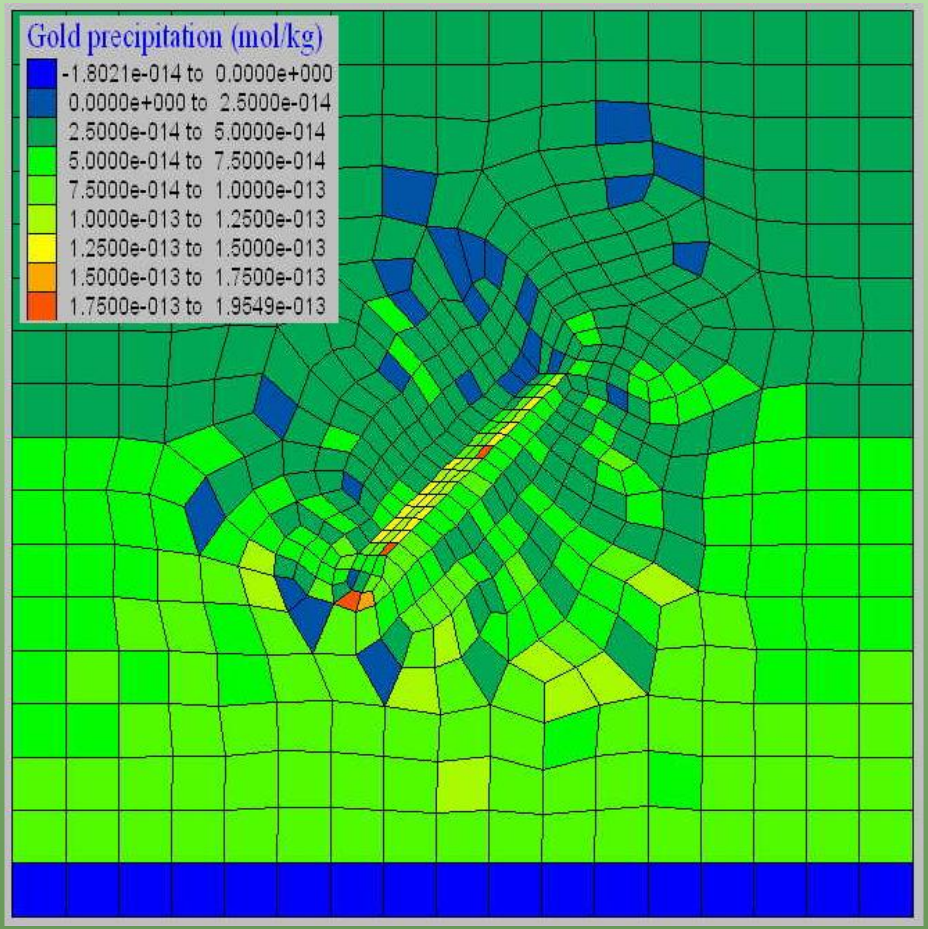

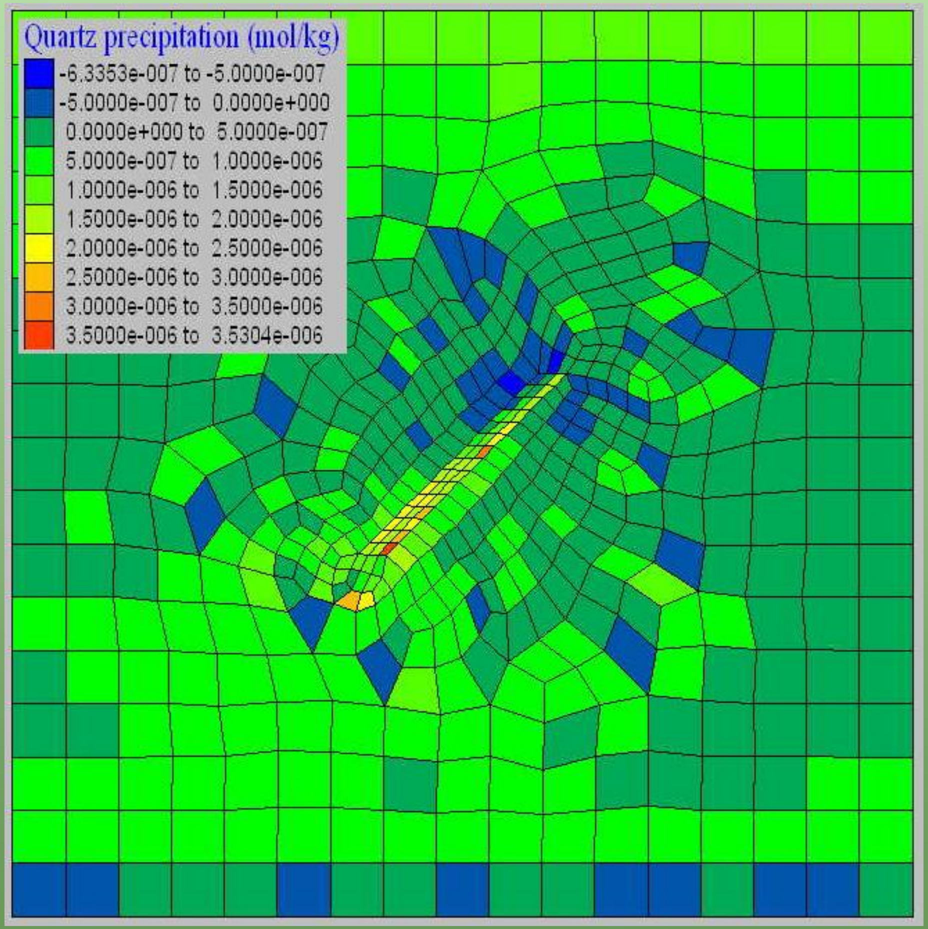

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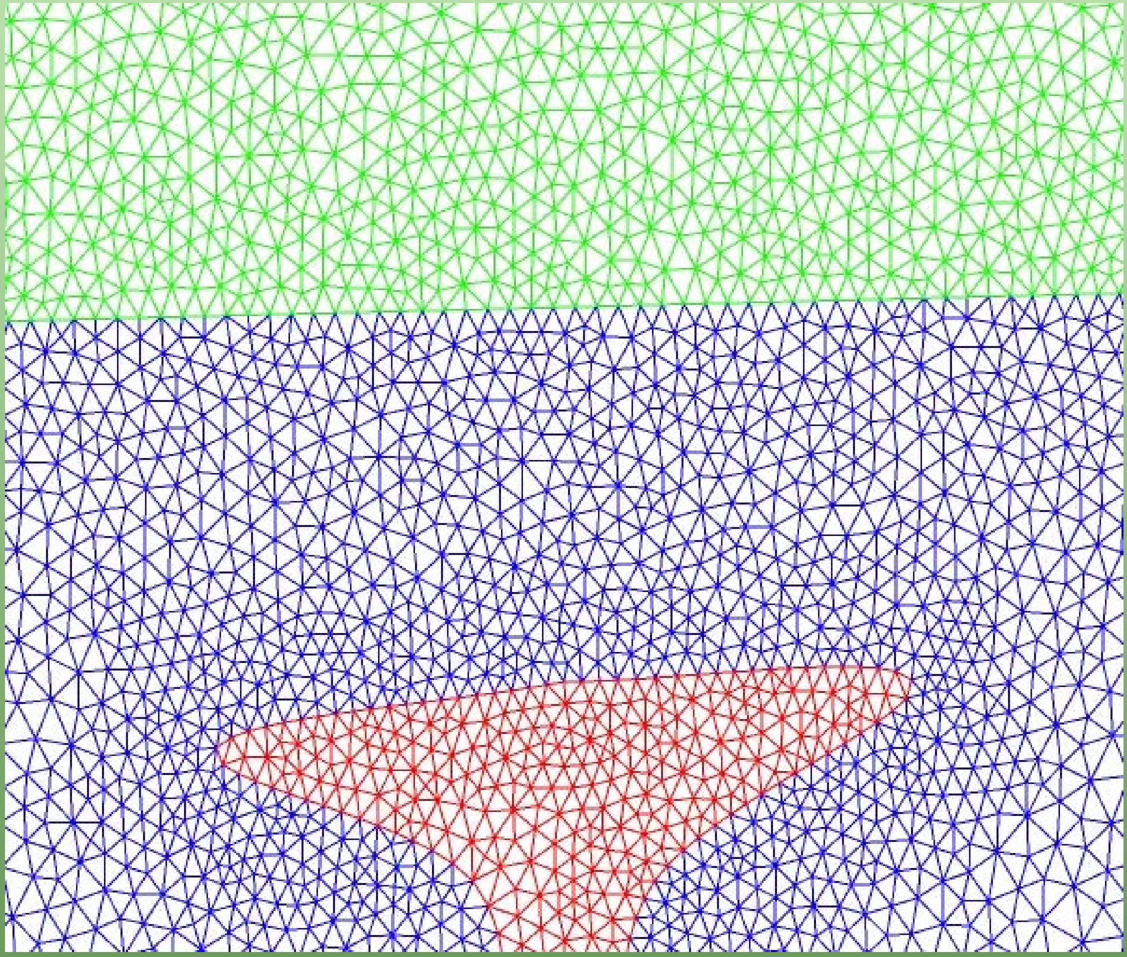
CHEMISTRY COUPLED WITH HEAT AND FLUID FLOW



Peter Hornby

COMPUTATIONAL SIMULATION – CHEMICAL TRACER

Frame 001 | 02 Feb 2006 | No Data Set

Model: LFG_HeatFlow_a_Tracer.avi

Period 1 to 246

LFG_HeatFlow Only

Tracer from Granite

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James Cleverley

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EFFICIENT SYSTEMS – "THE WORK FLOW"

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- Analyse exploration and/or geological problem
- Build geometry (in a form suitable for 3D computational simulation)
- Do computational simulations
- Visualise outputs
- Interpret outputs
- Report on results

EFFICIENT SYSTEMS – MESH CONSTRUCTION (OLD)

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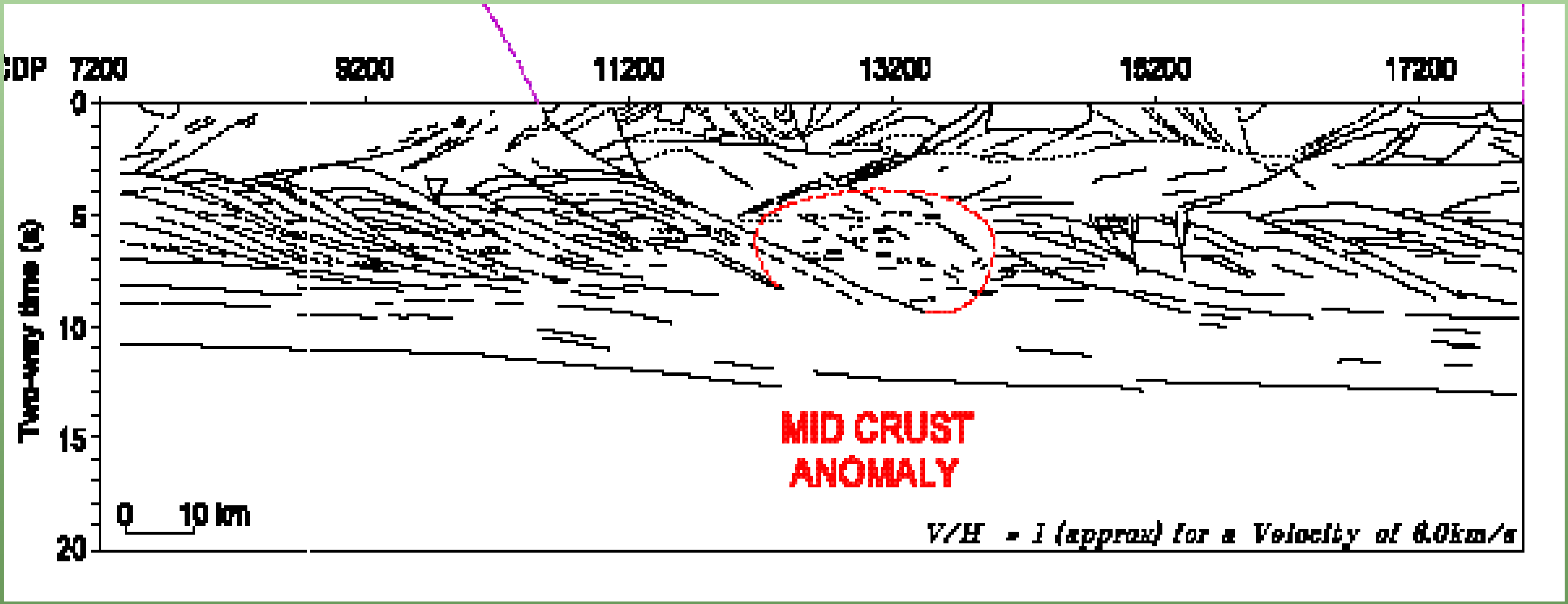
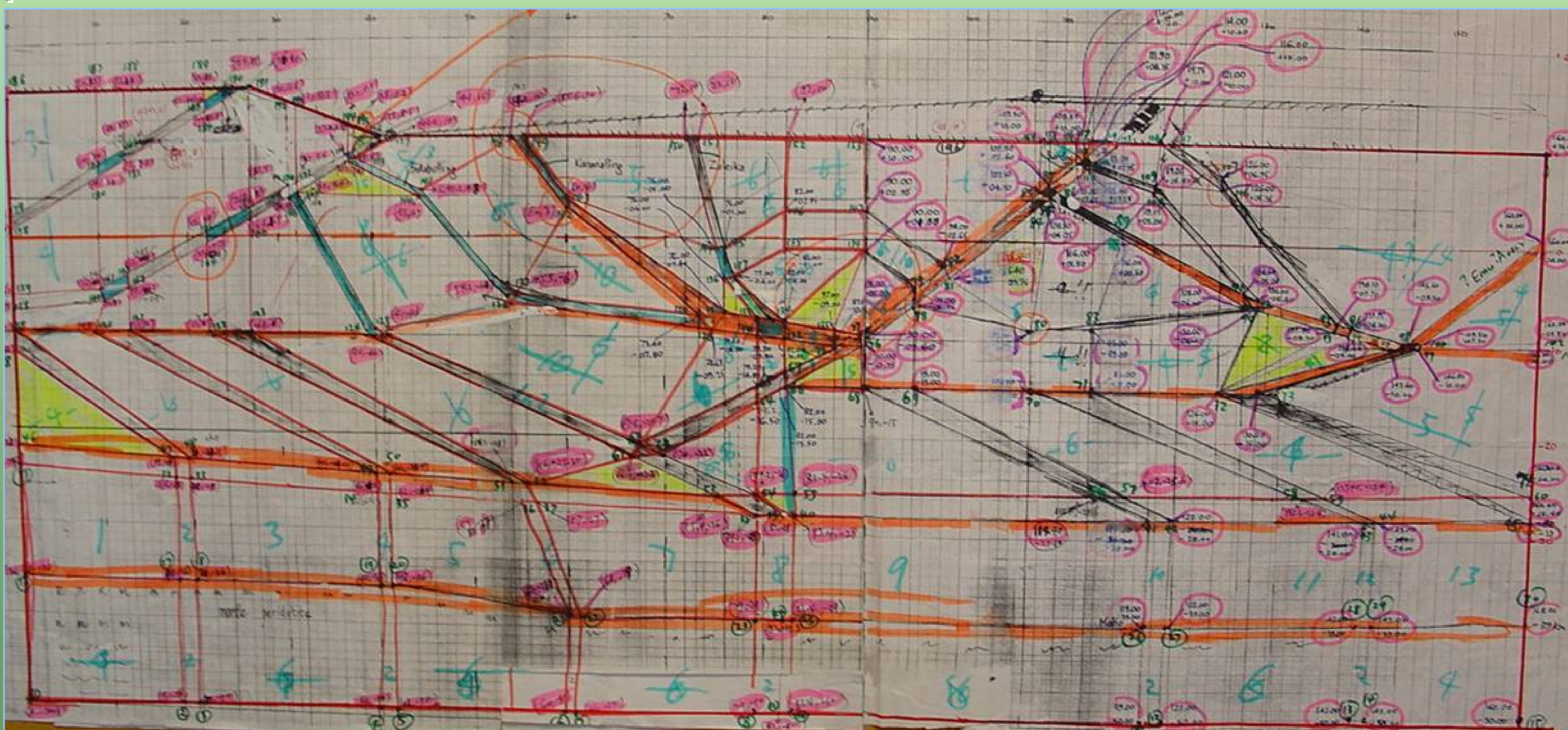
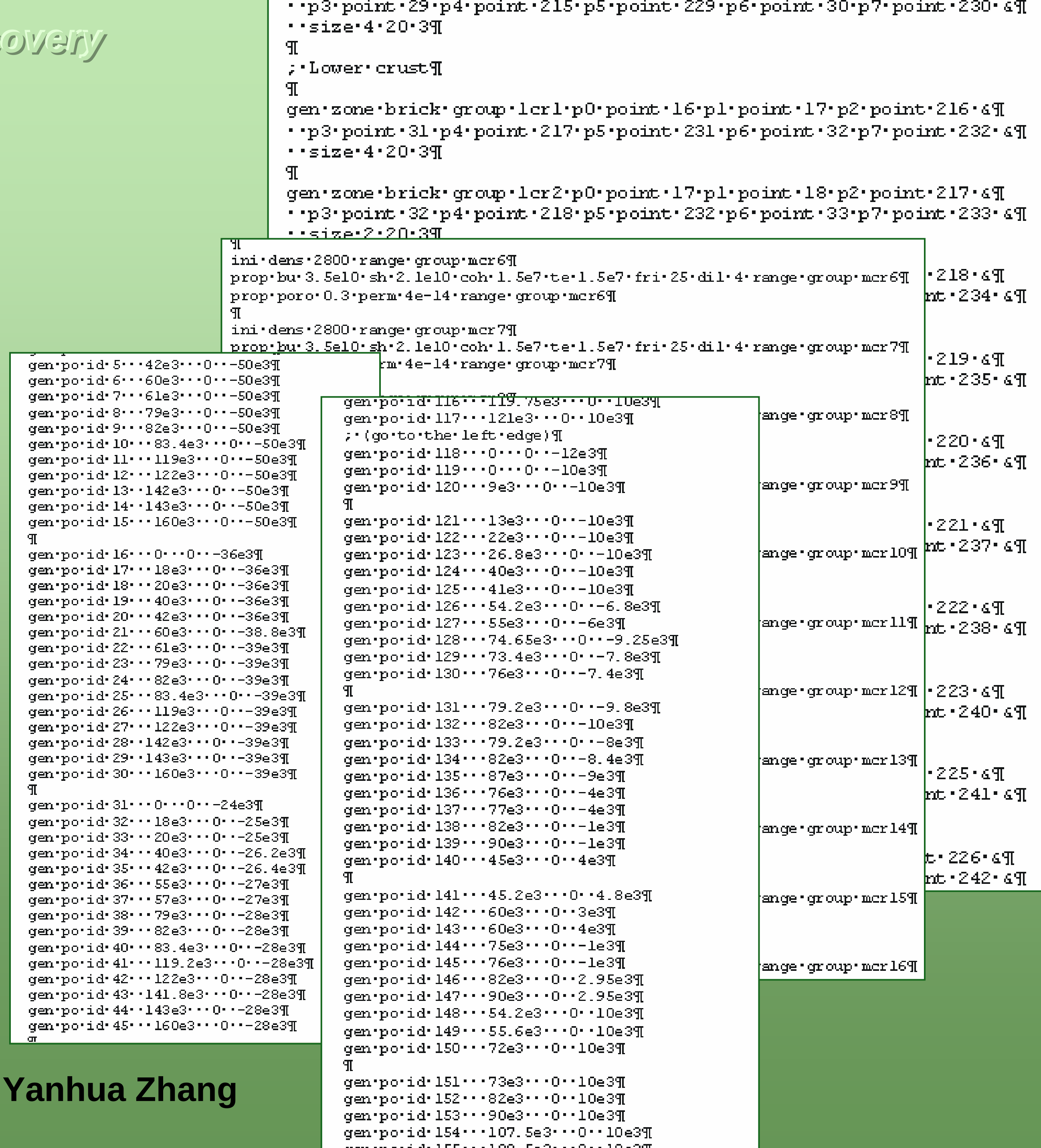


Geometry (model blocks) design and coordinates of points were sketched on graphic paper to assist modelling building process



Yanhua Zhang

A text model input file of 1885 Lines (31 Pages), containing x-y-z coordinates, was developed to build the geometry of the Yilgarn 3D model.



```
  p3 point 29 p4 point 215 p5 point 229 p6 point 30 p7 point 230 &
  size 4 20 3

; Lower crust

gen zone brick group lcr1 p0 point 16 p1 point 17 p2 point 216 &
  p3 point 31 p4 point 217 p5 point 231 p6 point 32 p7 point 232 &
  size 4 20 3

gen zone brick group lcr2 p0 point 17 p1 point 18 p2 point 217 &
  p3 point 32 p4 point 218 p5 point 232 p6 point 33 p7 point 233 &
  size 2 20 3
```

```
ini dens 2800 range group mcr6
prop bu 3.5e10 sh 2.1e10 coh 1.5e7 te 1.5e7 fri 25 dil 4 range group mcr6
prop poro 0.3 perm 4e-14 range group mcr6

ini dens 2800 range group mcr7
prop bu 3.5e10 sh 2.1e10 coh 1.5e7 te 1.5e7 fri 25 dil 4 range group mcr7
```

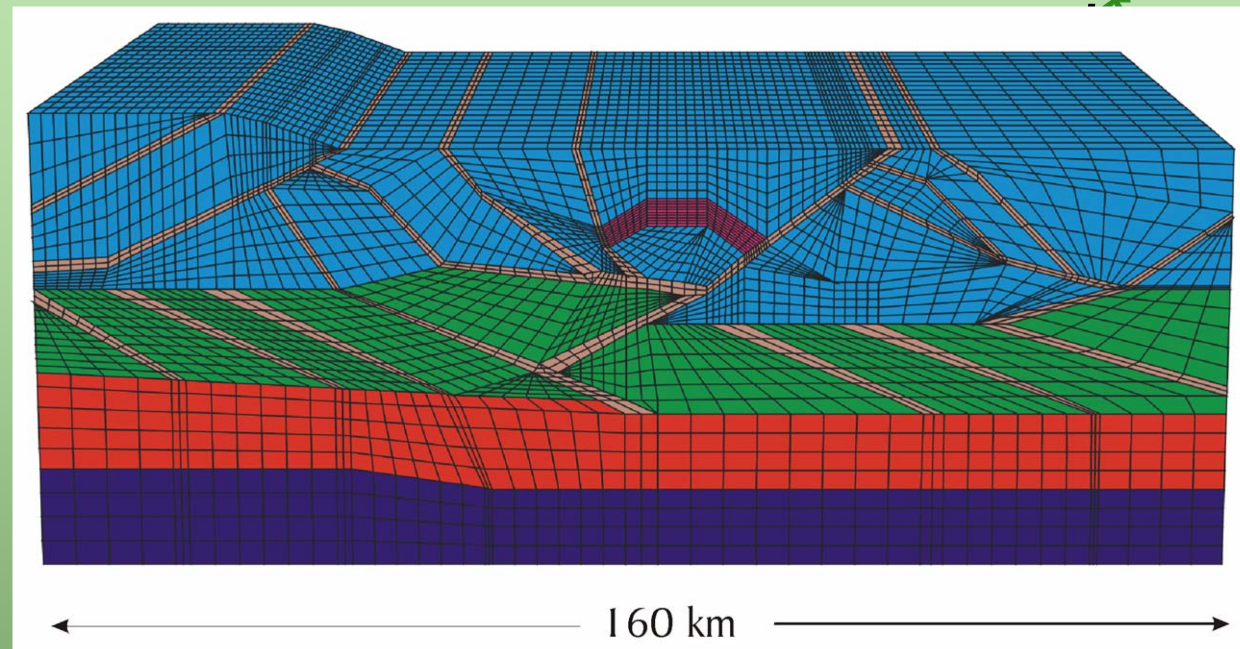
```
gen po id 5   42e3   0  -50e3
gen po id 6   60e3   0  -50e3
gen po id 7   61e3   0  -50e3
gen po id 8   79e3   0  -50e3
gen po id 9   82e3   0  -50e3
gen po id 10   83.4e3   0  -50e3
gen po id 11   119e3   0  -50e3
gen po id 12   122e3   0  -50e3
gen po id 13  142e3   0  -50e3
gen po id 14  143e3   0  -50e3
gen po id 15   160e3   0  -50e3

gen po id 16   0   0  -36e3
gen po id 17   18e3   0  -36e3
gen po id 18   20e3   0  -36e3
gen po id 19   40e3   0  -36e3
gen po id 20   42e3   0  -36e3
gen po id 21   60e3   0  -38.8e3
gen po id 22   61e3   0  -39e3
gen po id 23   79e3   0  -39e3
gen po id 24   82e3   0  -39e3
gen po id 25   83.4e3   0  -39e3
gen po id 26   119e3   0  -39e3
gen po id 27   122e3   0  -39e3
gen po id 28  142e3   0  -39e3
gen po id 29  143e3   0  -39e3
gen po id 30   160e3   0  -39e3

gen po id 31   0   0  -24e3
gen po id 32   18e3   0  -25e3
gen po id 33   20e3   0  -25e3
gen po id 34   40e3   0  -26.2e3
gen po id 35   42e3   0  -26.4e3
gen po id 36   55e3   0  -27e3
gen po id 37   57e3   0  -27e3
gen po id 38   79e3   0  -28e3
gen po id 39   82e3   0  -28e3
gen po id 40   83.4e3   0  -28e3
gen po id 41   119.2e3   0  -28e3
gen po id 42   122e3   0  -28e3
gen po id 43  141.8e3   0  -28e3
gen po id 44  143e3   0  -28e3
gen po id 45   160e3   0  -28e3
```

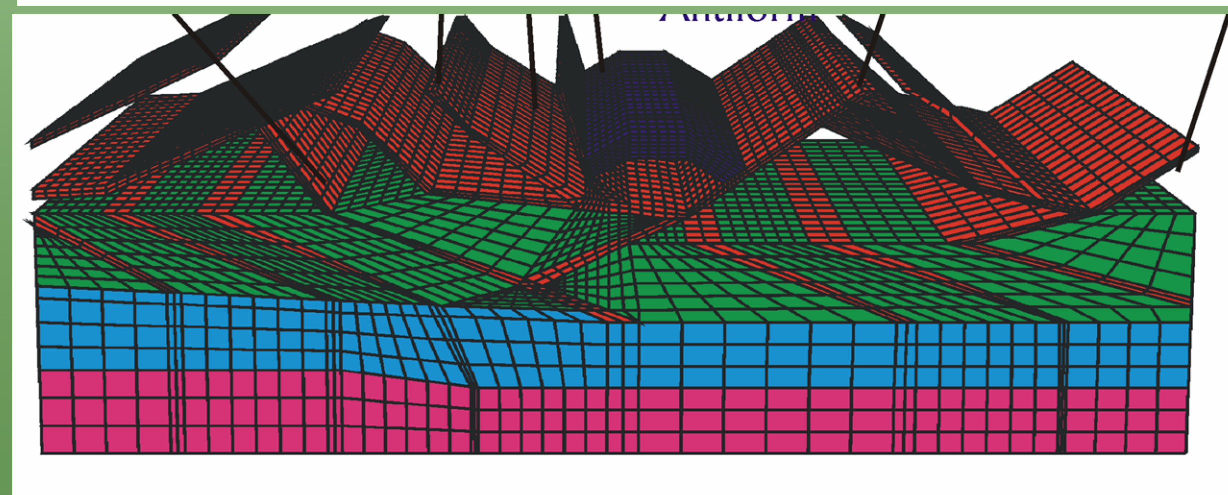
```
gen po id 117   121e3   0  10e3
; (go to the left edge)
gen po id 118   0   0  -12e3
gen po id 119   0   0  -10e3
gen po id 120   9e3   0  -10e3

gen po id 121   13e3   0  -10e3
gen po id 122   22e3   0  -10e3
gen po id 123   26.8e3   0  -10e3
gen po id 124   40e3   0  -10e3
gen po id 125   41e3   0  -10e3
gen po id 126   54.2e3   0  -6.8e3
gen po id 127   55e3   0  -6e3
gen po id 128   74.65e3   0  -9.25e3
gen po id 129   73.4e3   0  -7.8e3
gen po id 130   76e3   0  -7.4e3

gen po id 131   79.2e3   0  -9.8e3
gen po id 132   82e3   0  -10e3
gen po id 133   79.2e3   0  -8e3
gen po id 134   82e3   0  -8.4e3
gen po id 135   87e3   0  -9e3
gen po id 136   76e3   0  -4e3
gen po id 137   77e3   0  -4e3
gen po id 138   82e3   0  -1e3
gen po id 139   90e3   0  -1e3
gen po id 140   45e3   0  4e3

gen po id 141   45.2e3   0  4.8e3
gen po id 142   60e3   0  3e3
gen po id 143   60e3   0  4e3
gen po id 144   75e3   0  -1e3
gen po id 145   76e3   0  -1e3
gen po id 146   82e3   0  2.95e3
gen po id 147   90e3   0  2.95e3
gen po id 148   54.2e3   0  10e3
gen po id 149   55.6e3   0  10e3
gen po id 150   72e3   0  10e3

gen po id 151   73e3   0  10e3
gen po id 152   82e3   0  10e3
gen po id 153   90e3   0  10e3
gen po id 154   107.5e3   0  10e3
```

Yanhua Zhang

Constructed Model Geometry

- Faults were modelled as planer zones or segments of planer zones
- With wedge blocks (more likely to have illegal geometry, once deformed)
- Prismatic structure (2.5D)

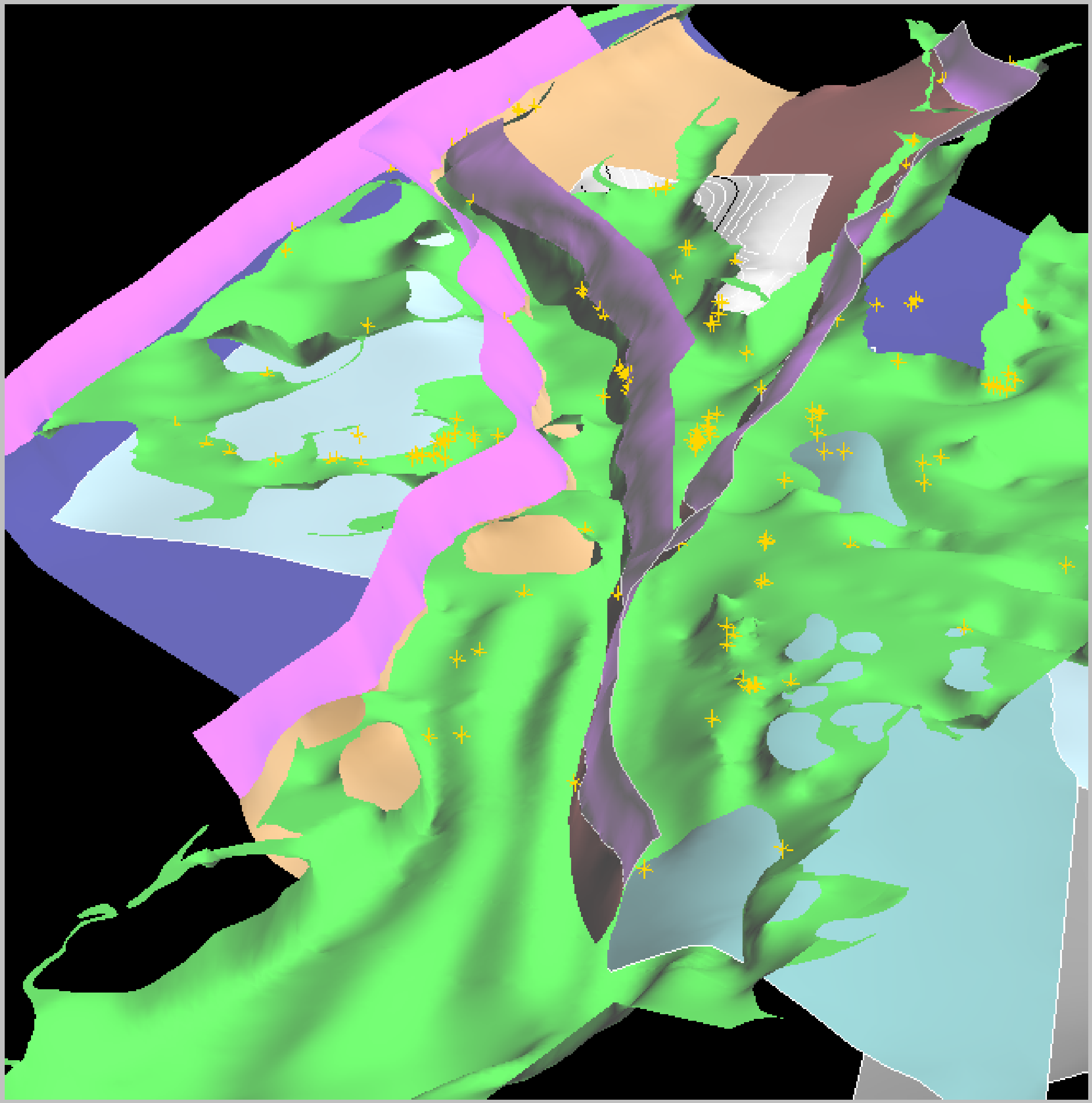




Yanhua Zhang

Predictive Mineral Discovery

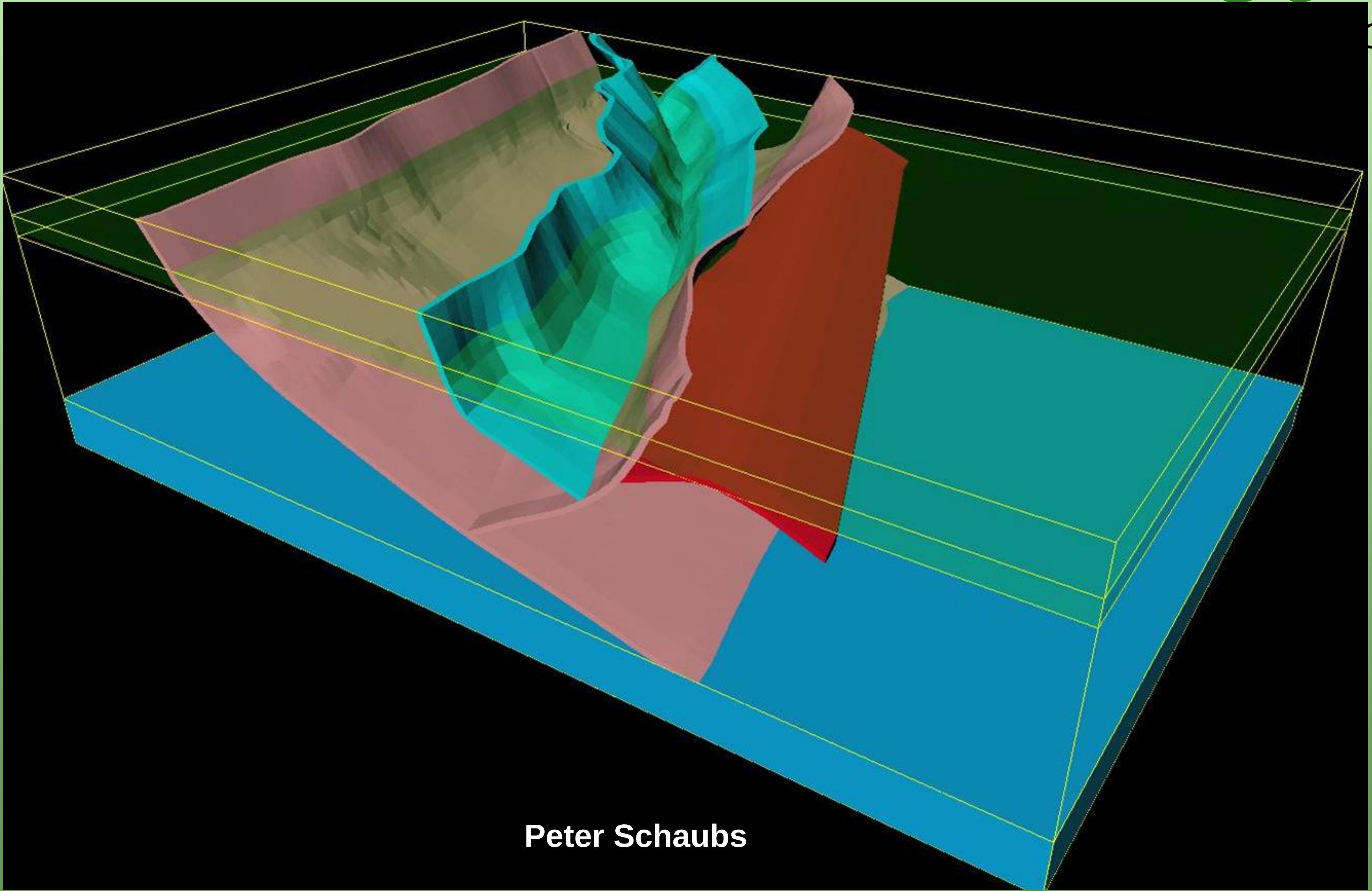
EFFICIENT SYSTEMS – MESH CONSTRUCTION (NEW)



Geoscience Australia

Predictive Mineral Discovery

EFFICIENT SYSTEMS – MESH CONSTRUCTION (NEW)



EFFICIENT COMPUTATION – DESKTOP MODELLING TOOLKIT

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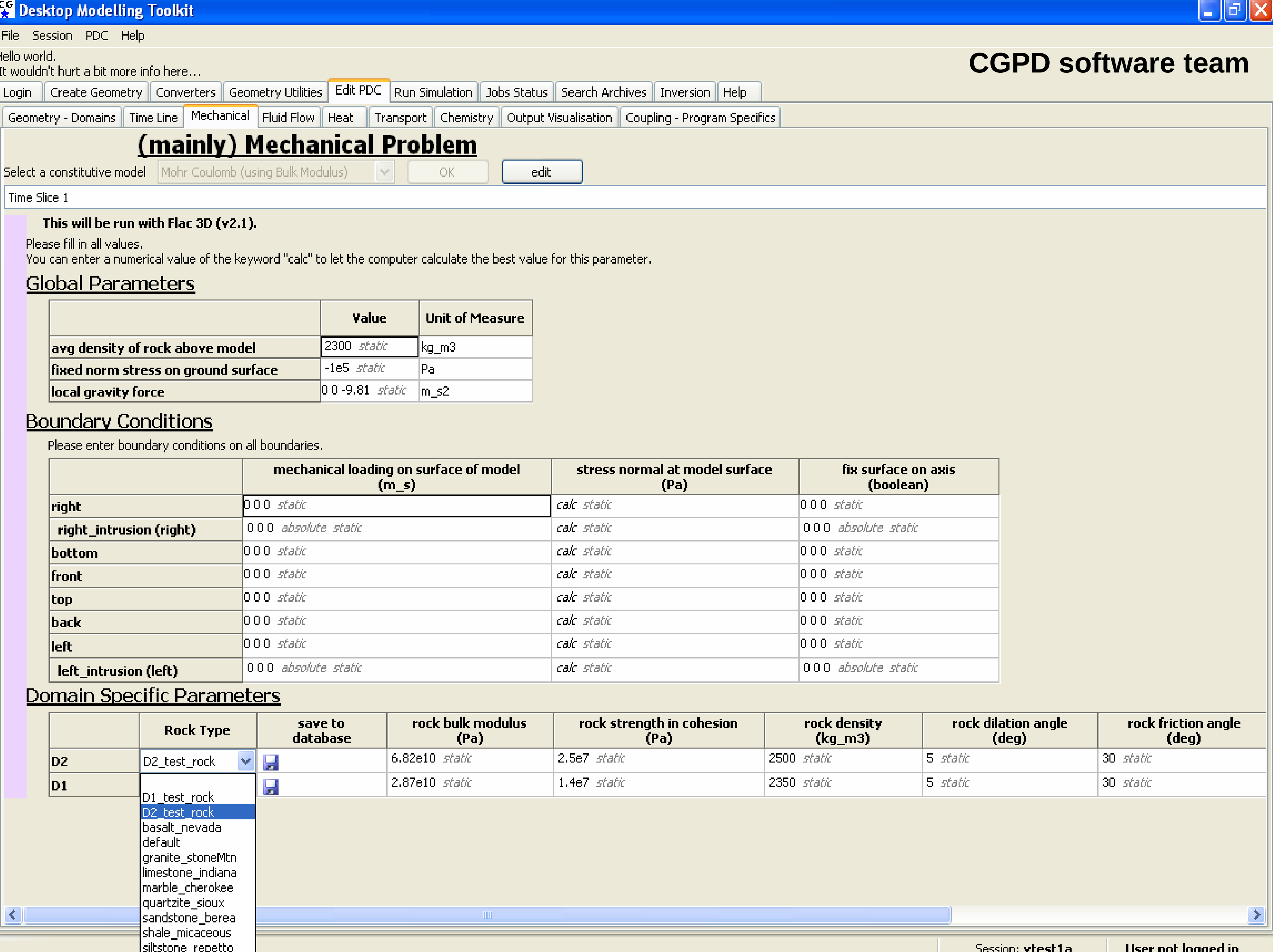
- A single interface on your desktop for specifying and running problems.
  - DMT GUI
- A ‘grid computing’ environment for use of single-, cluster- or super-computer resources.
  - GLOBUS / GT4
  - Condor
  - Vendor wrappers
- An archive system to hold data.
  - Storage Resource Broker (SRB)

How does it work?

- You provide a 3D geometry (xmml4fem file)
- Use the GUI to specify a problem (mech / fluid / thermal / chem / transport) and a timeline
- You send it to the grid (GT4 queues your job)
- Grid finds resources to run your job
- Can query status of job (stage, cycle num, time)
- Results in your SRB (storage resource broker) directory



Desktop Modelling Toolkit
File Session PDC Help
Hello world.
It wouldn't hurt a bit more info here...
CGPD software team
Login Create Geometry Converters Geometry Utilities Edit PDC Run Simulation Jobs Status Search Archives Inversion Help
Geometry - Domains Time Line Mechanical Fluid Flow Heat Transport Chemistry Output Visualisation Coupling - Program Specifics
(mainly) Mechanical Problem
Select a constitutive model
Mohr Coulomb (using Bulk Modulus)
OK
edit
Time Slice 1
This will be run with Flac 3D (v2.1).
Please fill in all values.
You can enter a numerical value of the keyword "calc" to let the computer calculate the best value for this parameter.
Global Parameters
Value
Unit of Measure
avg density of rock above model
2300 static
kg_m3
fixed norm stress on ground surface
-1e5 static
Pa
local gravity force
0 0 -9.81 static
m_s2
Boundary Conditions
Please enter boundary conditions on all boundaries.
mechanical loading on surface of model (m_s)
stress normal at model surface (Pa)
fix surface on axis (boolean)
right
0 0 0 static
calc static
0 0 0 static
right_intrusion (right)
0 0 0 absolute static
calc static
0 0 0 absolute static
bottom
0 0 0 static
calc static
0 0 0 static
front
0 0 0 static
calc static
0 0 0 static
top
0 0 0 static
calc static
0 0 0 static
back
0 0 0 static
calc static
0 0 0 static
left
0 0 0 static
calc static
0 0 0 static
left_intrusion (left)
0 0 0 absolute static
calc static
0 0 0 absolute static
Domain Specific Parameters
Rock Type
save to database
rock bulk modulus (Pa)
rock strength in cohesion (Pa)
rock density (kg_m3)
rock dilation angle (deg)
rock friction angle (deg)
D2
D2_test_rock
6.82e10 static
2.5e7 static
2500 static
5 static
30 static
D1
2.87e10 static
1.4e7 static
2350 static
5 static
30 static
D1_test_rock
D2_test_rock
basalt_nevada
default
granite_stoneMtn
limestone_indiana
marble_cherokee
quartzite_sioux
sandstone_berea
shale_micaceous
siltstone_repetto
Session: ytest1a
User not logged in

Current and (near) projected capabilities

- Problem domains:
  - Deformation
  - Damage mechanics
  - Fluid and transport
  - Thermal
  - Chemical
- Vendor codes:
  - Flac3d 2.0 Unix
  - Flac3d 2.1 Windows
  - FastfloRT
  - Finley
- FastFlo plugins:
  - User-defined temp gradient eqn
  - User-defined pore press gradient eqn
- Flac3d plugins:
  - Plasticity state – permeability coupling
  - Model Shortening
  - Slip/strike contractions
- Inversion (parameter search) tool

PEOPLE – E&T PROGRAM

Syllabus Mineral Resources 520.351

Semester 1 2005

Lecture and Lab times:

Wednesdays	1-2	lecture in LT2, Geography & Geology
Wednesdays	2-5	lab in 3rd year lab, GP2
Thursdays	1-2	lecture in ENCM 1.51, Engineering
Fridays	11-12	lecture in Woolnough LT, Geography & Geology

Contact details of lecturers:

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Telephone: 6488 3423
Email: pneumayr@bigpond.com.au

Dr Klaus Gessner
Senior Lecturer, Earth Systems Modelling group
Centre for Exploration Targeting (CET) / School of Earth and Geographical Sciences
GP2, Room 2.7
Telephone: 6488 7148, 6436 8627 (CSIRO)
Email: kgessner@cyllene.uwa.edu.au

Dr Richard Durham
Associate Professor, Resource Engineering
School of Civil and Resource Engineering

RESEARCH FRONTIER – SELF CONSISTENT SIMULATION (CRUSTAL SCALE)

pmd*CRC

Courtesy: Klaus Regenauer-Lieb,

RESEARCH FRONTIER – THERMOMECHANICS

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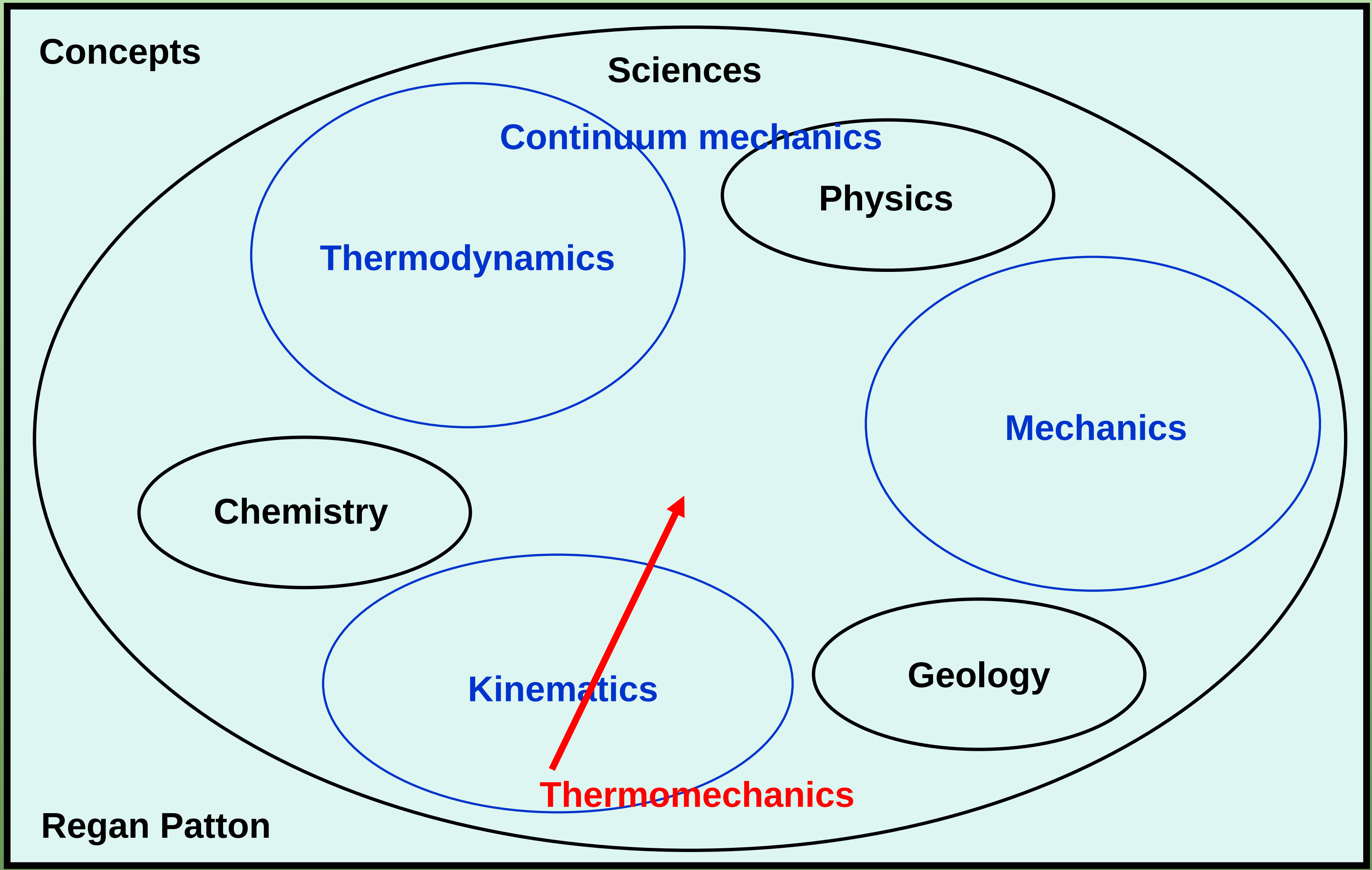

APPLICATION TO INDUSTRY TARGETING PROBLEMS DURING CRC

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- International:
  - USA Au
  - Canada U
  - Canada potash
  - Finland Cu-Zn
  - China Zn-Pb-Au-Ag
- Australia:
  - Isa (Qld) Cu +/- Au, Zn
  - Yilgarn (WA) Au
  - Gawler (SA) Au
  - Tasmanides (Vic, NSW) – Au
  - Tanami (NT) - Au
  - Petroleum (fault-seal research)

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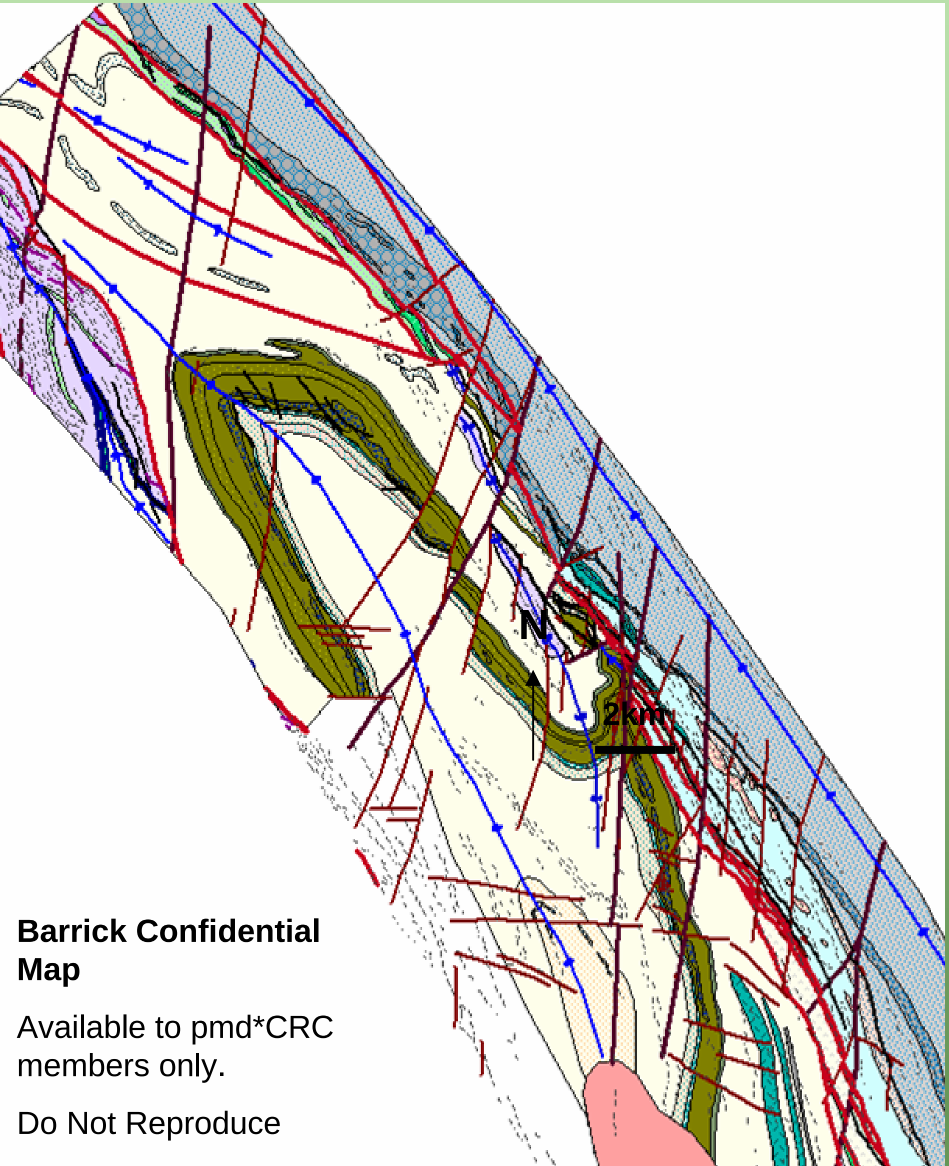
APPLICATION TO TARGETING

- Computational simulation is an adjunct to the conceptual thinking process
- Absorb all available whole system knowledge
- Start simple and work to complexity
- Multiple working hypotheses
- Two stage process:
  - “reverse engineer” the known deposit
  - predictive phase (cut to the chase/recognise the risk)

KUNDANA EXAMPLE



Barrick Confidential Map

Available to pmd*CRC members only.

Do Not Reproduce

Aims:

- use numerical modelling to understand the impact of fault intersection geometry on mineralisation
- use modelling to predict favourable fault orientations to assist with green-fields & brown-fields exploration target ranking and generation.

Templates

(buffer box & boundary conditions)

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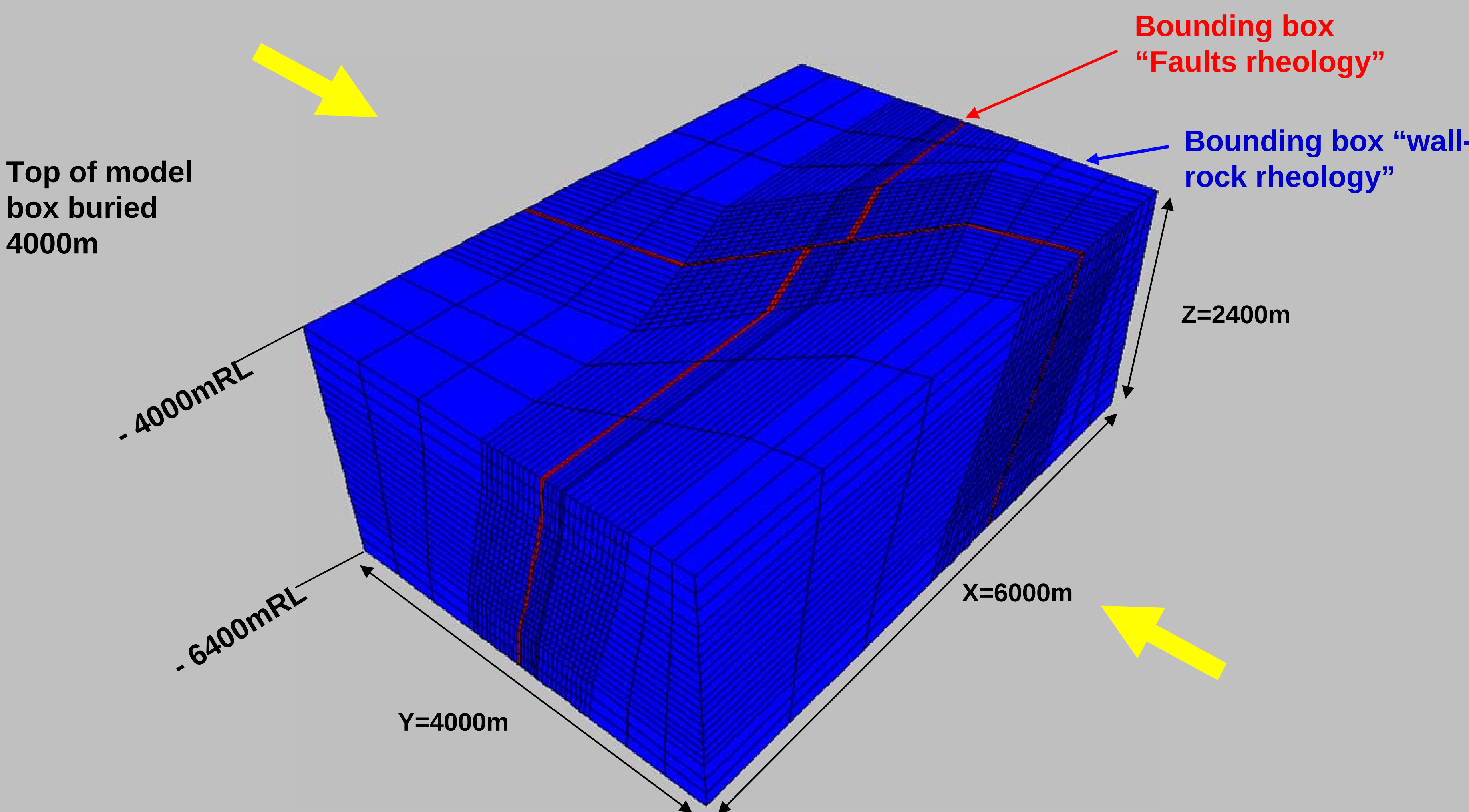

Warren Potma and Thomas Poulet

Predictive Mineral discovery

Block model of U.gradP (proxy for mineral precipitation): showing variation with far-field stress orientation

(Looking ~ sub-horizontally ENE)

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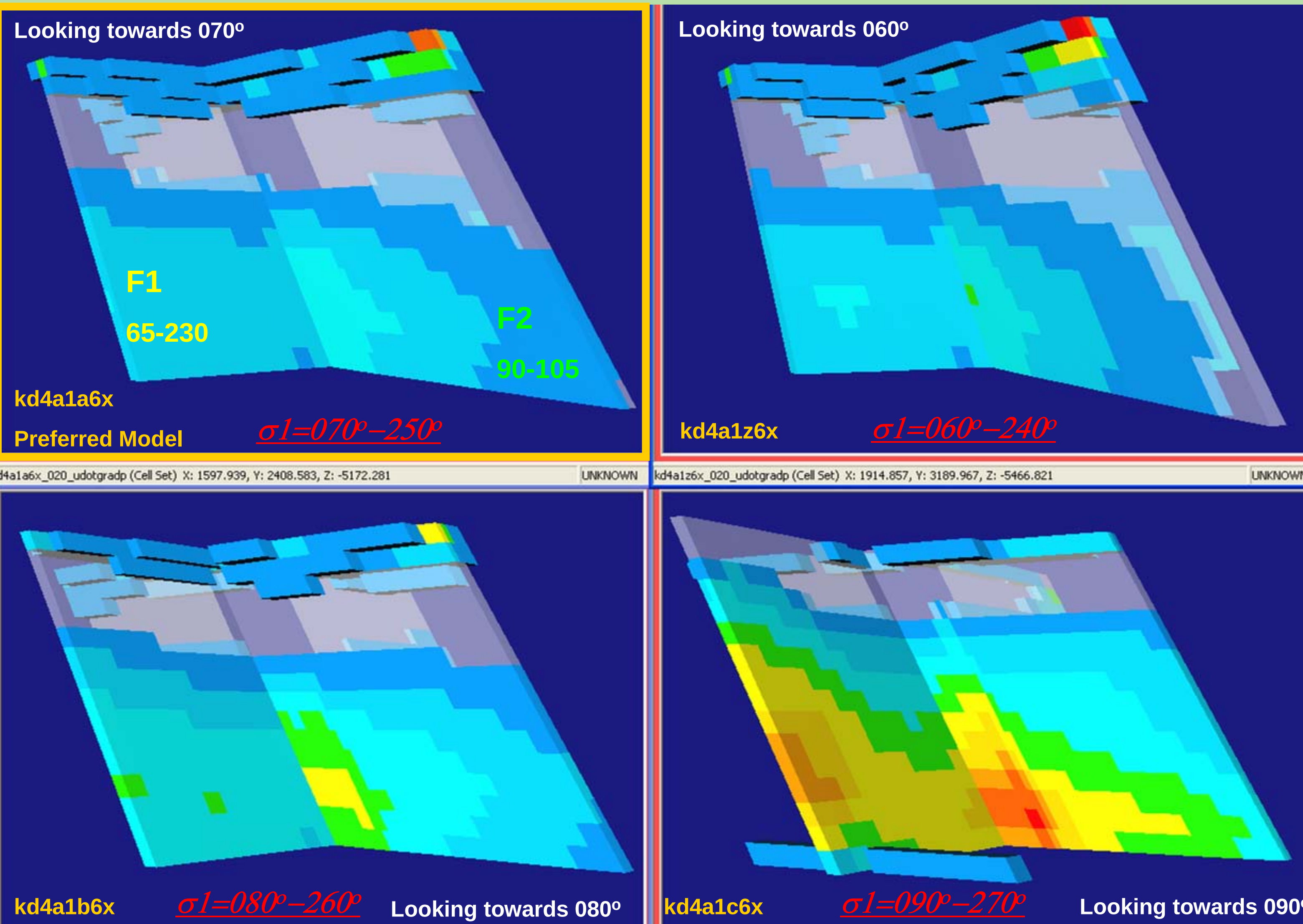
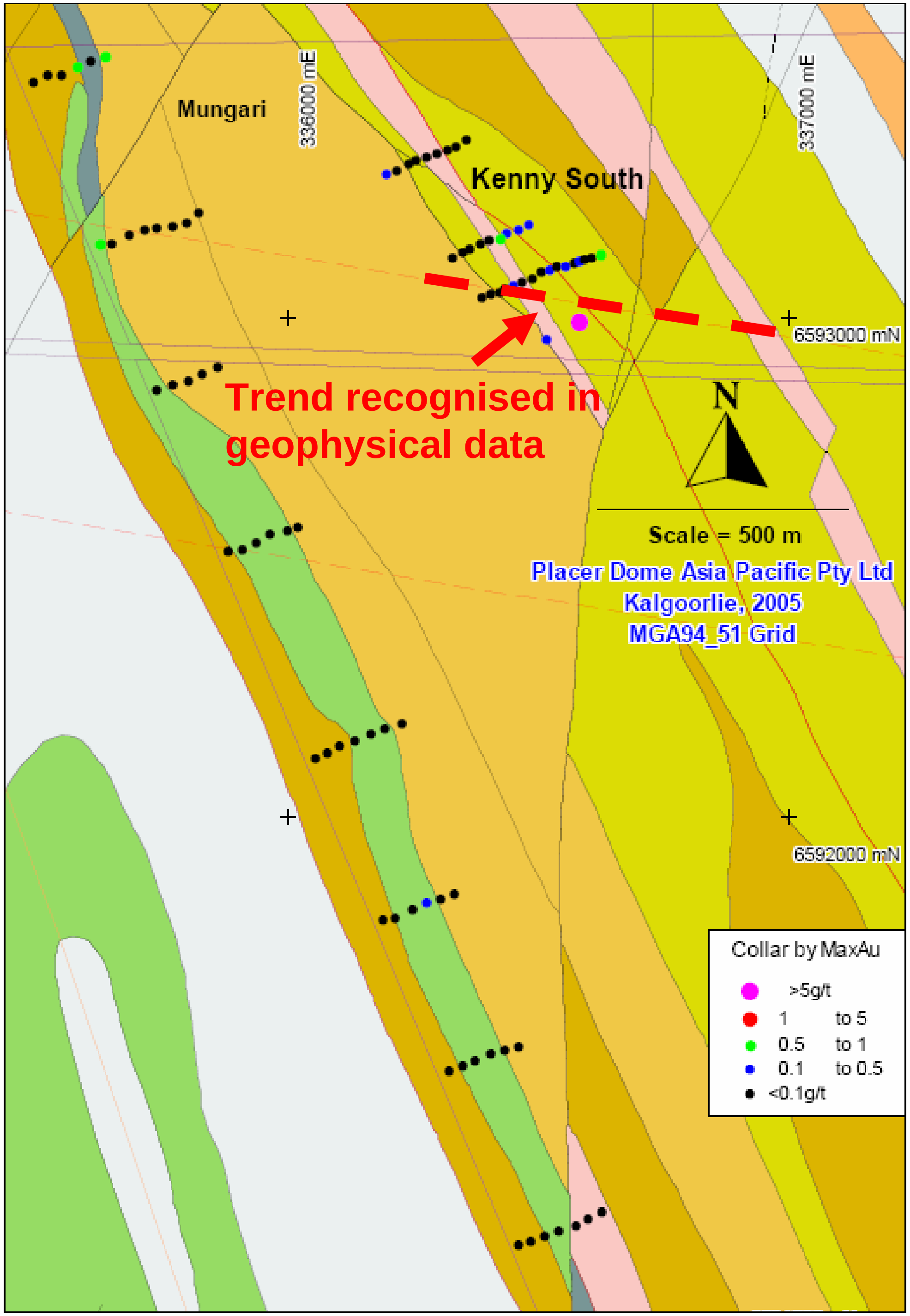


Block model colours depict values for U.GradP - a proxy for mineral precipitation:

- **Warm colours = greater potential for precipitation**
- **Cool colours = lesser potential for precipitation**
- **No blocks = minimal precipitation or potential dissolution**

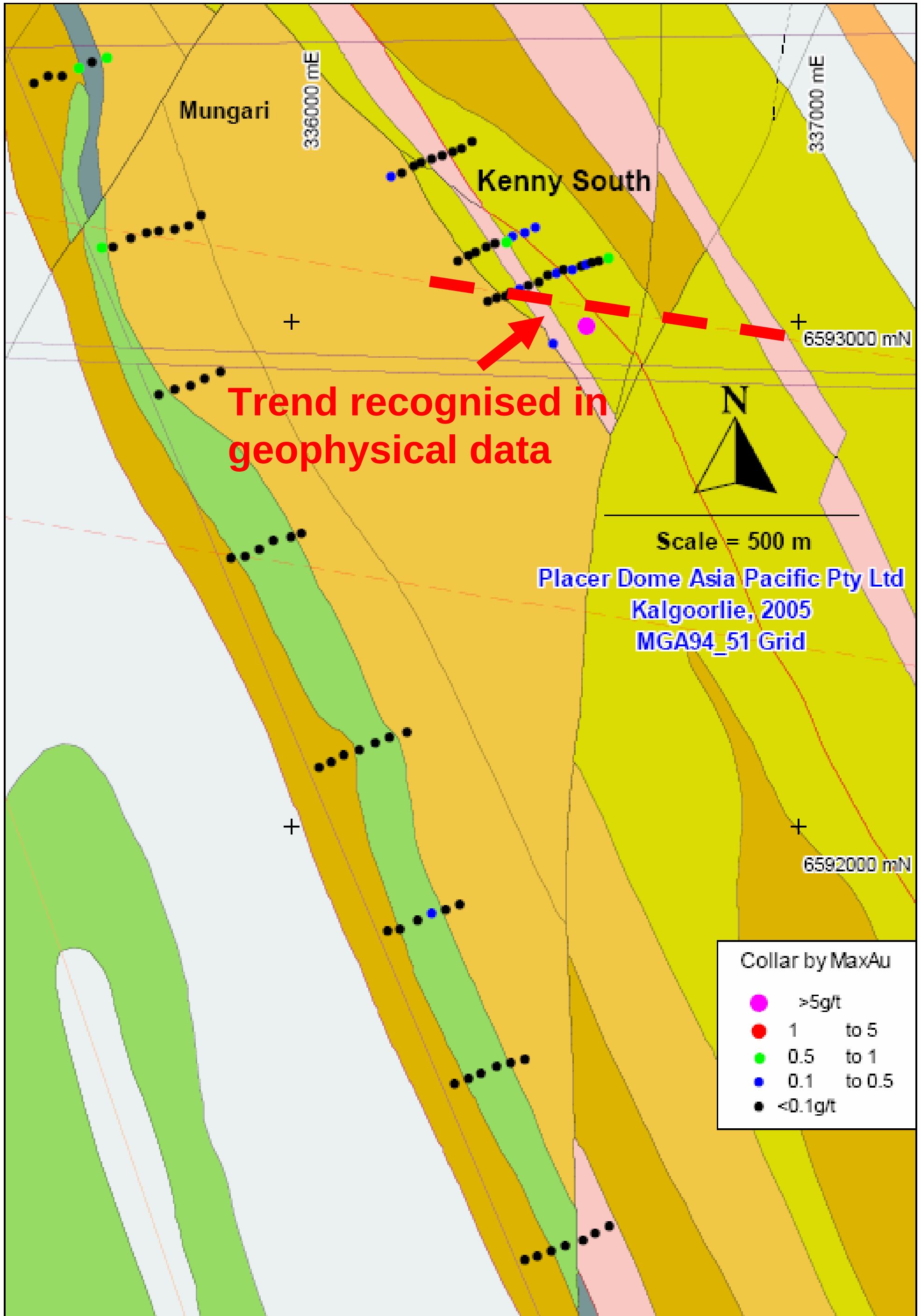
Warren Potma

KUNDANA



Mungari
336000 mE
337000 mE
Kenny South
6593000 mN
Trend recognised in geophysical data
N
Scale = 500 m
Placer Dome Asia Pacific Pty Ltd
Kalgoorlie, 2005
MGA94_51 Grid
6592000 mN
Collar by MaxAu
>5g/t
1 to 5
0.5 to 1
0.1 to 0.5
<0.1g/t

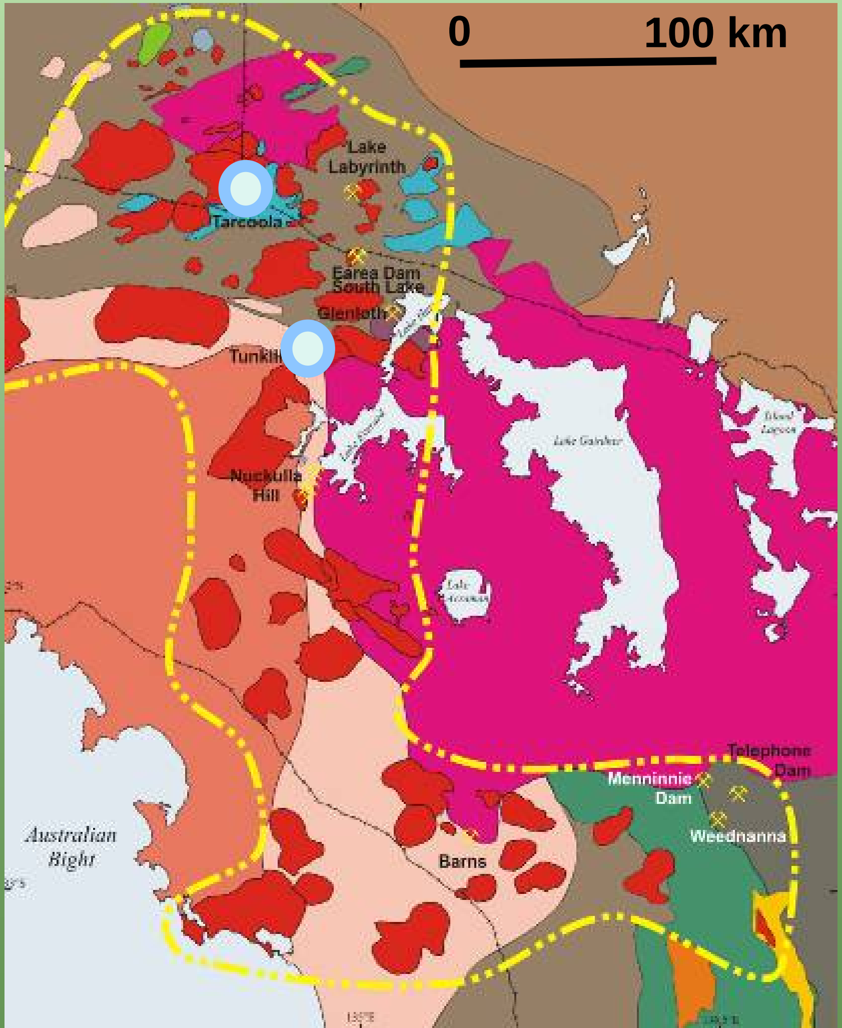

HOLE ID: KSRD 002
TRAY N°
From.
169.3
To:
179.8
21
174.0
Contains visible gold
Courtesy - Barrick



KUNDANA
Where was the value add?

- Reliability – with new drilling orientation, more likely to find ore that's there
- FAR – targeted on more favourable structural intersections, hence fewer misplaced holes

GAWLER



PIRSA's challenge in the Gawler:

- **What combination of factors will make a 5 million oz high grade gold deposit?**

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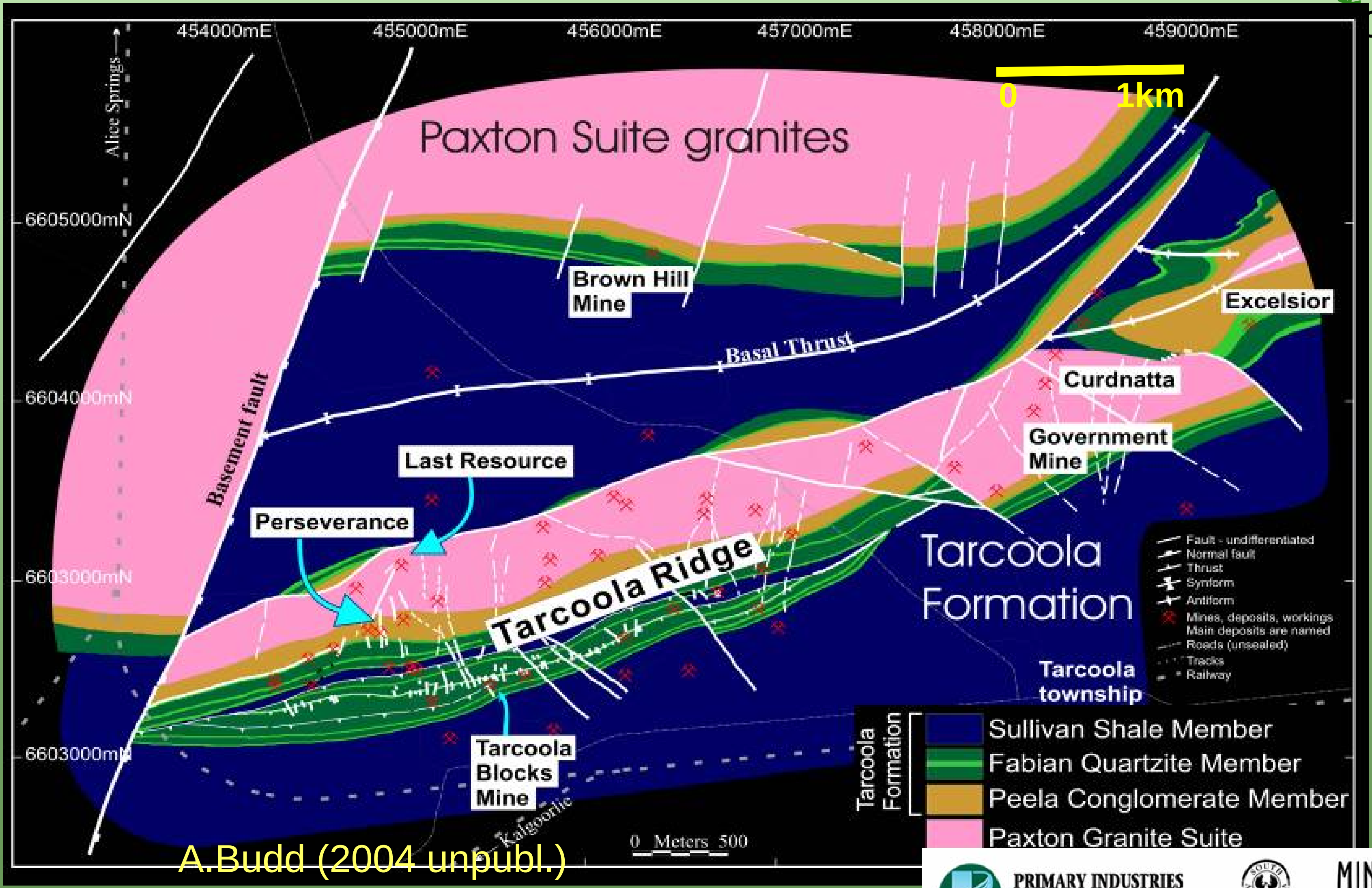
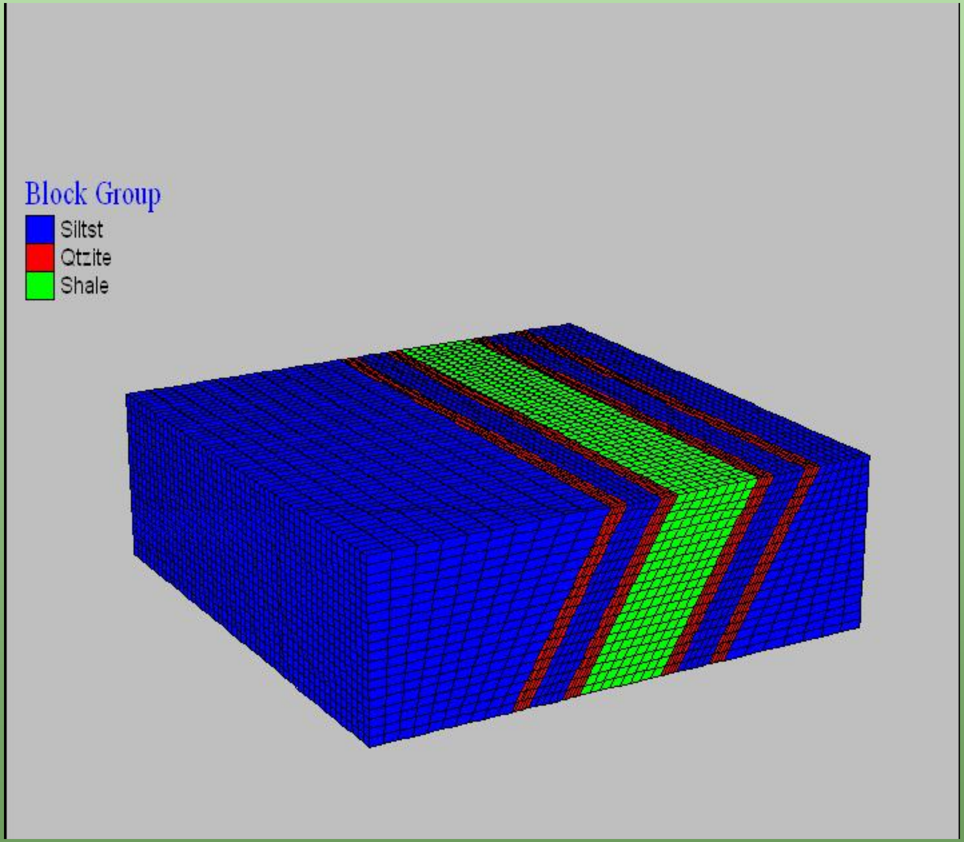
MINERALS & ENERGY

Reverse Engineering – Tarcoola Gold Field



A.Budd (2004 unpubl.)

Reverse Engineering – how do the mineralised faults form?



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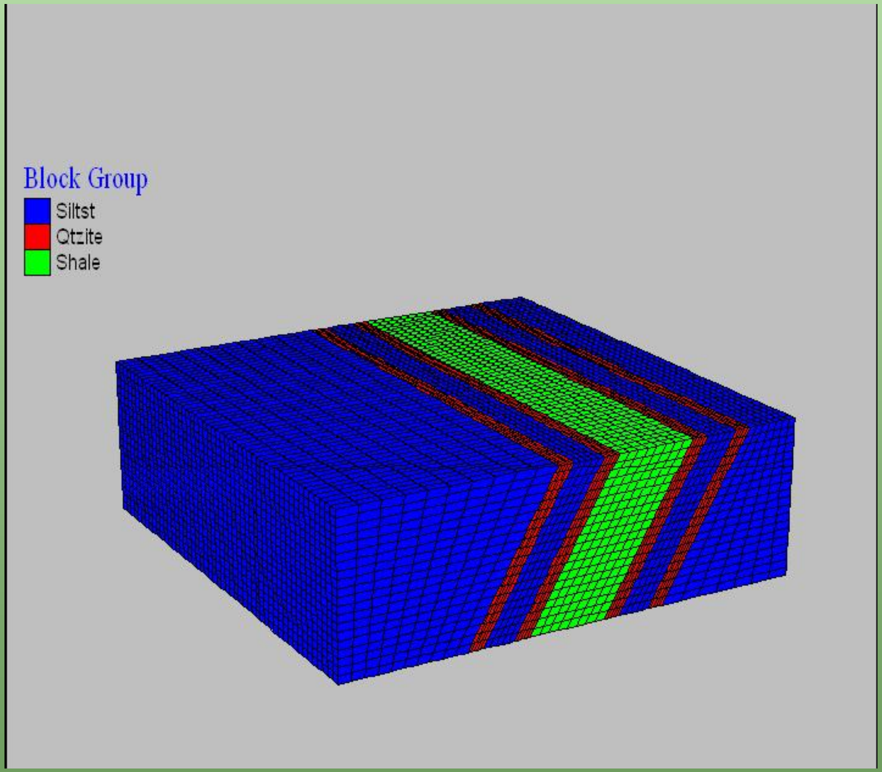
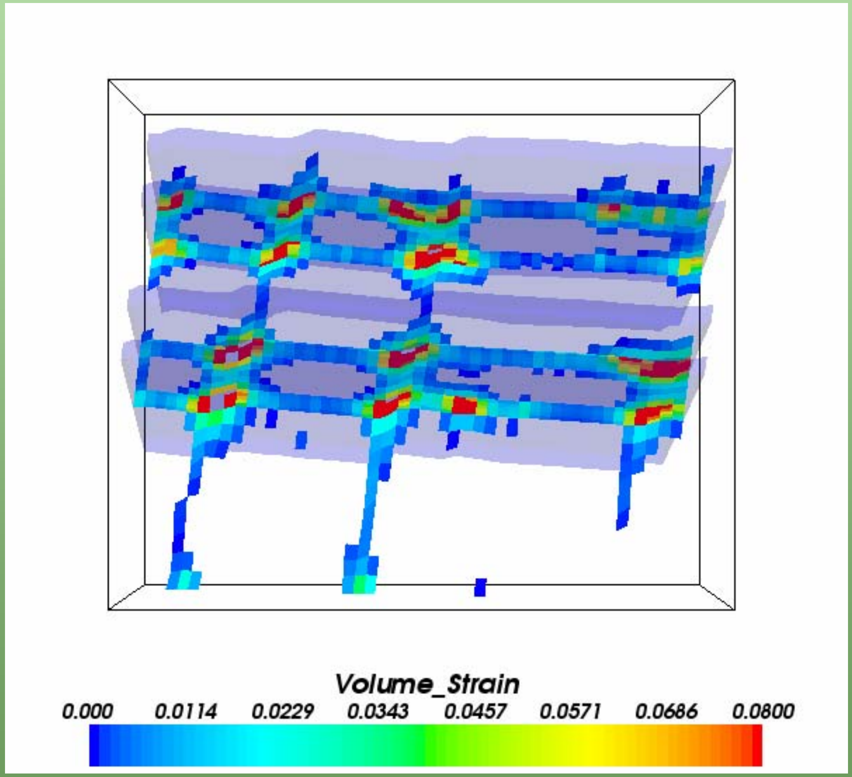
"Reverse Engineering"

Geo-mechanical modelling predicts dilation in the quartzites
BUT gets correct results from several different stress histories





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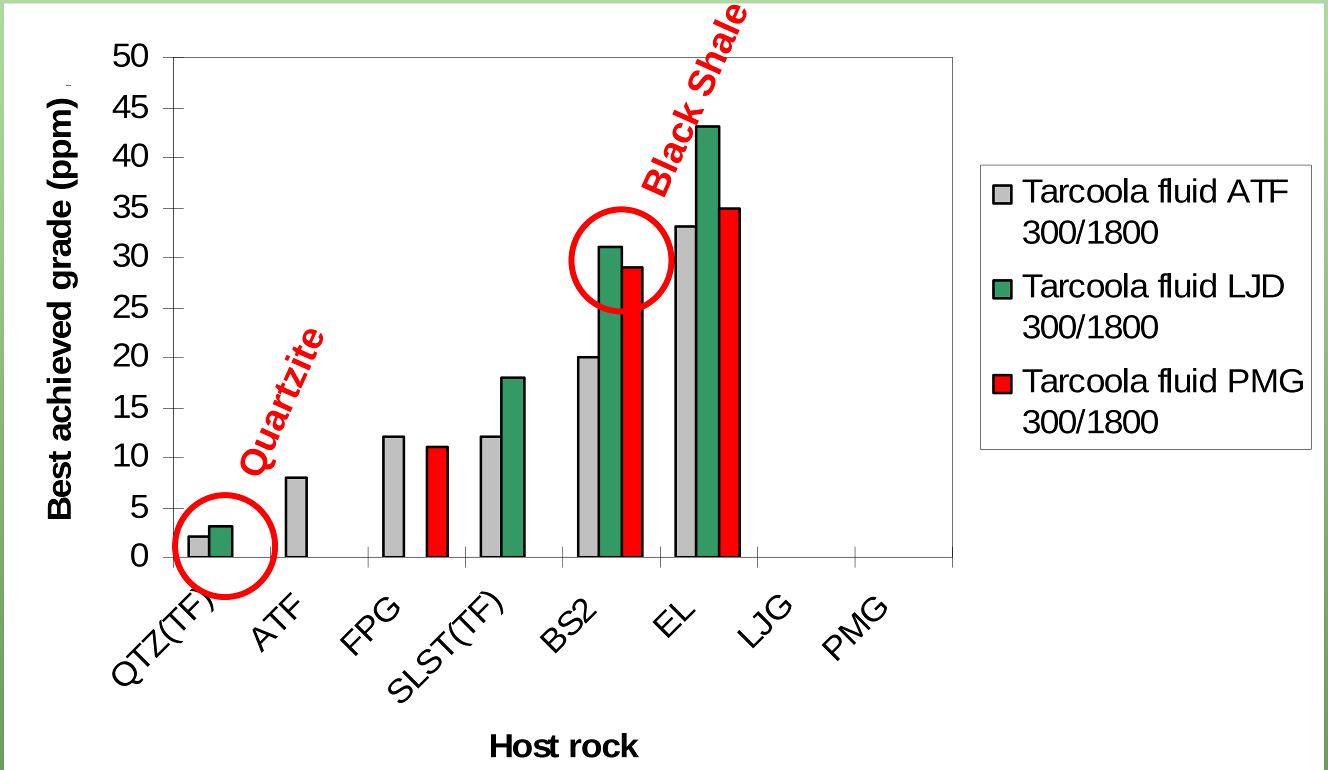
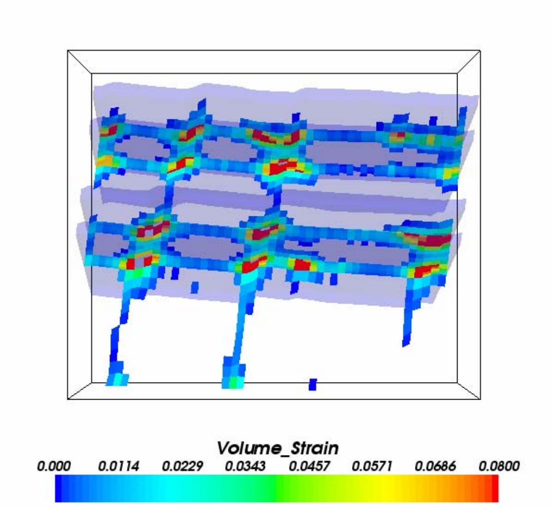
"Reverse Engineering"

pmd*CRC

Chemical modelling shows that adjacent carbonaceous shales (and some other rock types) are more favourable, thereby explaining the ore position



Courtesy: Evgeniy Bastrakov, Geoscience Australia



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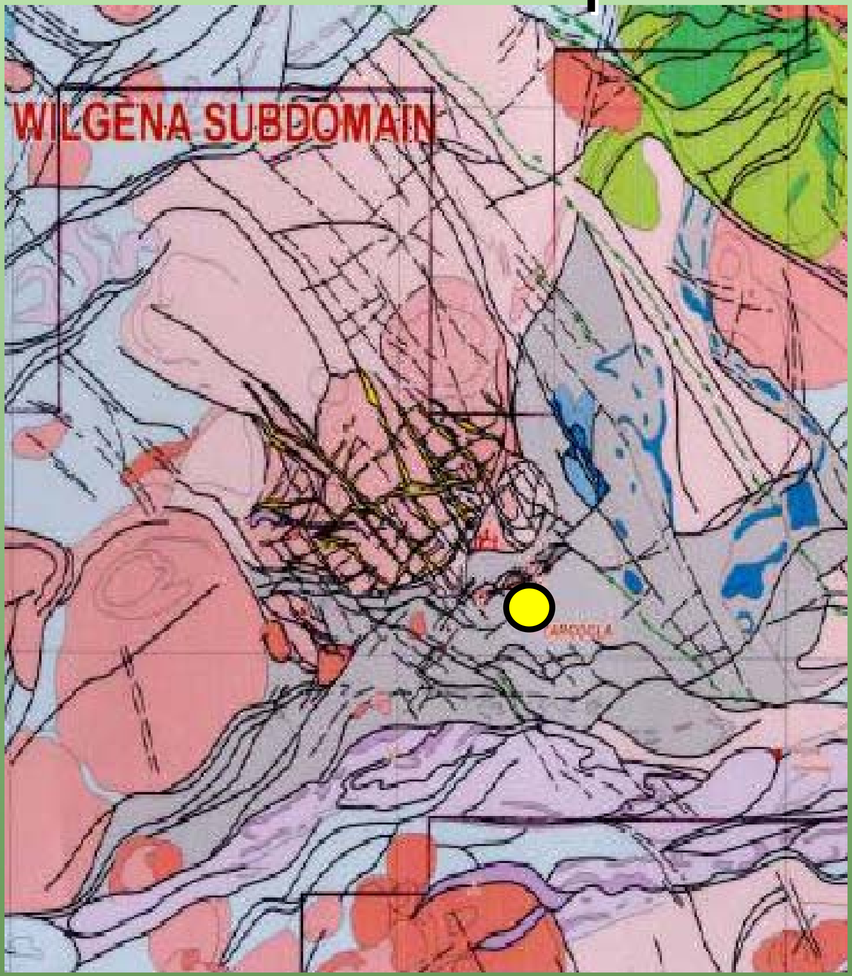
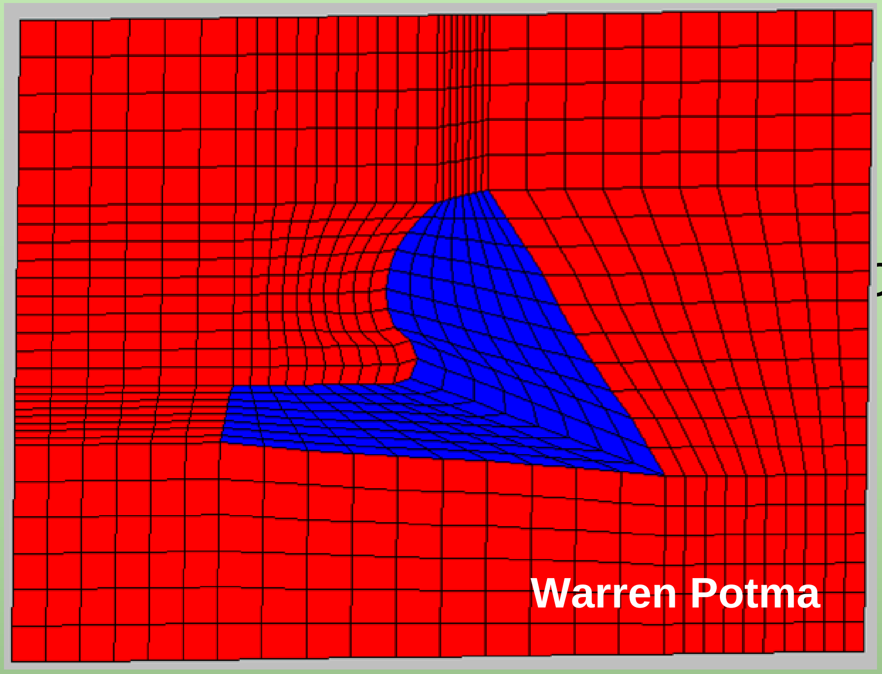
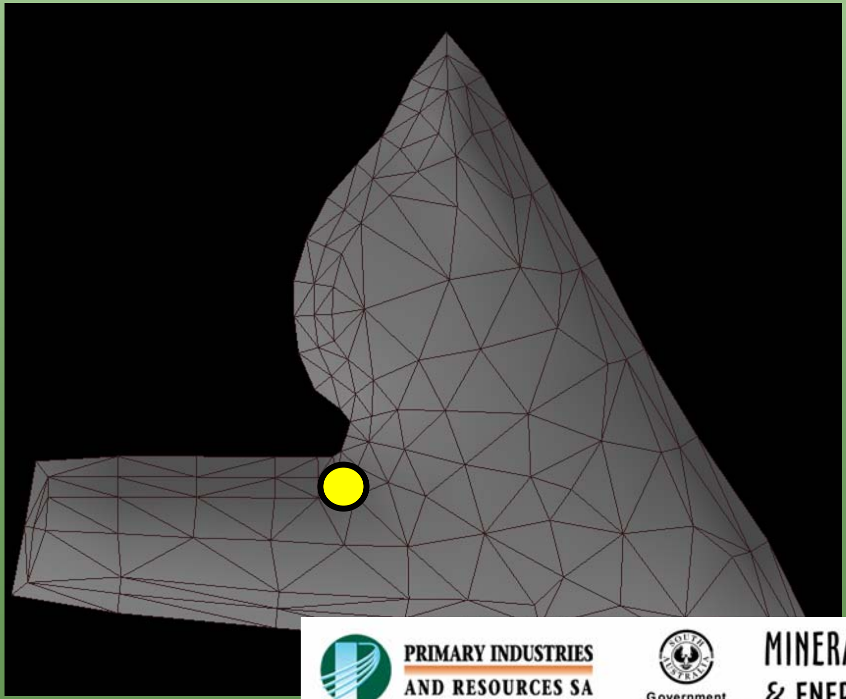
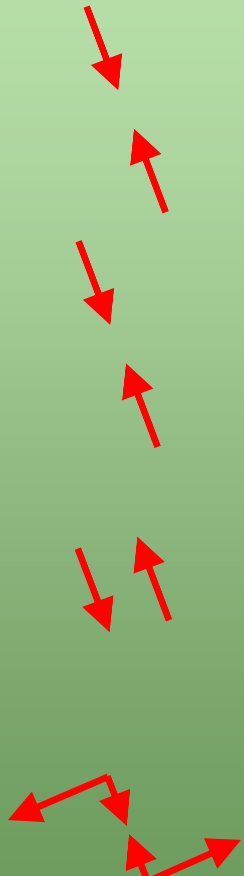
"Prediction" at the next scale up







Suite of models



- **NNW-SSE compression** only deformation (160-340 deg)
- **NNW-SSE compression** only deformation with **strain softening** behaviour (160-340 deg)
- **Sinistral strike-slip** deformation along NNW-SSE plane (E block to the NNW)
- **Sinistral Transpression** (compression component NNW-SSE, 6:1 sinistral strike-slip:compression component)

"Prediction" at the next scale up (for highest probability result)

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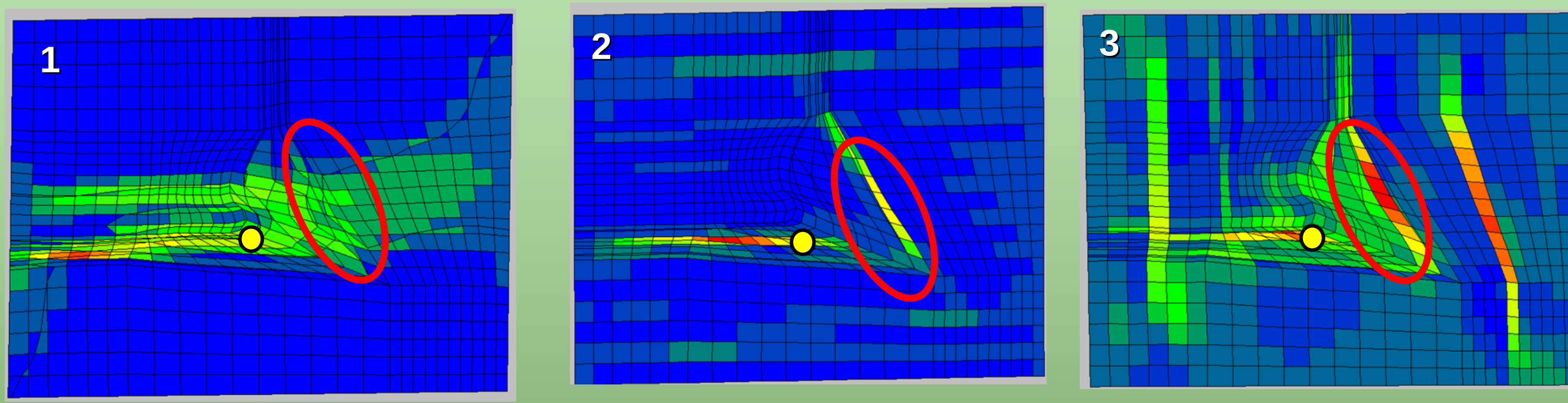
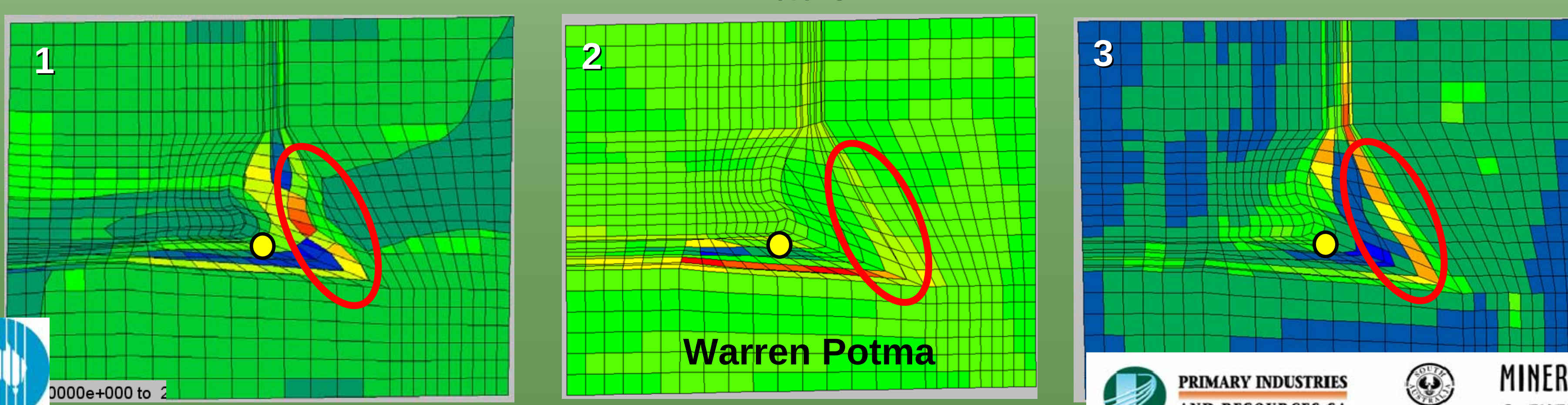
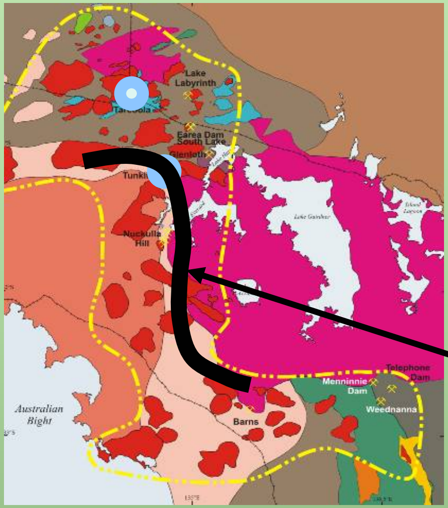
Shear Strain

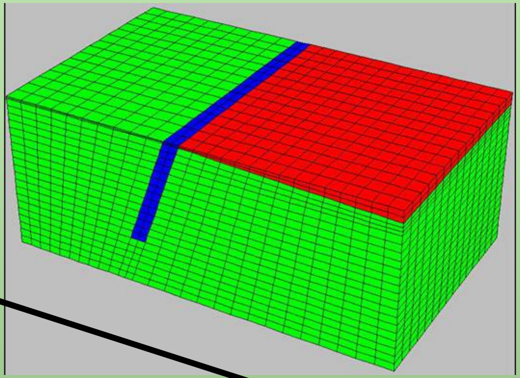


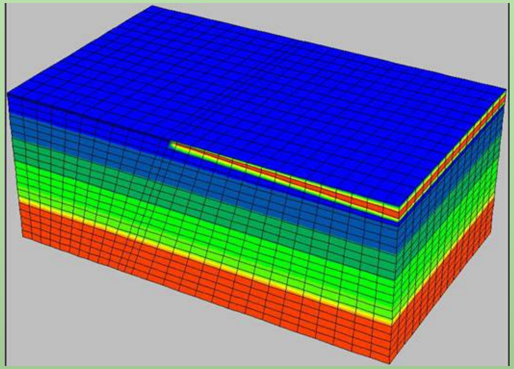
Dilation



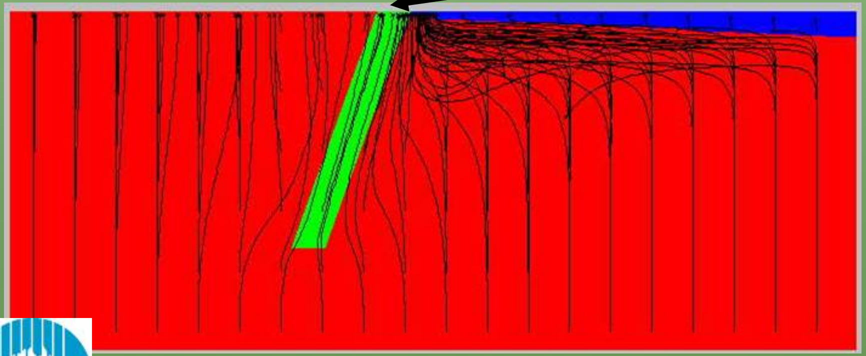
And the next scale again

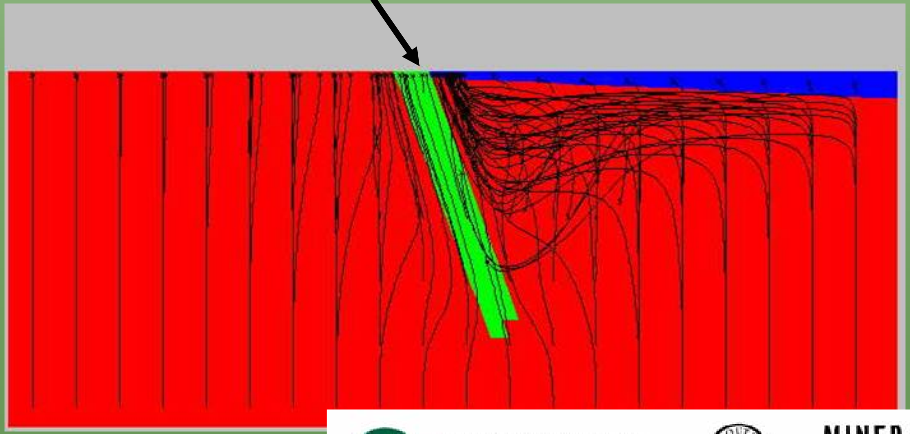




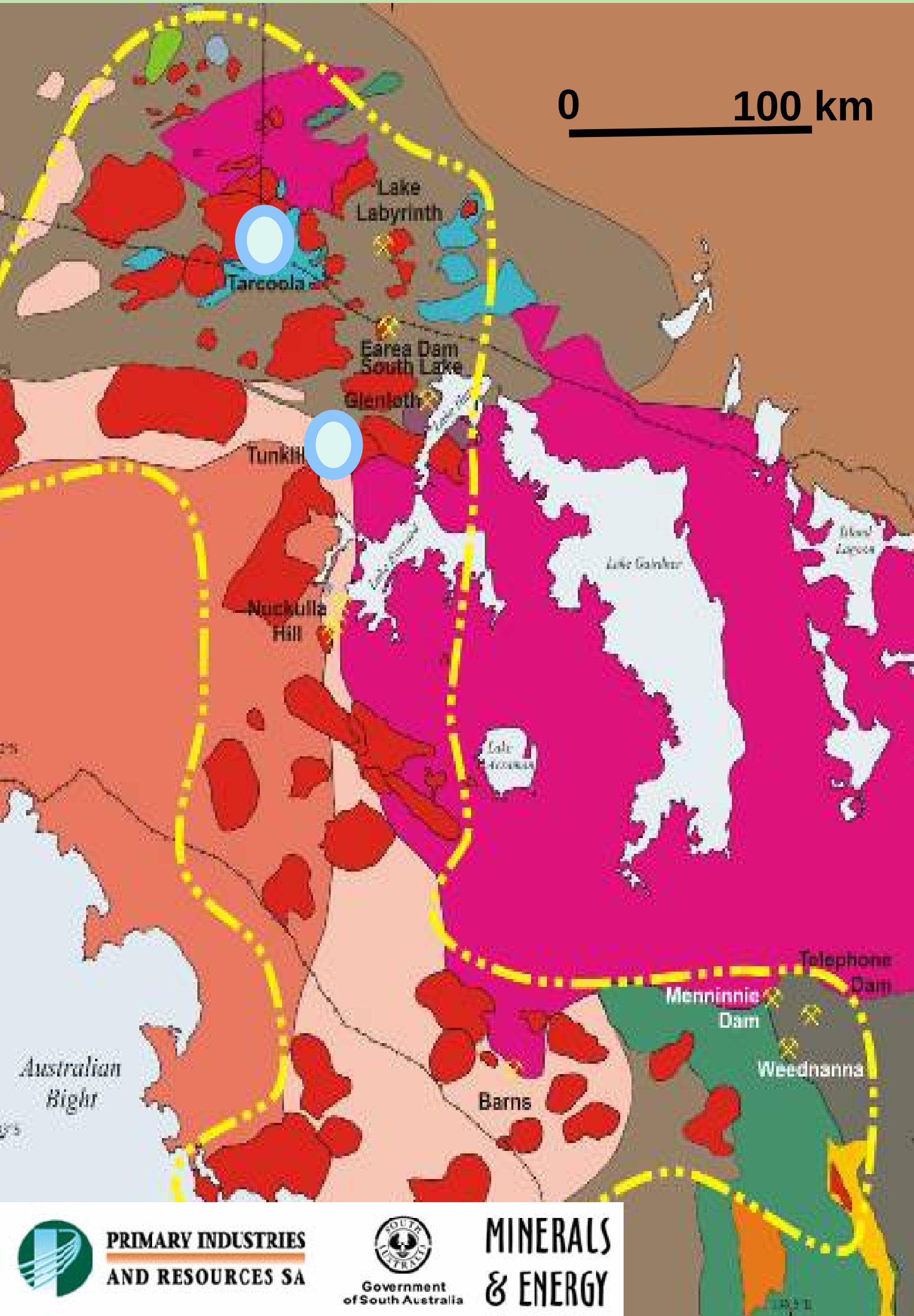


…….where we do not even know the dip of the Yarlbrinda Shear Zone





Yanhua Zhang



GAWLER
The value add?

*pmd*CRC*

- Multiple working hypotheses and little data
- Targeting and focused data acquisition across scale
- Reliability – moderate reliability targets in areas where no targeting method is available
- FAR – method for discriminating numerous calcrete anomalies
- Potential to identify major undiscovered ore system

Conclusions

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- Brittle Domain – hydrothermal ore systems – obvious potential for value-add using deformation/fluid flow/thermal up to terrane scale
- Major strides in reactive transport starting to generate equivalent impact
- Very large efficiency gains leading to application in normal exploration programs
- Research frontier is in the lower crust and mantle and has potential to offer equal assistance to global scale targeting in the future

CSIRO