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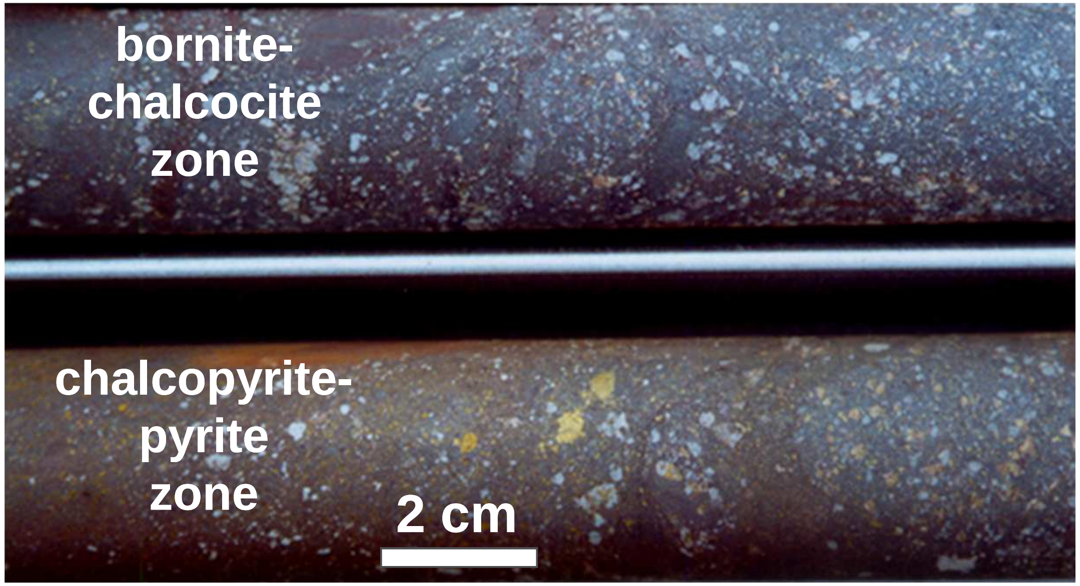
The Olympic IOCG Province (Gawler Craton):
Lithospheric- to district-scale controls on ore formation, and targeting of IOCG mineral systems

Olympic Dam



Roger Skirrow

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(Acknowledgements:
Gawler Project team in GA;
Geological Survey of SA)

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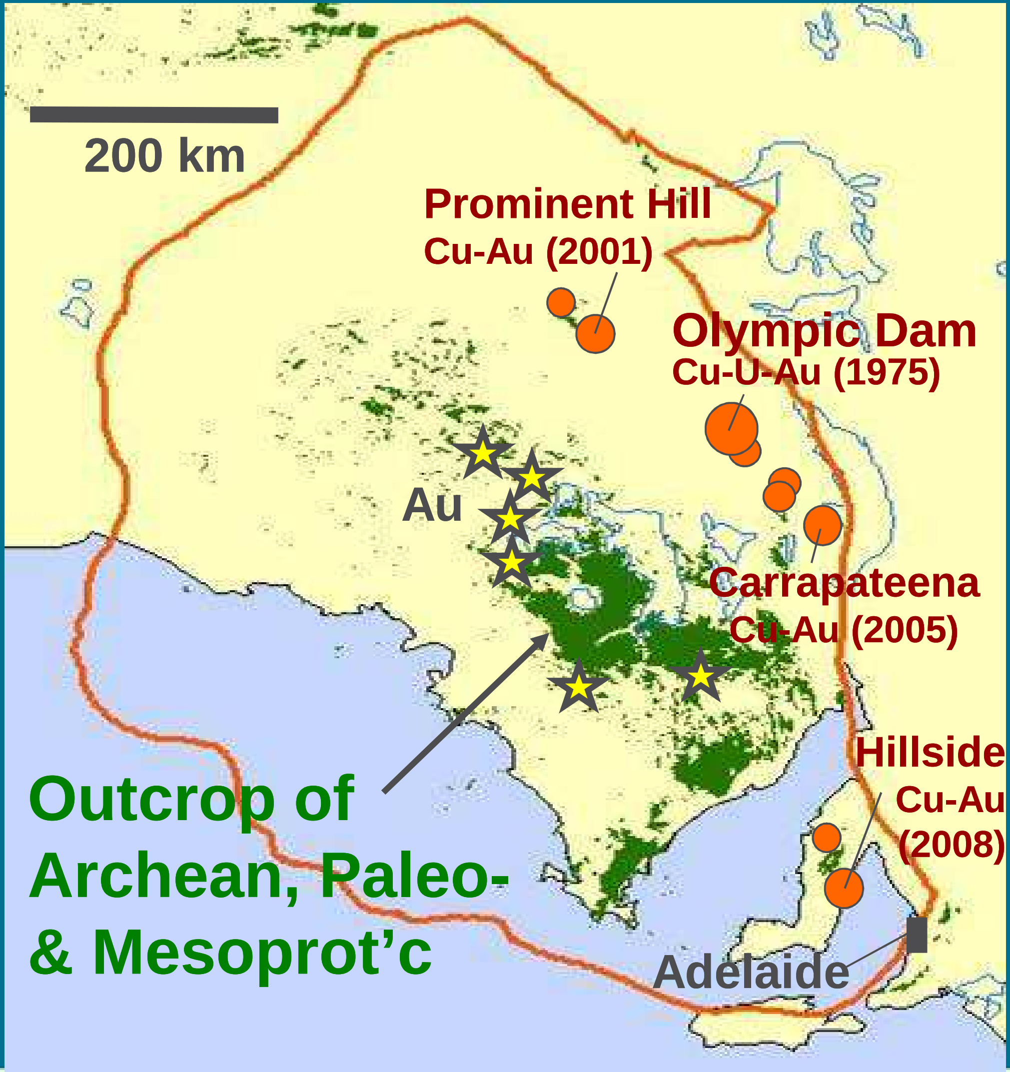
www.ga.gov.au

Gawler Craton: hosting the world's premier IOCG(U) province



Olympic Dam resource:
9.58 billion tonnes @ 0.82% Cu, 0.31 g/t Au, 0.26 kg/tonne U_3O_8, + LREE, Ag
(2013, www.bhpbilliton.com.au)

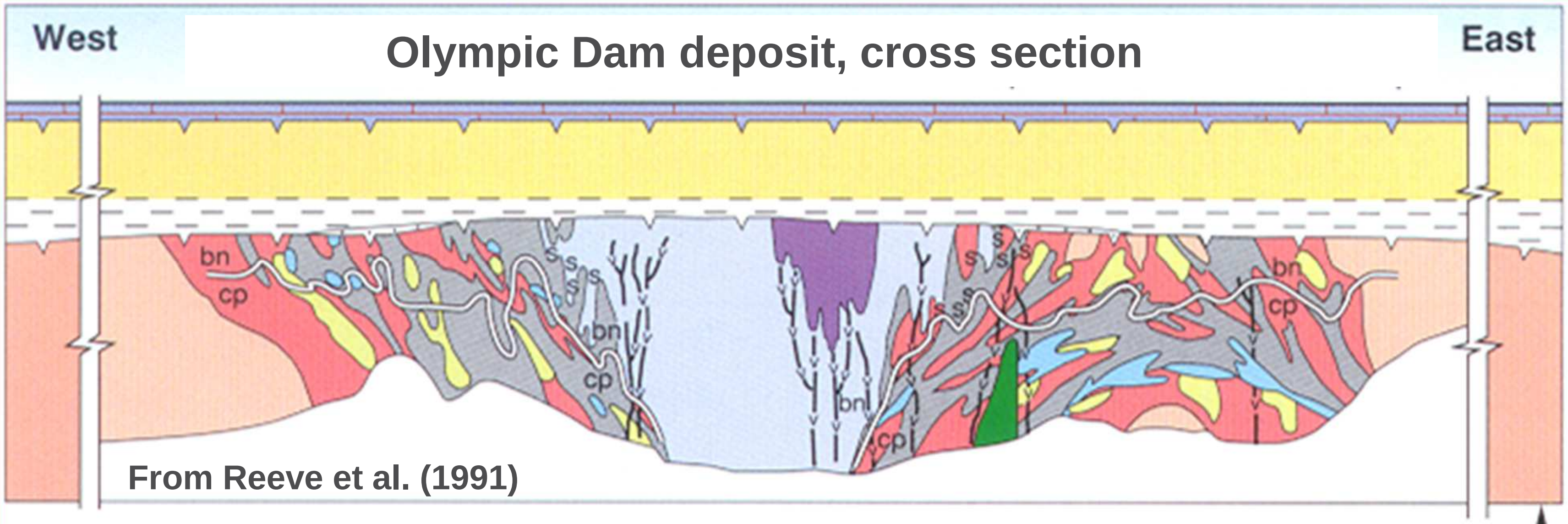
Carrapateena:
760 Mt @ 0.79% Cu, 0.3 g/t Au
(2013, www.ozminerals.com.au)

Prominent Hill:
210 Mt @ 1.2% Cu, 0.5 g/t Au
(2012, www.ozminerals.com.au)

Hillside:
330 Mt @ 0.6% Cu, 0.16 g/t Au
(2012, www.rexminerals.com.au)

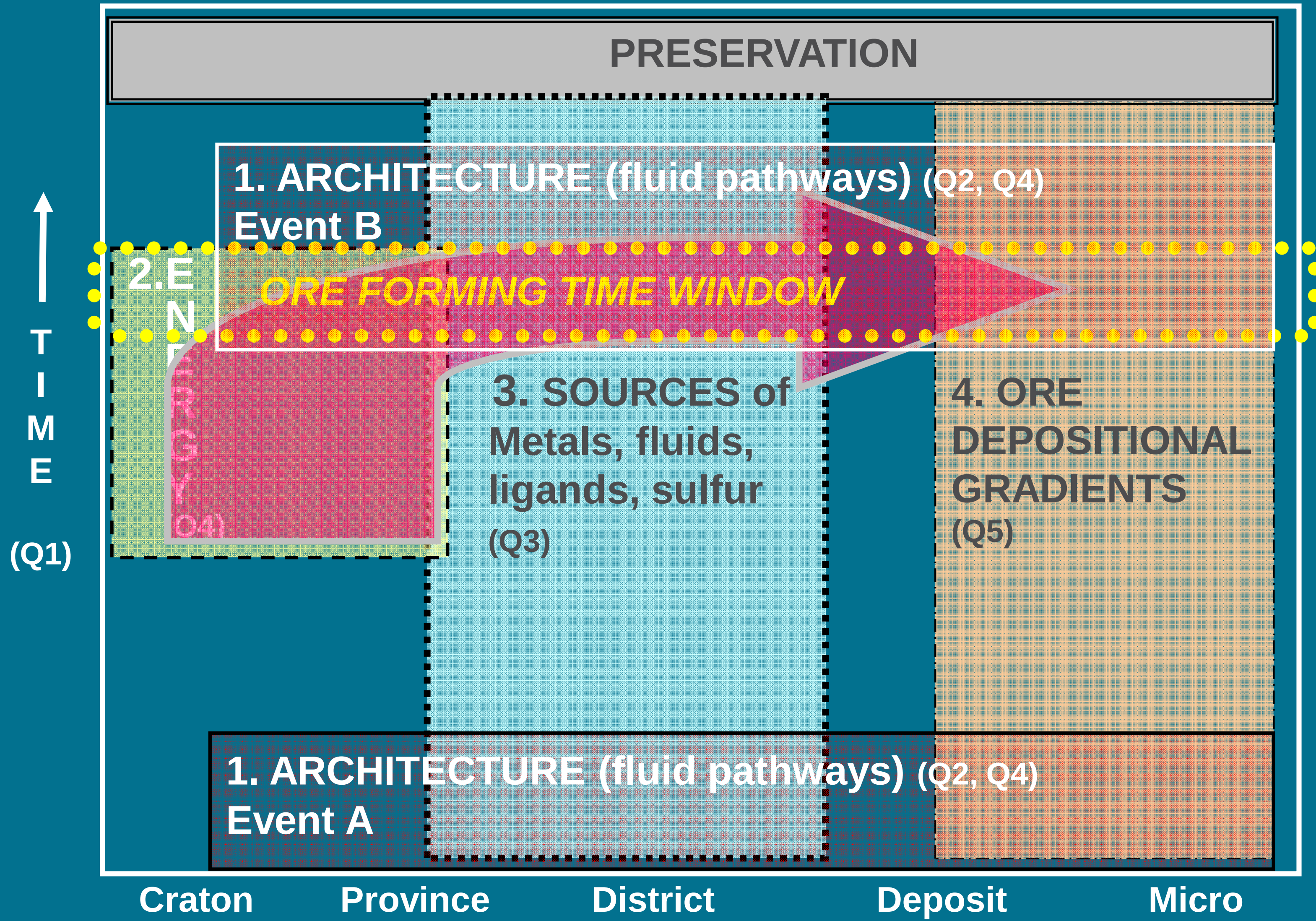
“ . . . it is in the total ore environment that we must seek to recognise critical patterns. Patterns give us features which can be extrapolated and which, therefore, help answer that most vital question, *where to look*”.

(Roy Woodall, 1983, Geoscience Canada)



From Reeve et al. (1991)

MINERAL SYSTEM – geological components



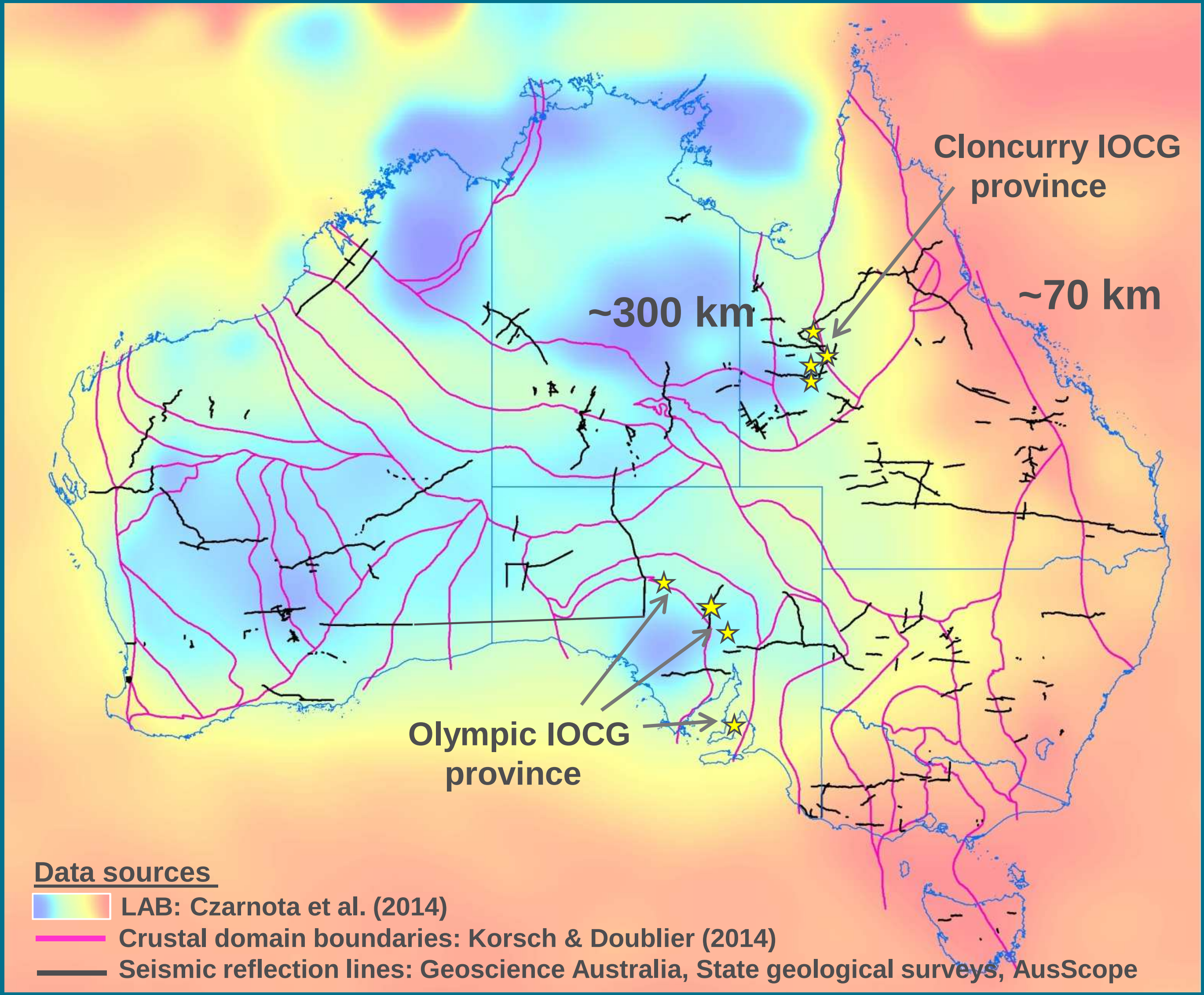
*[Adapted from Five Questions Q1-Q5 of the pmd*CRC and Wyborn et al., 1994]*

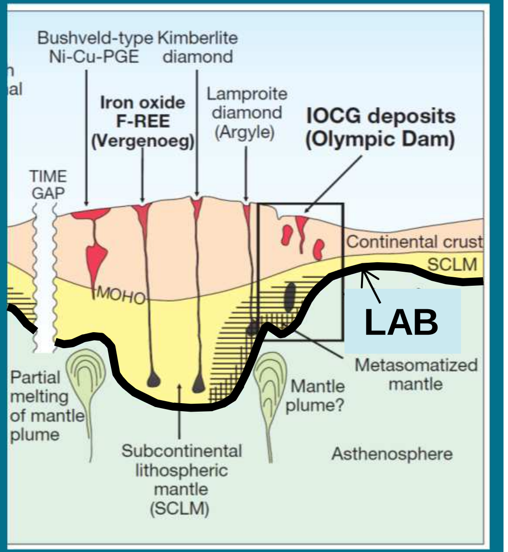
(From Skirrow, 2009, GA Record 2009/40)

1. Lithospheric architecture of IOCG hydrothermal systems

Trans-crustal to trans-lithospheric breaks control IOCG province locations

Lithosphere-asthenosphere boundary (LAB) depth, major crustal domain boundaries, and IOCG deposits



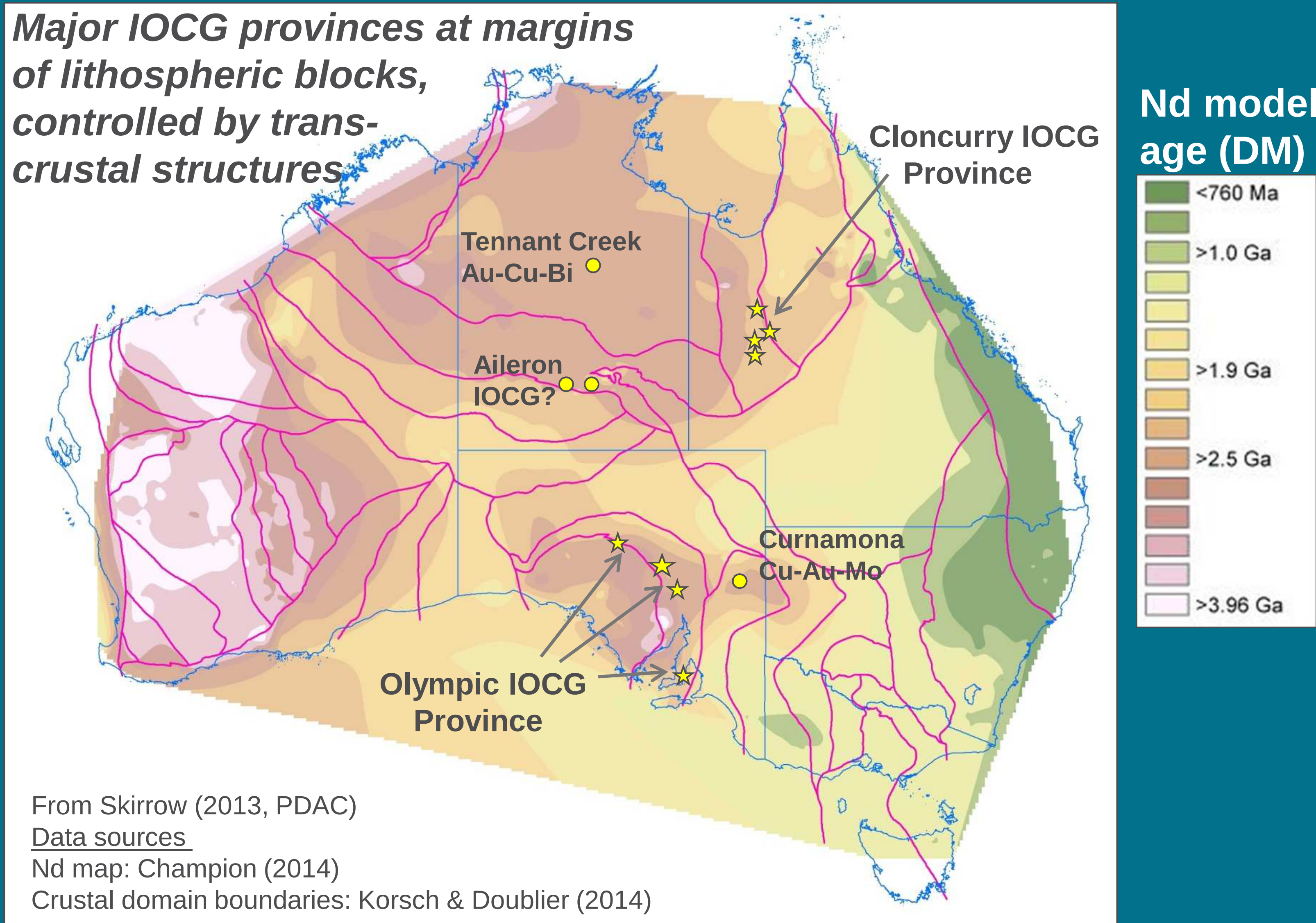


(Groves et al., 2011)

(caveat: image shows present day lithospheric architecture, not necessarily that at times of ore formation)

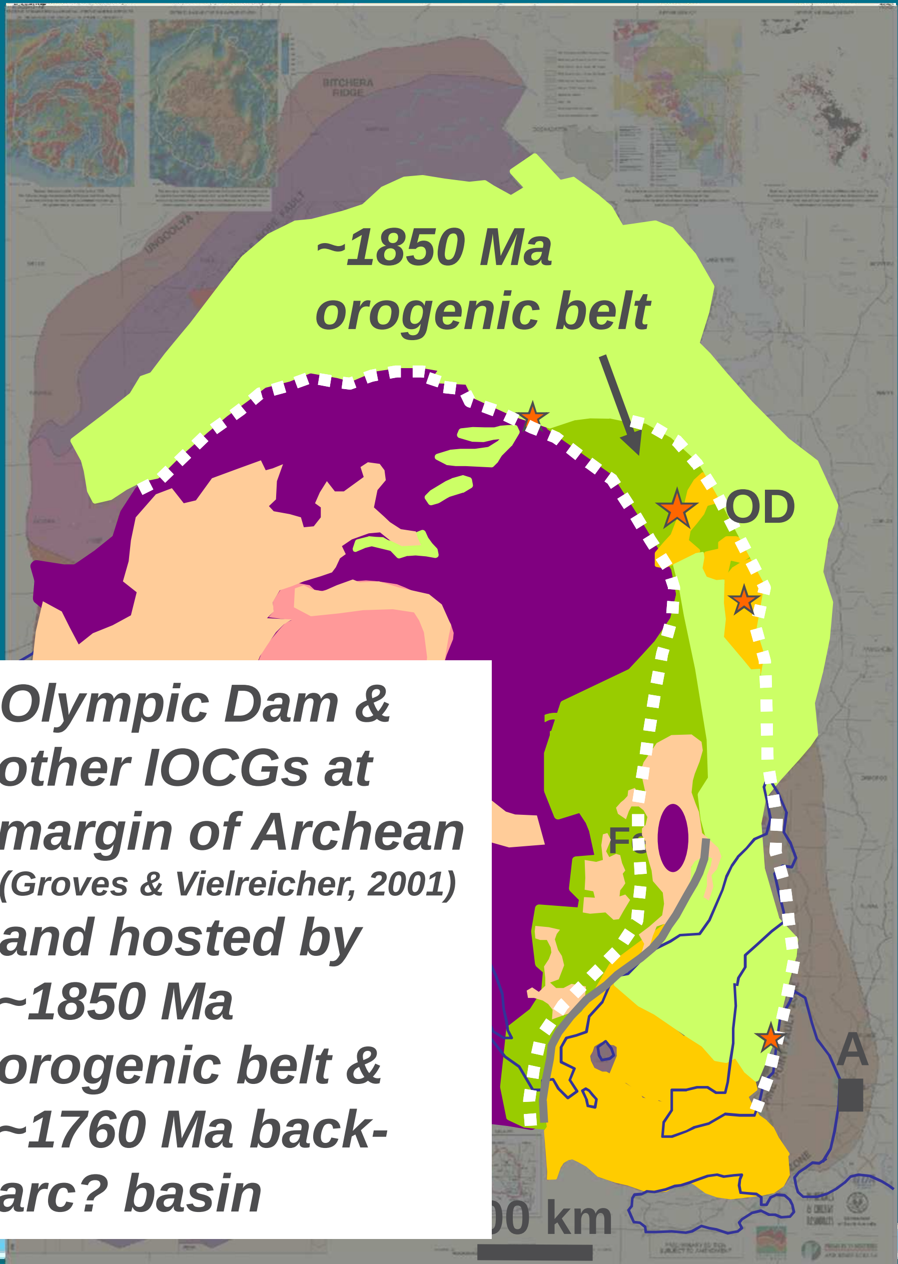
Relative crustal age (based on Nd isotope model ages of granites), major crustal domain boundaries, and IOCG deposits

Major IOCG provinces at margins of lithospheric blocks, controlled by trans-crustal structures



From Skirrow (2013, PDAC)
<u>Data sources</u>
Nd map: Champion (2014)
Crustal domain boundaries: Korsch & Doublier (2014)

Gawler Craton evolution



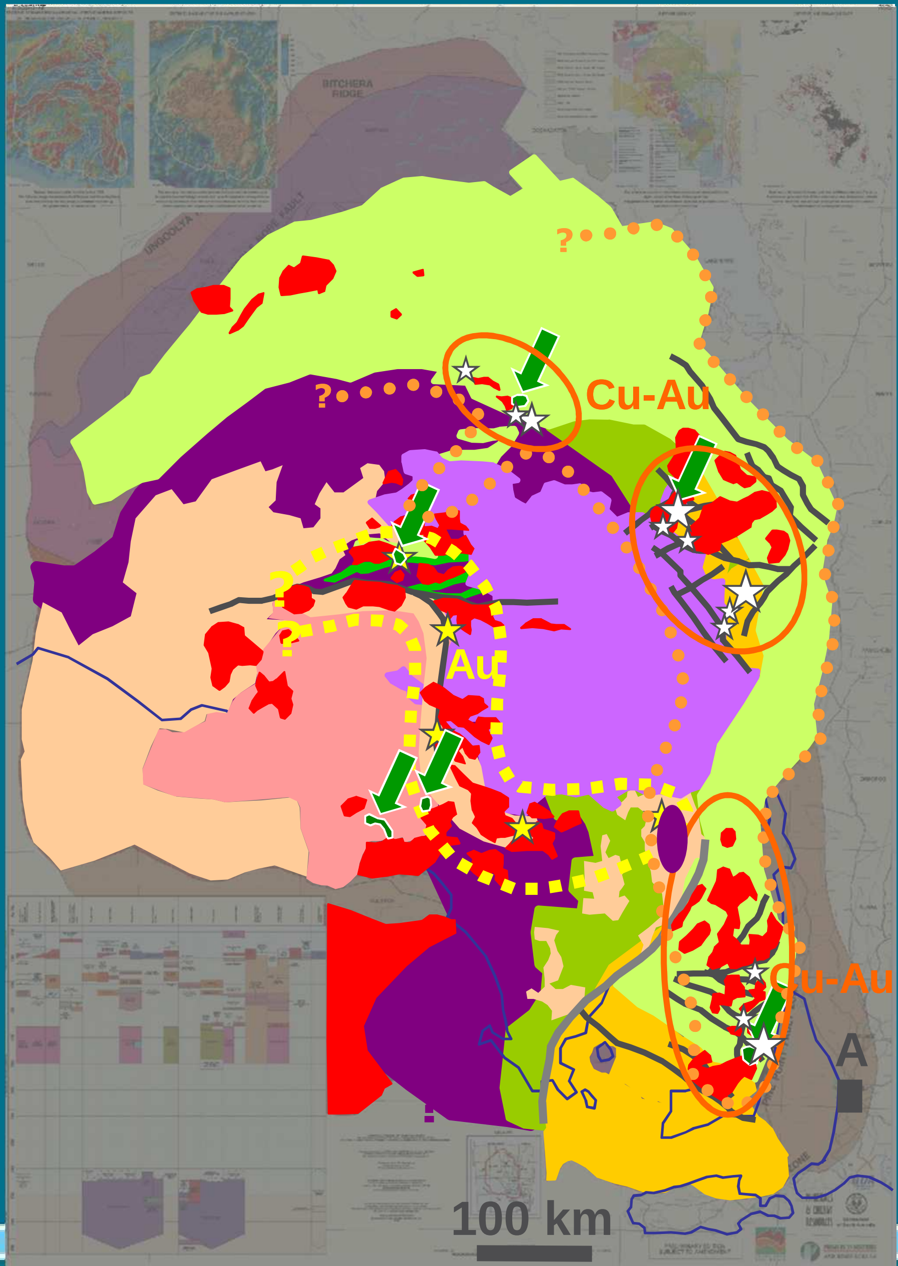
Olympic Dam & other IOCGs at margin of Archean
(Groves & Vielreicher, 2001)
and hosted by ~1850 Ma orogenic belt & ~1760 Ma back-arc? basin

- 3150-2520 Ma: Archean metamorphics including meta-komatiites
- <2000-1850 Ma: BIF, carbonates, siliciclastics; passive margin
- 1850 Ma: granitoids, syn-orogenic
- 1760-1740 Ma: siliciclastics, felsic volcs, BIF; continental margin extension
- ~1720-1670 Ma: granitoid and mafic intrusions, syn-orogenic

shear zone – Kimban Orogeny

- ~1620 Ma: I-type ?arc-like granitoids

Olympic IOCG(U) Province



~1590 Ma: Gawler Range Volcanics (bimodal, mainly felsic, co-magmatic with Hiltaba Suite)

~1595-1575 Ma: Hiltaba Suite granitoids (high-T A- and I-types) and mafic intrusions;

faults

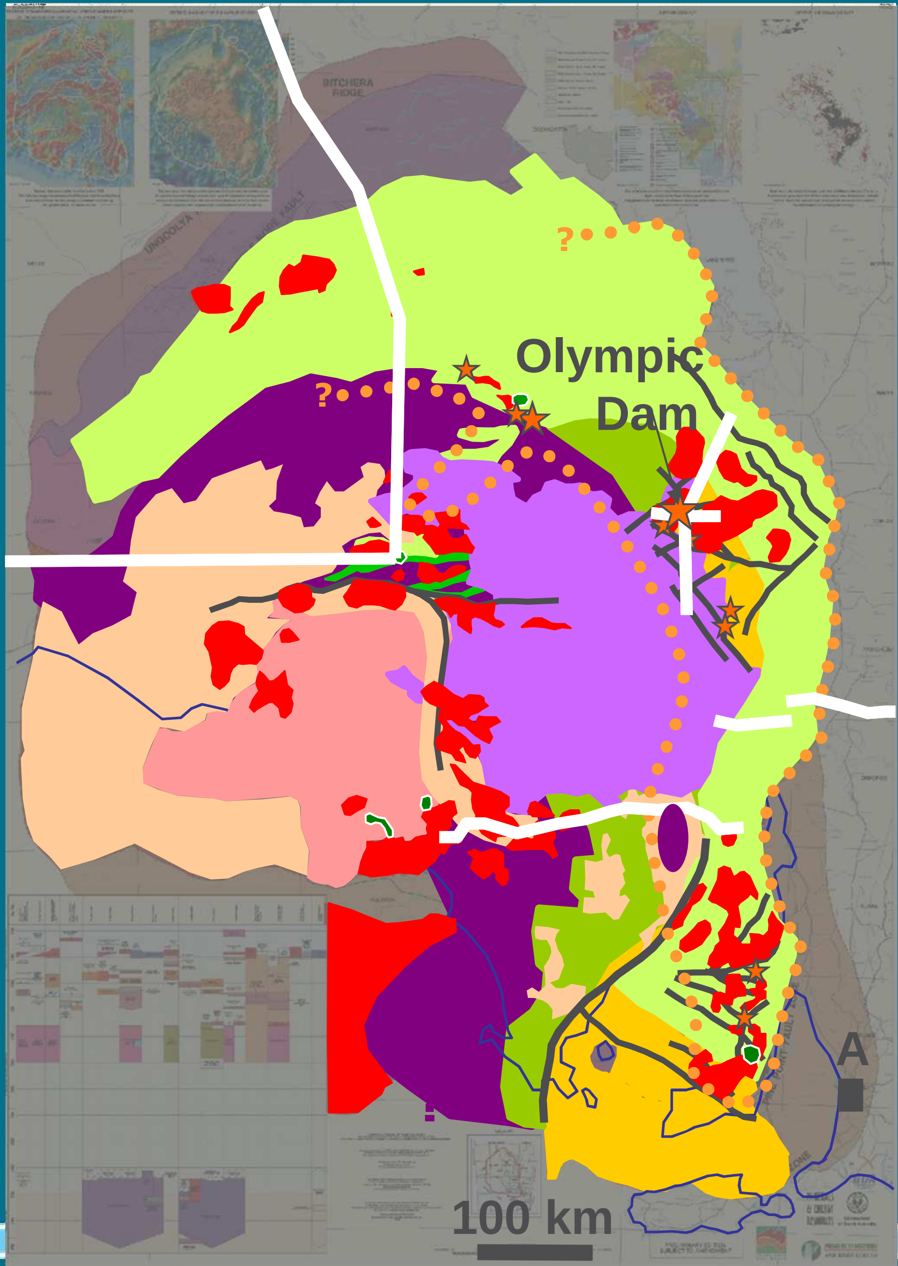
~1595-1575 Ma: Olympic IOCG Province;

3 ‘footprints’ (2002-2006)

~1600-1580 Ma: Central Gawler Au Province

Cu-Au (-U) spatially & temporally assoc’d with <u>some</u> Hiltaba-GRV and mafic-u/maf intrusions

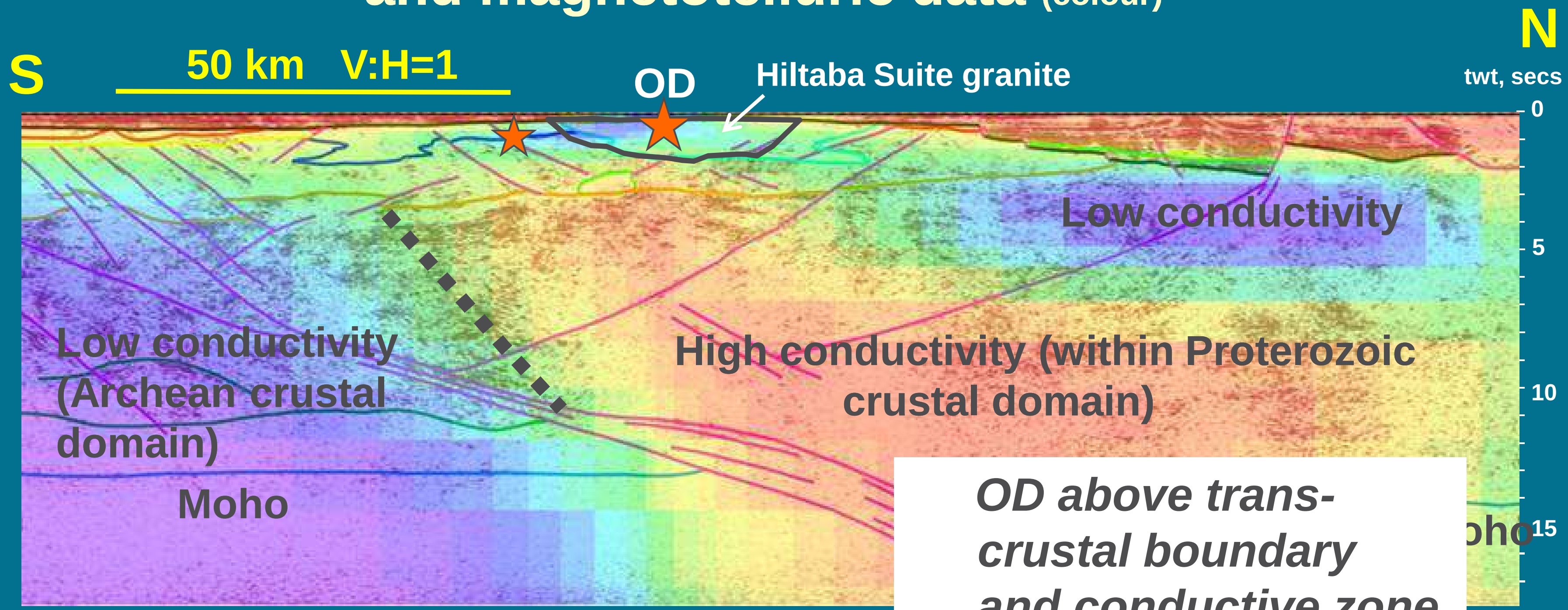
Carrapateena (2005), Hillside (2008)



Deep crustal seismic reflection survey lines 2003-2014, some with magneto-telluric data

(Geoscience Australia, PIRSA/DMITRE, Auscope)

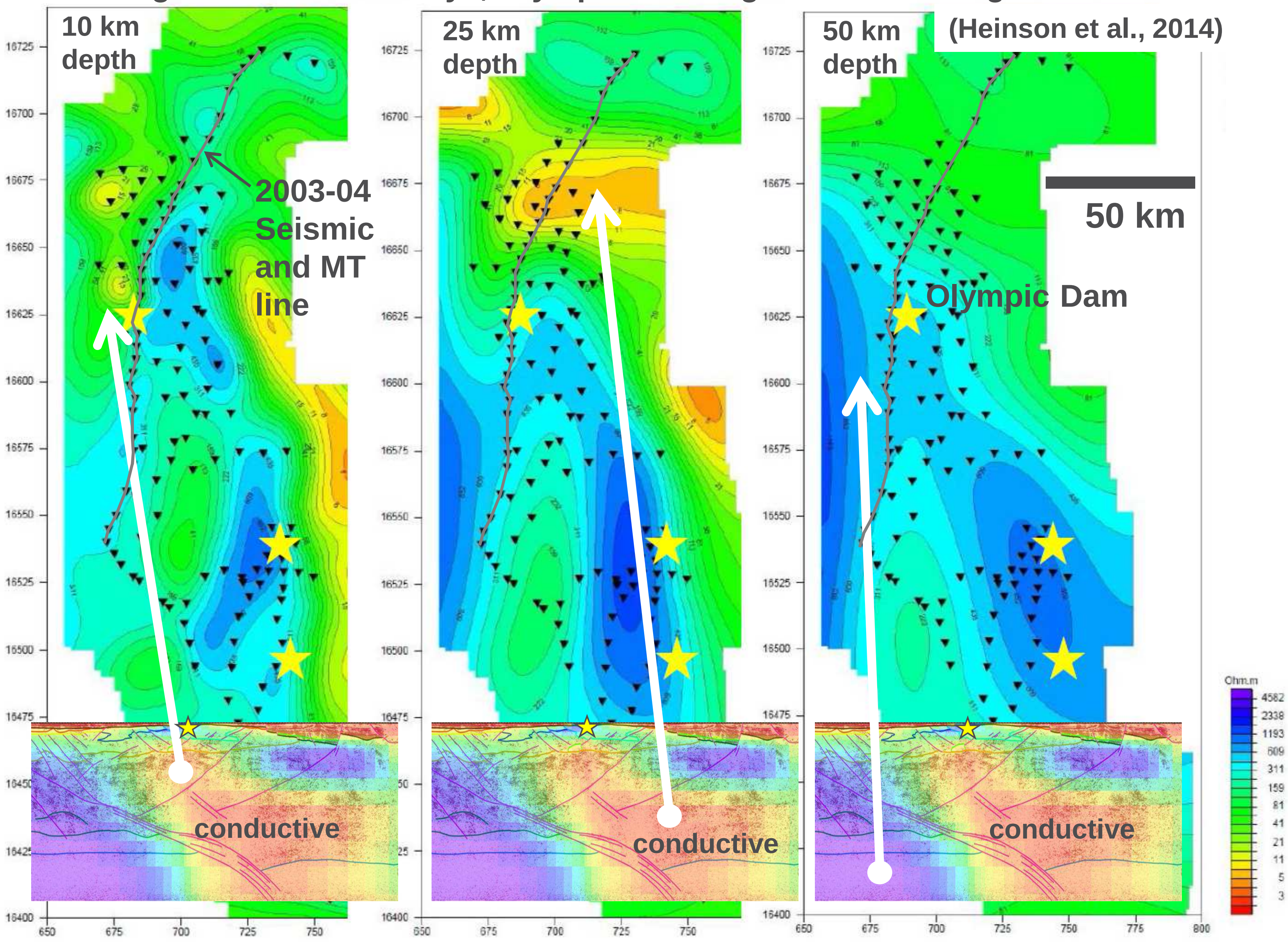
Olympic Dam region crustal architecture: 2003-04 seismic reflection data (greyscale texture) and magnetotelluric data (colour)



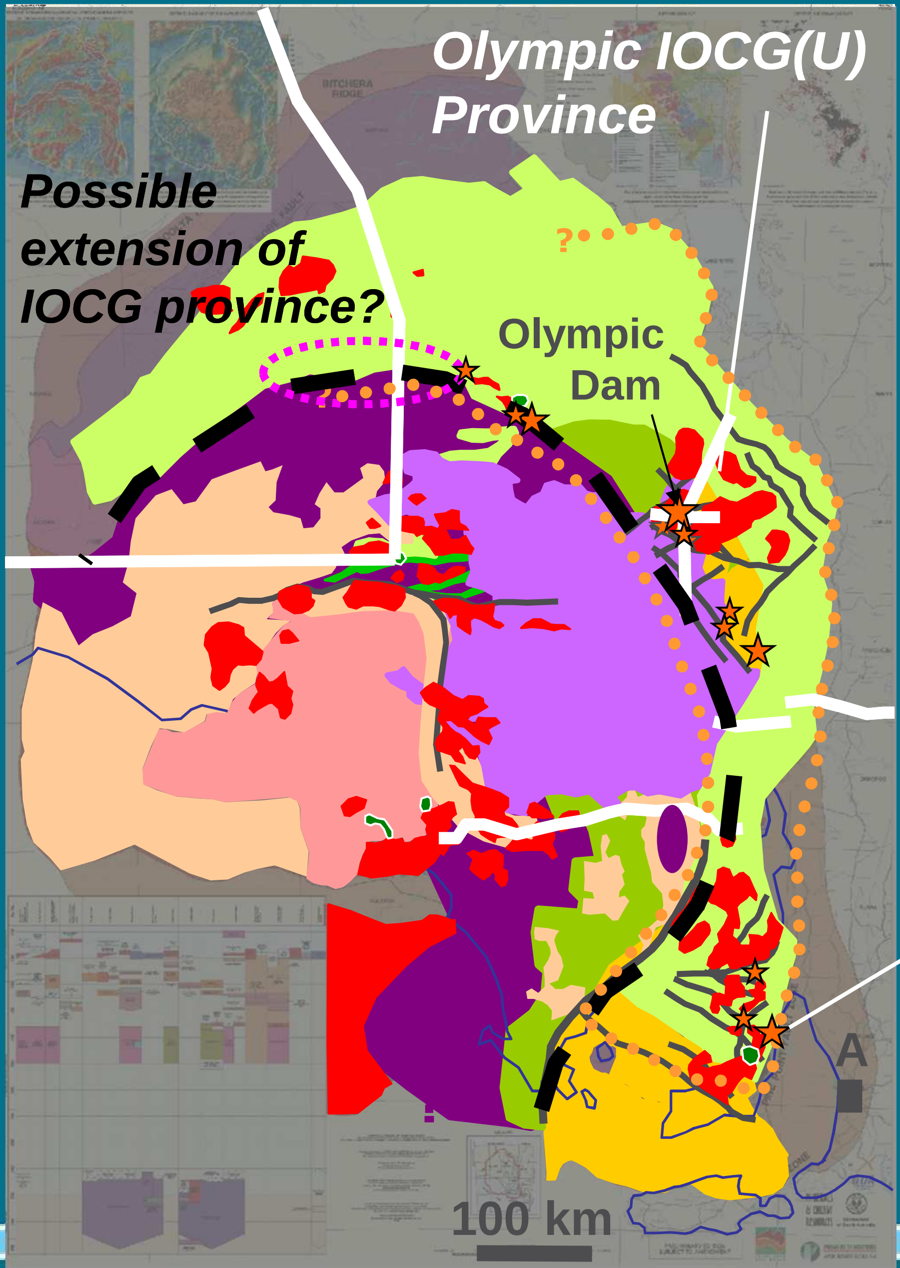
OD above trans-crustal boundary and conductive zone (source unknown)

Coloured MT image courtesy R. Gill, G. Heinson, N. Direen at The University of Adelaide, and published in Thiel et al., (2004), Heinson et al. (2006).
MT image overlays GA-PIRSA seismic data with interpretive linework by GA-PIRSA-UofA (Lyons & Goleby, 2005).

2014: magneto-telluric surveys, Olympic Dam region – confirming 2004 results



Craton-scale controls on IOCGs



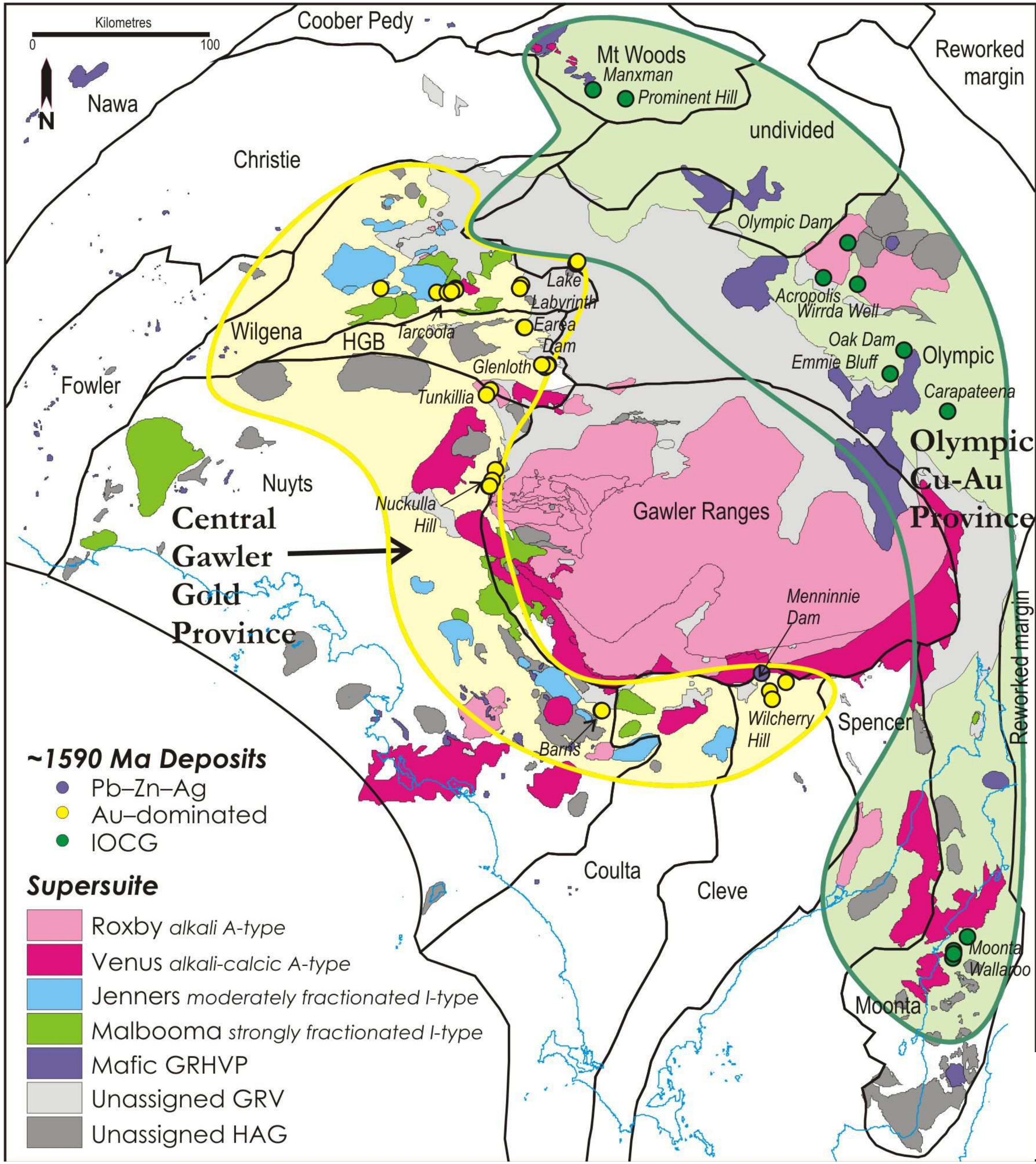
Margin of Archean litho-sphere now mapped in 5 seismic lines, MT, Nd isotope data, and seismic tomo-graphic data.

A fundamental control on location of the IOCG province

Hillside Cu-Au magnetite (-hematite)

2. Energy sources (drivers) for IOCG hydrothermal systems:

Felsic and mafic magmatism of Hiltaba-GRV event (but geodynamic driver unresolved)



Hiltaba Suite – Gawler Range Volcanics magmatism

(~1595-1575 Ma)

- Crustal melts (<30km): high-T A- and I-type granitoids & volcanics
- Mafic & ultramafic intrusions & volcs mainly in east
- Felsics >> mafics (volume), *unlike* most plume-related
- *Not* arc-like magmatic footprint
- Geochemically *unlike* most back-arc magmas;
- Cu-Au-U spatially with higher-T A-types in east
- Au spatially with I-types in west

(Budd, 2005, 2006)

Mantle melts at Wirrda Well Cu-Au deposit

"Post-mineralisation alkaline picrite* dykes"

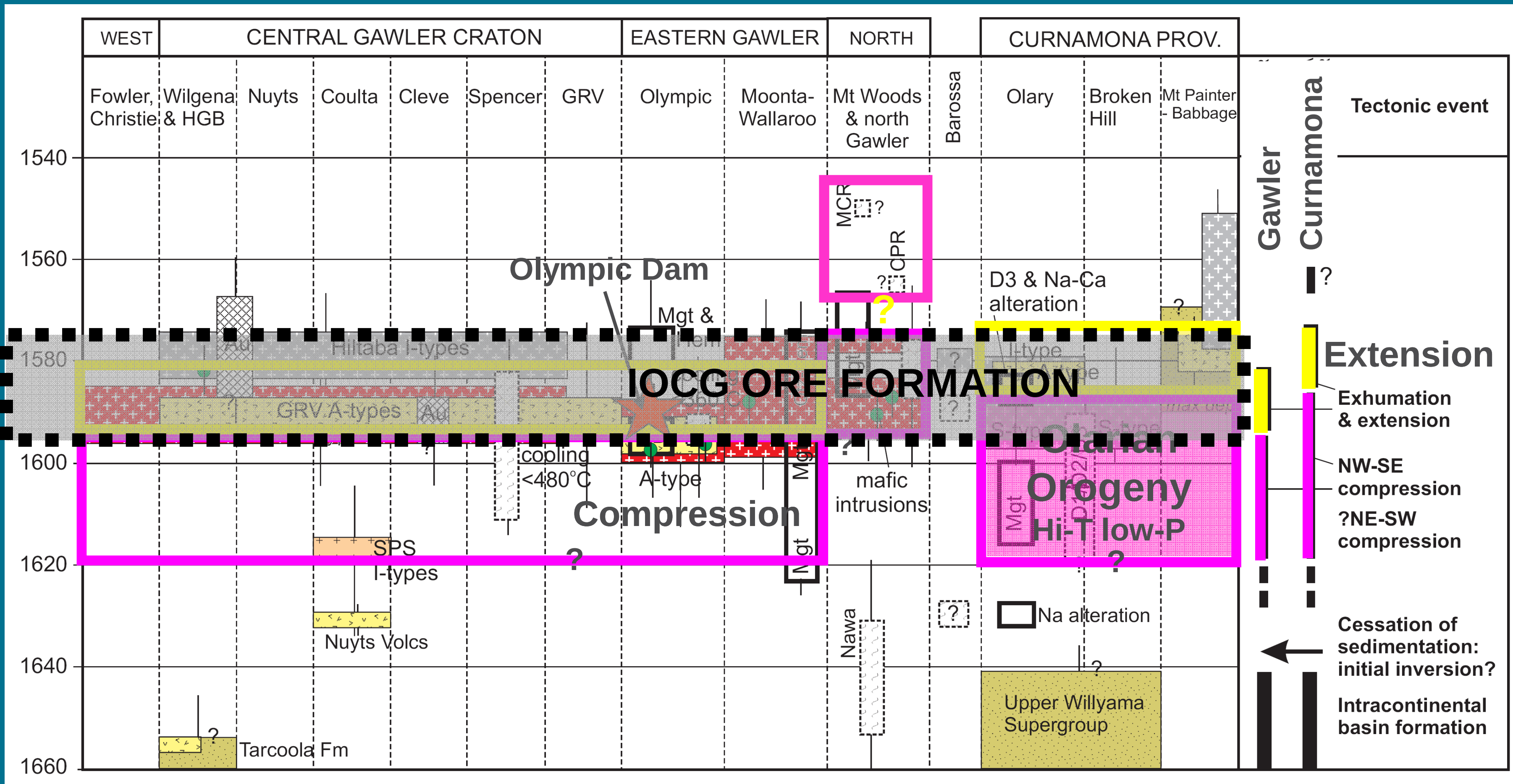
400-500 ppm Cr; chromite inclusions in olivine

Apatite dated ~1590 Ma

Source: BHP Billiton (Ehrig et al., 2013, SA Explorers Conference)

* Picrite has composition between basalt and komatiite

Gawler Craton & Curnamona Province in time and space: The IOCG ore-forming time window 1595-1575 Ma



Widespread compression to extension (diachronous), then compression (north only)

(From Skirrow, 2009, GAC Shortcourse Notes, No. 20)

Proposed IOCG settings at ~1590 Ma:

No shortage of possible geodynamic drivers but any viable model needs to be consistent with tectonic and magmatic evolution

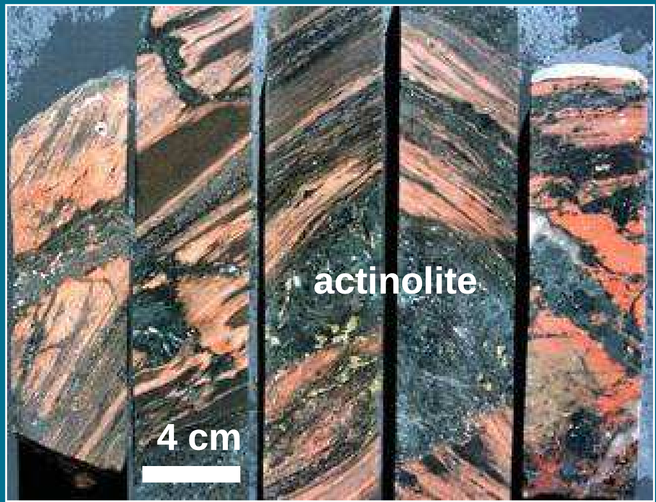
- **Intracontinental rift, anorogenic magmatism (Giles, 1988; Creaser, 1989, 1996; Drexel et al., 1993; Daly et al., 1998; Hitzman, 2000)**
- **Subduction related: continental back-arc:**
  - **Subduction in southwest: Ferris et al. (2002);**
  - **Subduction in north: Wade et al. (2006);**
  - **Subduction in southwest then east: Giles et al. (2004); Betts & Giles (2006)**
  - **Subduction in east: Kositcin et al. (2009)**
- **Subduction zone migrating over mantle plume (Betts, 2004; Betts et al., 2009)**
- **Foreland basin (Hand et al., 2007)**
- **Lithospheric delamination (Skirrow, 2009)**
- **Mantle plume; metasomatised SCLM melting (Groves et al., 2010)**

3. Metal, sulfur and fluid sources in IOCG hydrothermal systems:

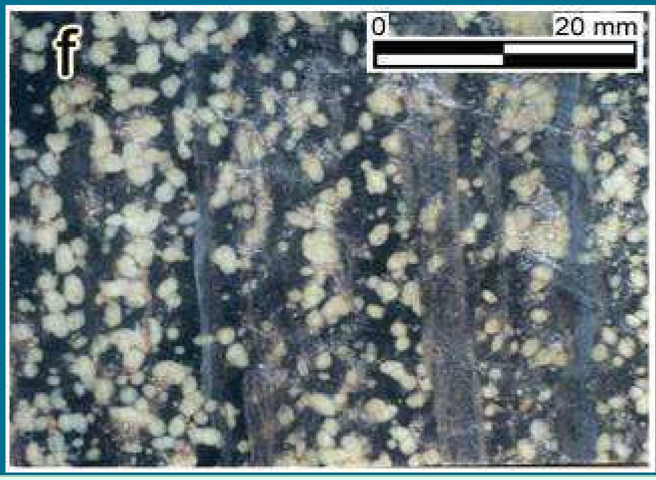
Two fluids necessary, with probable magmatic and non-magmatic inputs

Regional-scale (1) Na-Ca and (2) Fe-K (-Ca) (magnetite-bearing) alteration

Na-Ca (Moonta-Wallaroo)

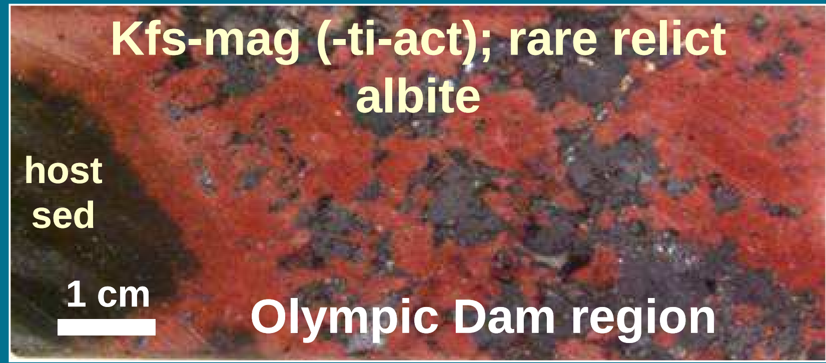


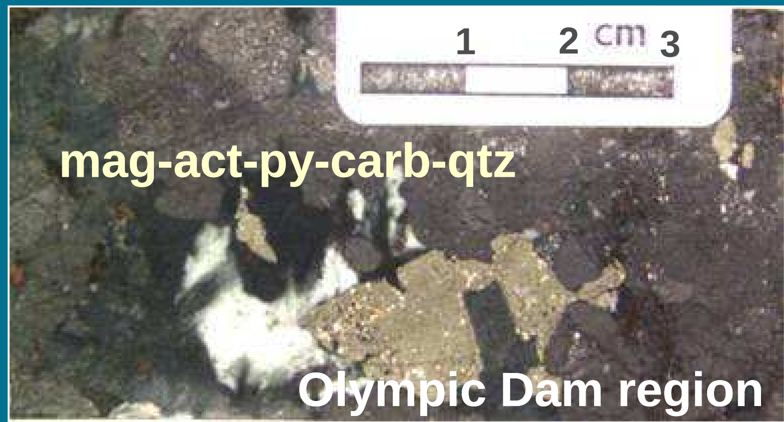
Albitisation along foliation in seds, assoc with actinolite

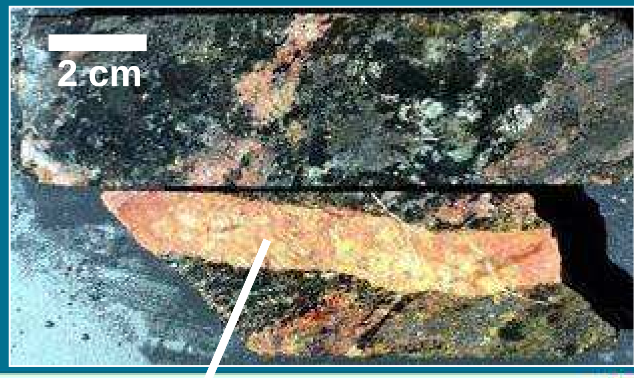


Scapolite (Na-Ca-Cl) alteration of metaseds

Fe-K (-Ca) alteration







Wallaroo: mag-bt & mag-alb + minor chalcopyrite-pyrite

Granite cutting alteration

Hematite-sericite-chlorite-carbonate alteration & Cu-Au-U mineralisation

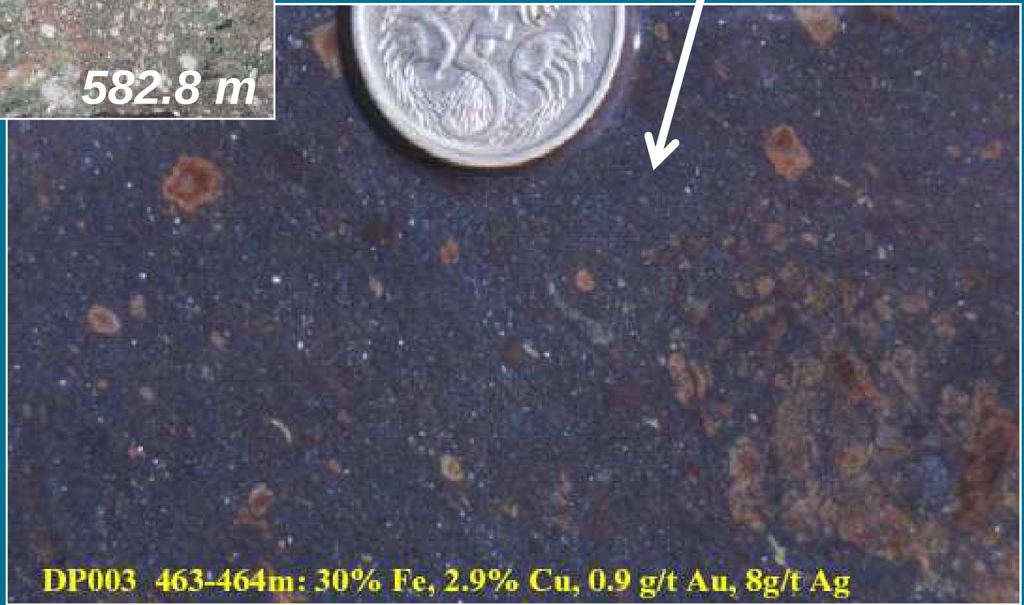
Carrapateena CAR02: 178 m @ 1.83% Cu, 0.6 g/t Au

Breccia of chlorite-hematite-sericite altered granite clasts in hematite-chalcopyrite-bornite-rich matrix
(with traces of relict magnetite)

(photo with permission of TeckCominco; assay results from RMG Services, PACE, 2005)

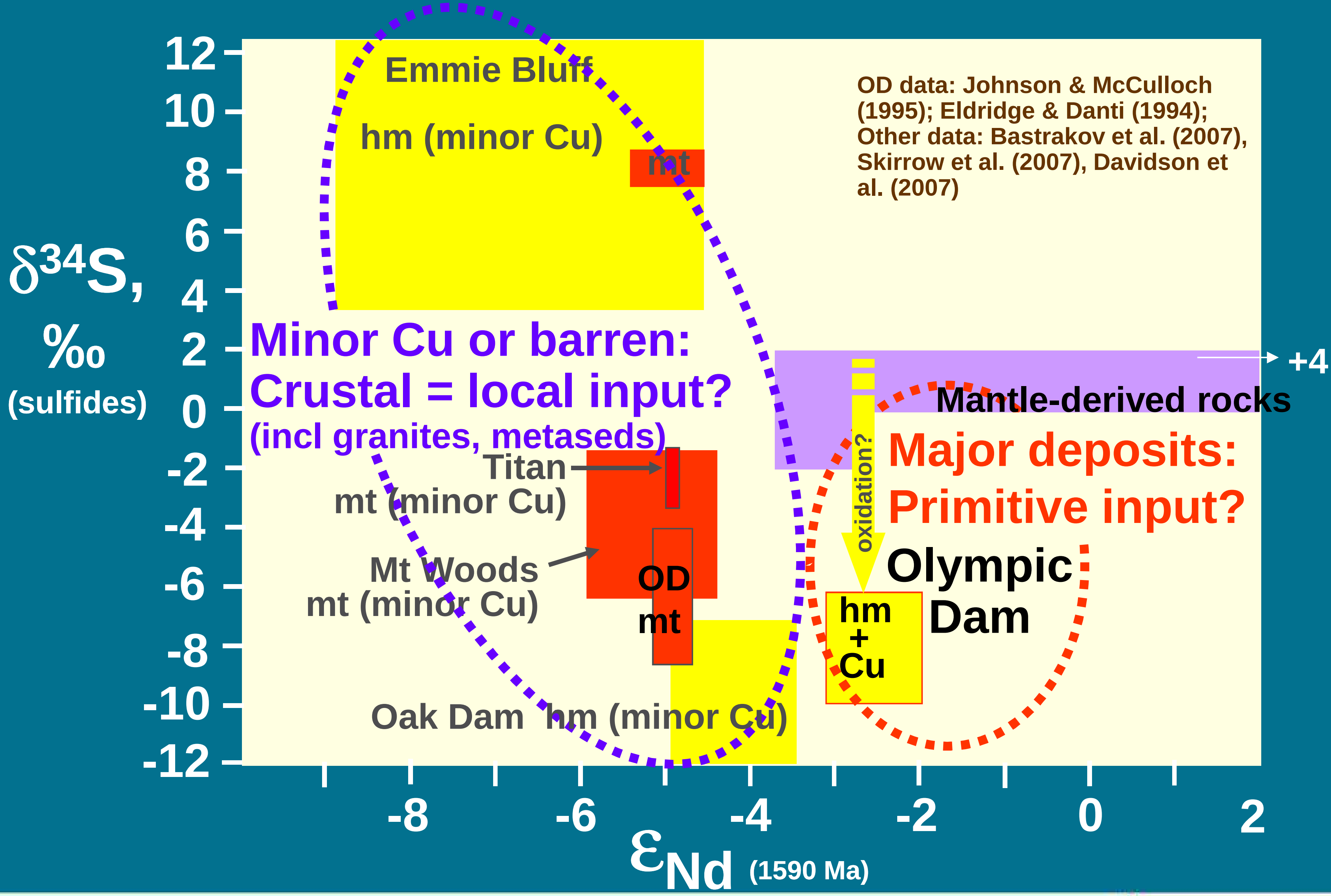
Prominent Hill

Breccia of hematite-sericite altered wallrock, hematite, bornite, chalcocite, Au, U



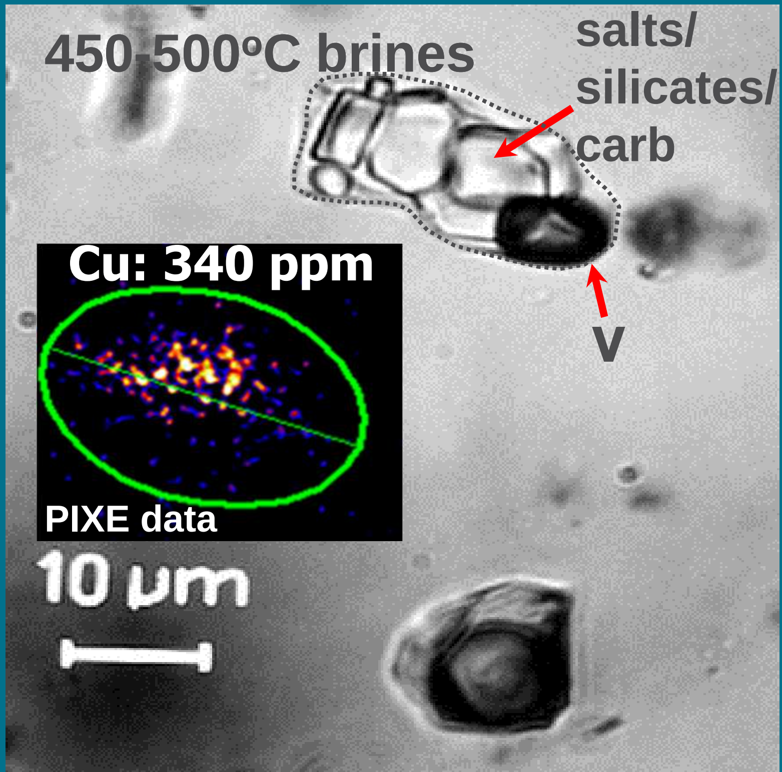
Source: Minotaur Resources website, 2003

Sulfur versus Nd isotopes: distinguishing the giants?



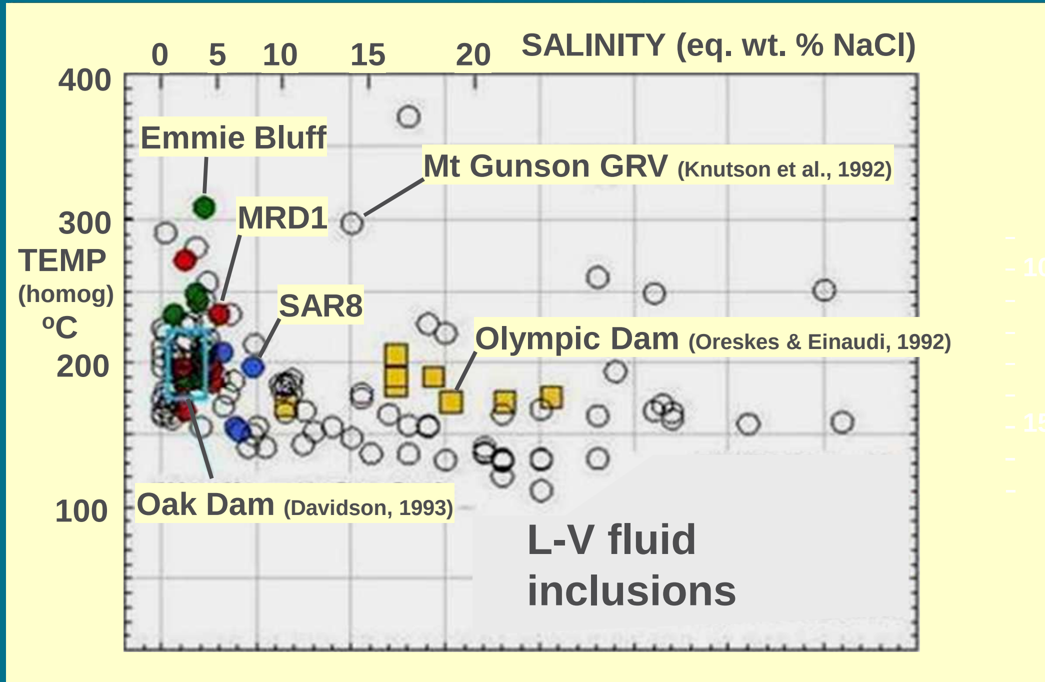
Gawler Craton IOCG fluids

Fluid A: magnetite-related hypersaline hi-temp brine



OD district: fluid inclusions in quartz intergrown with magnetite, K-feldspar, actinolite; minor pyrite, chalcopyrite

Fluid B: hematite-related low-mod temp fluids

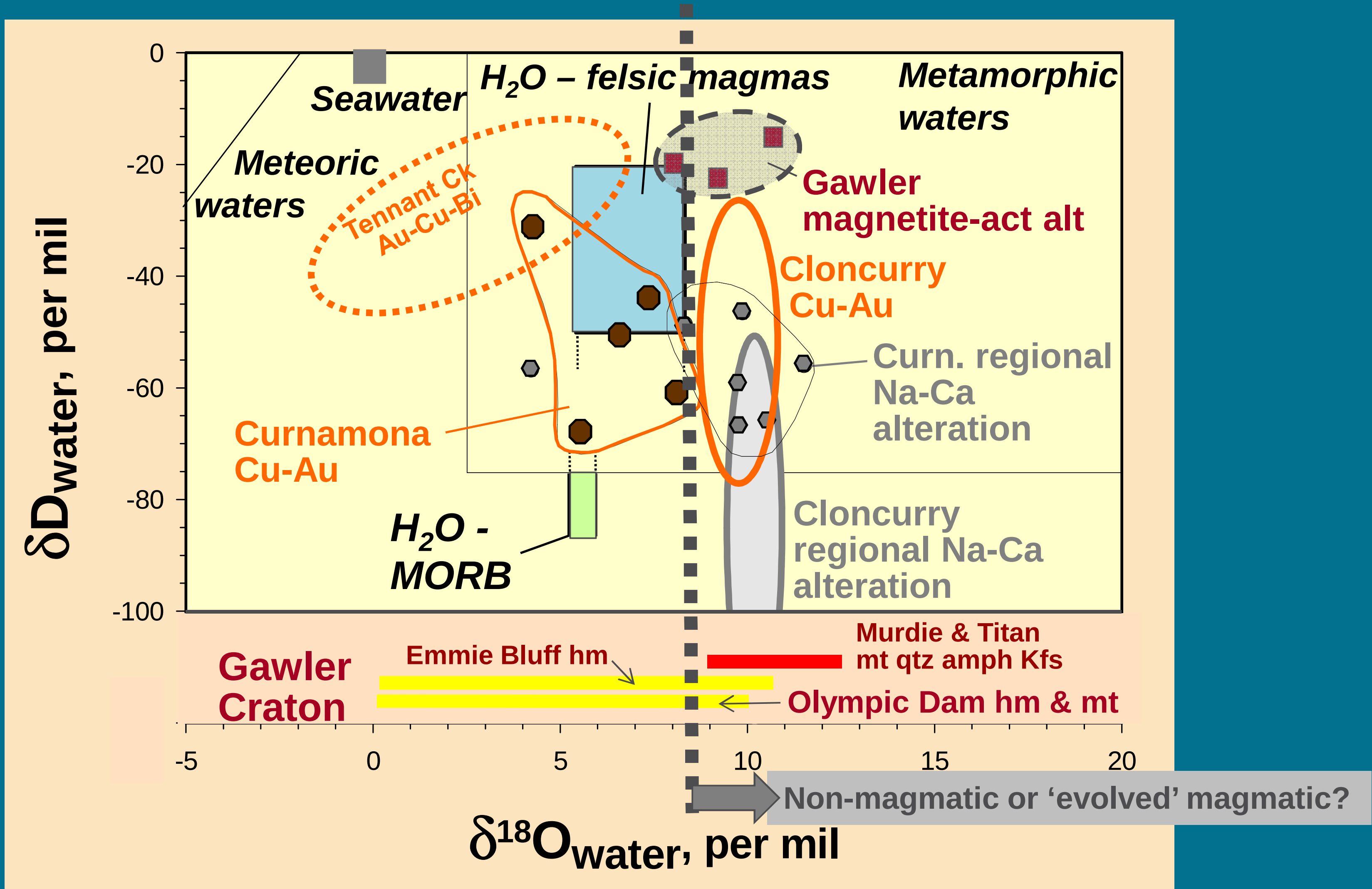


Associated with Cu-Au-U deposition

(from Bastrakov et al., 2007)

Fe-K-Ca and Na-Ca alteration: non-magmatic brines?

Oxygen-hydrogen isotopes: Australian IOCG systems



Reference fields from Taylor (1986), Sheppard (1986); Cloncurry fields from Mark et al. (2001); Olary data from Skirrow et al. (2000); Tennant Creek data from Wedekind (1990), Skirrow (1993); Gawler data from Gow (1996), Oreskes & Einaudi (1992), Bastrakov et al. (2007)

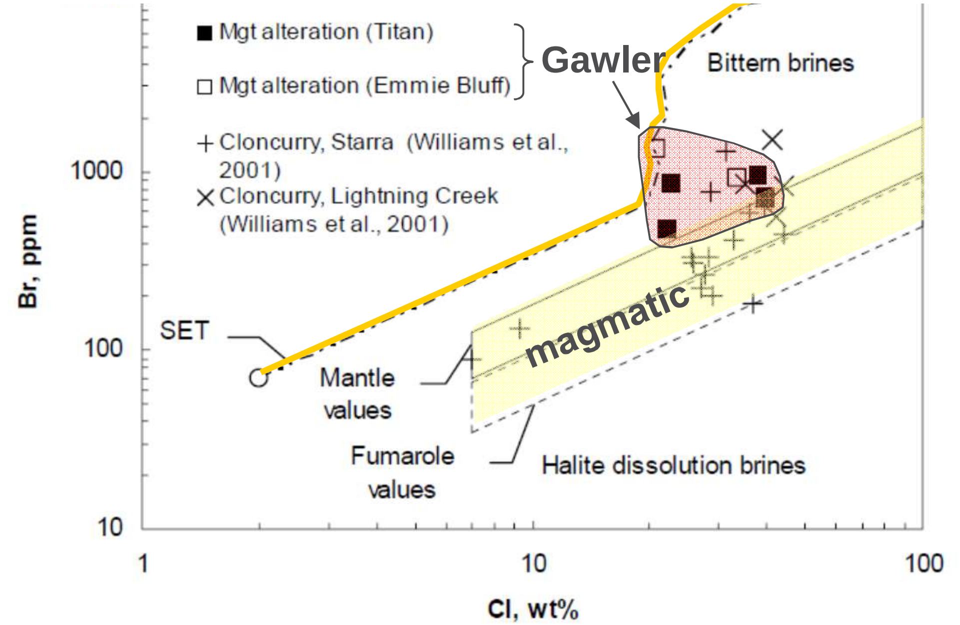
Halogen origins in IOCG hypersaline brines

Gawler Craton, Cloncurry and Carajás (Brazil) districts: variable magmatic AND non-magmatic inputs

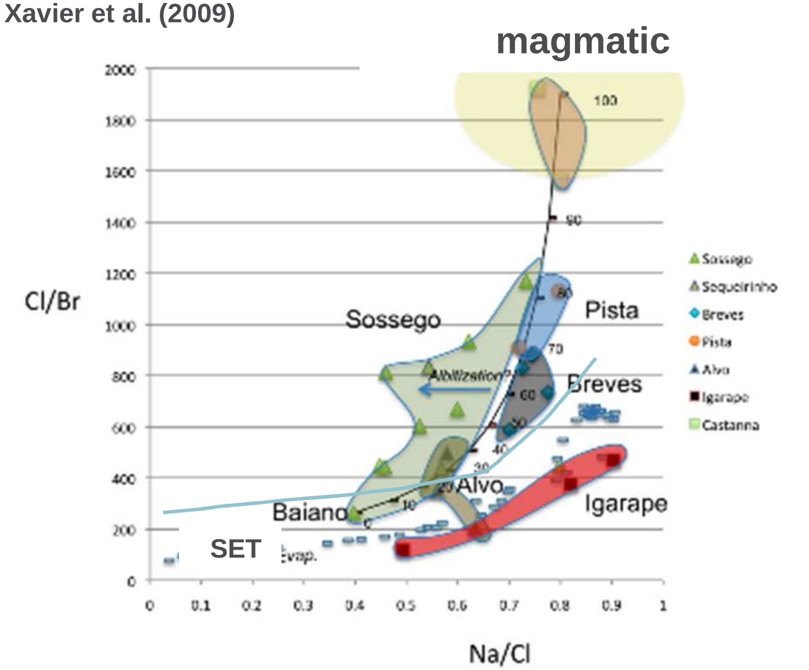
Gawler Craton IOCG fluid A origin: bittern brines ± magmatic halogen contributions; Cloncurry IOCG- & magnetite-related brine origins: magmatic and bittern brines

Carajás: variable mixing between magmatic fluids and bittern brines suggested to have formed the range of deposits

PIXE analyses of fluid inclusions:
Williams et al. (2001), Bastrakov et al. (2007)

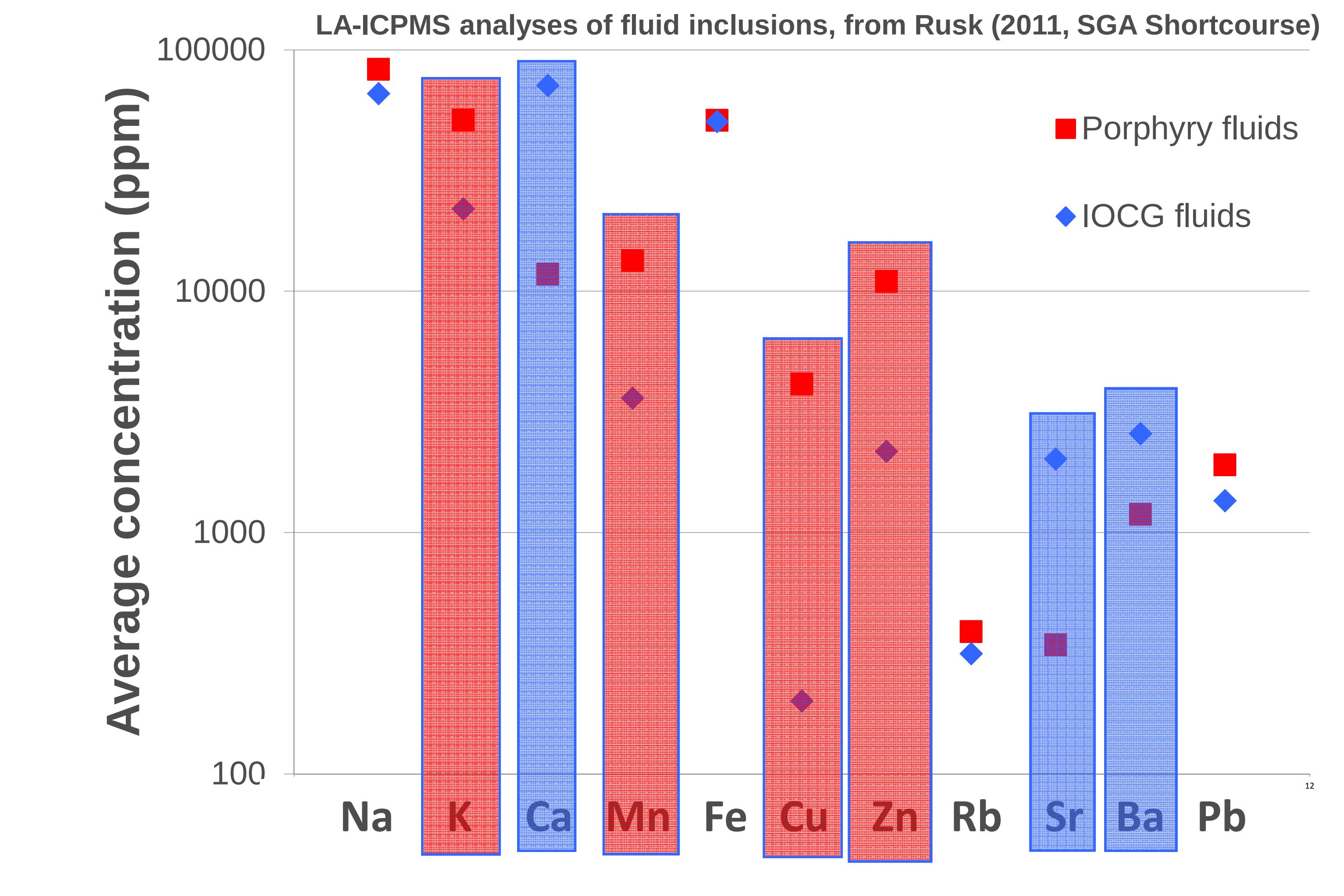


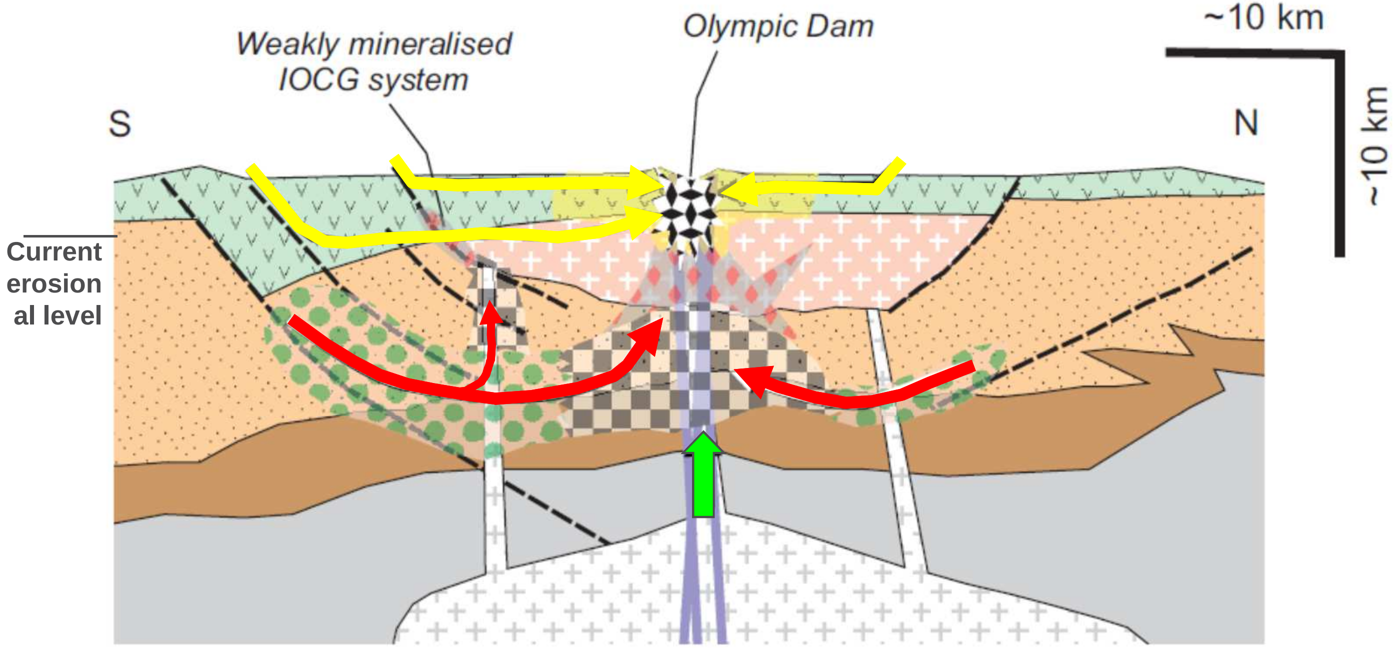
ICPMS analyses of fluid inclusions:
Xavier et al. (2009)



Porphyry Cu and IOCG brine compositions differ

IOCG brines from Carajás deposits are strongly enriched in Ca, Sr and Ba and strongly depleted in K, Cu, Zn, and Mn relative to porphyry Cu brines.





Zoned IOCG(U) system – crustal scale

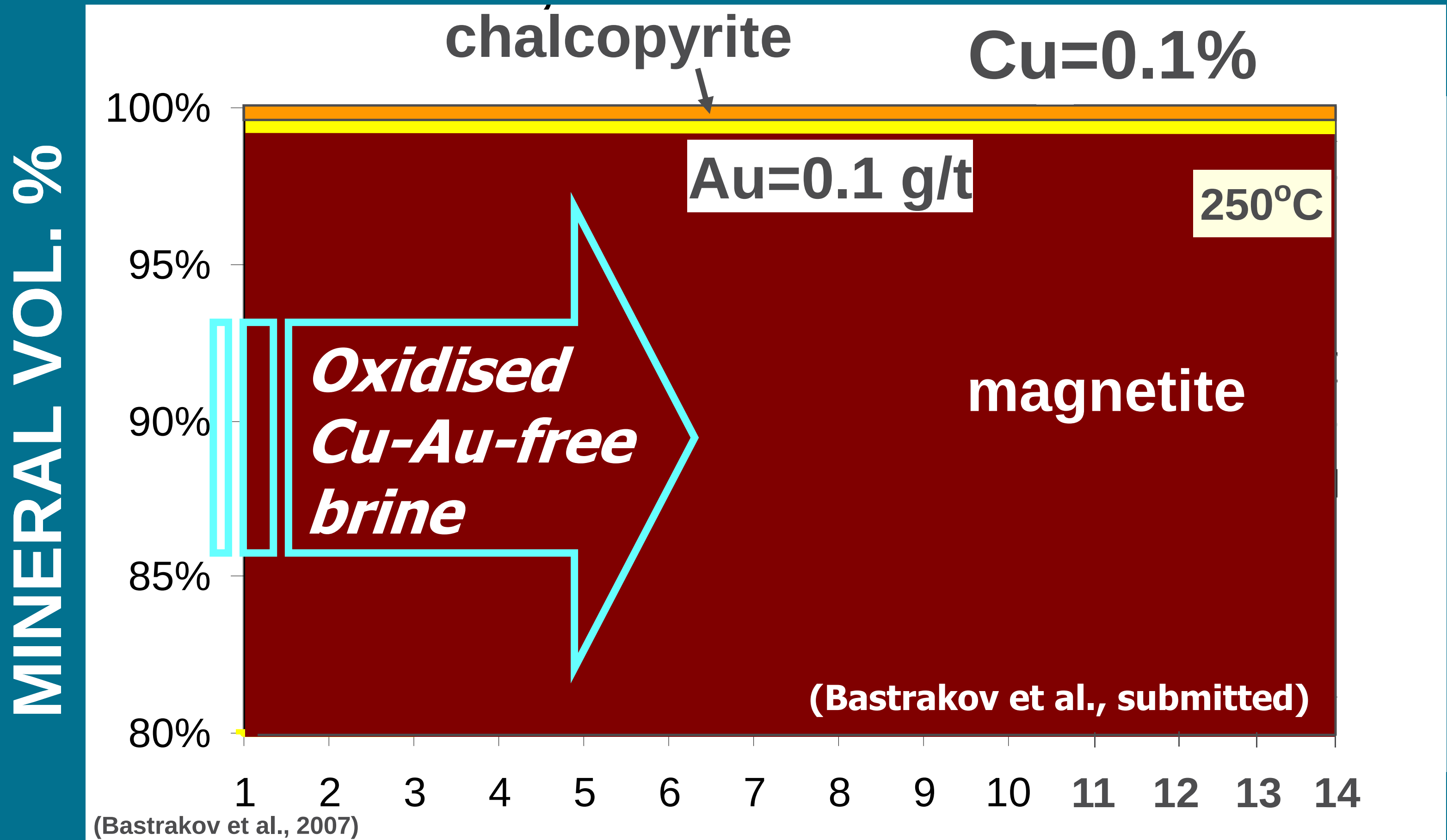
- Gawler Range Volcanics (felsic and mafic)
- Hiltaba Suite (granite); mafic/ultramafic dykes
- Paleoproterozoic continental margin or rift packages
- Archean(?) to Paleoproterozoic - partly mafic
- Archean(?) to Paleoproterozoic - undifferentiated
- Crustal melting zone with feeders to Hiltaba Suite
- Fault
- Cu-Au-U mineralisation & breccia
- Hypersaline fluids carrying Fe, K, Cu, Au, ± H_2S
- Magmatic volatiles & brine (CO_2, SO_2/H_2S, F, P, Fe)
- Heated groundwaters: very oxidised, carrying SO_4^{2-}, Cu, U, Au, REE
- Na-Ca (albite-calcsilicate) alteration: leaching of Fe, K, Cu, Au by brines
- Fe^{2+}-K (magnetite-biotite) alteration
- Fe^{2+}-K ± CO_2 (magnetite-Kfeldspar±carb) alteration: minor Cu-Au
- Fe^{3+}-OH-CO_2 (hematite-sericite-chlorite-carbonate) alteration

From Hayward & Skirrow (2011)

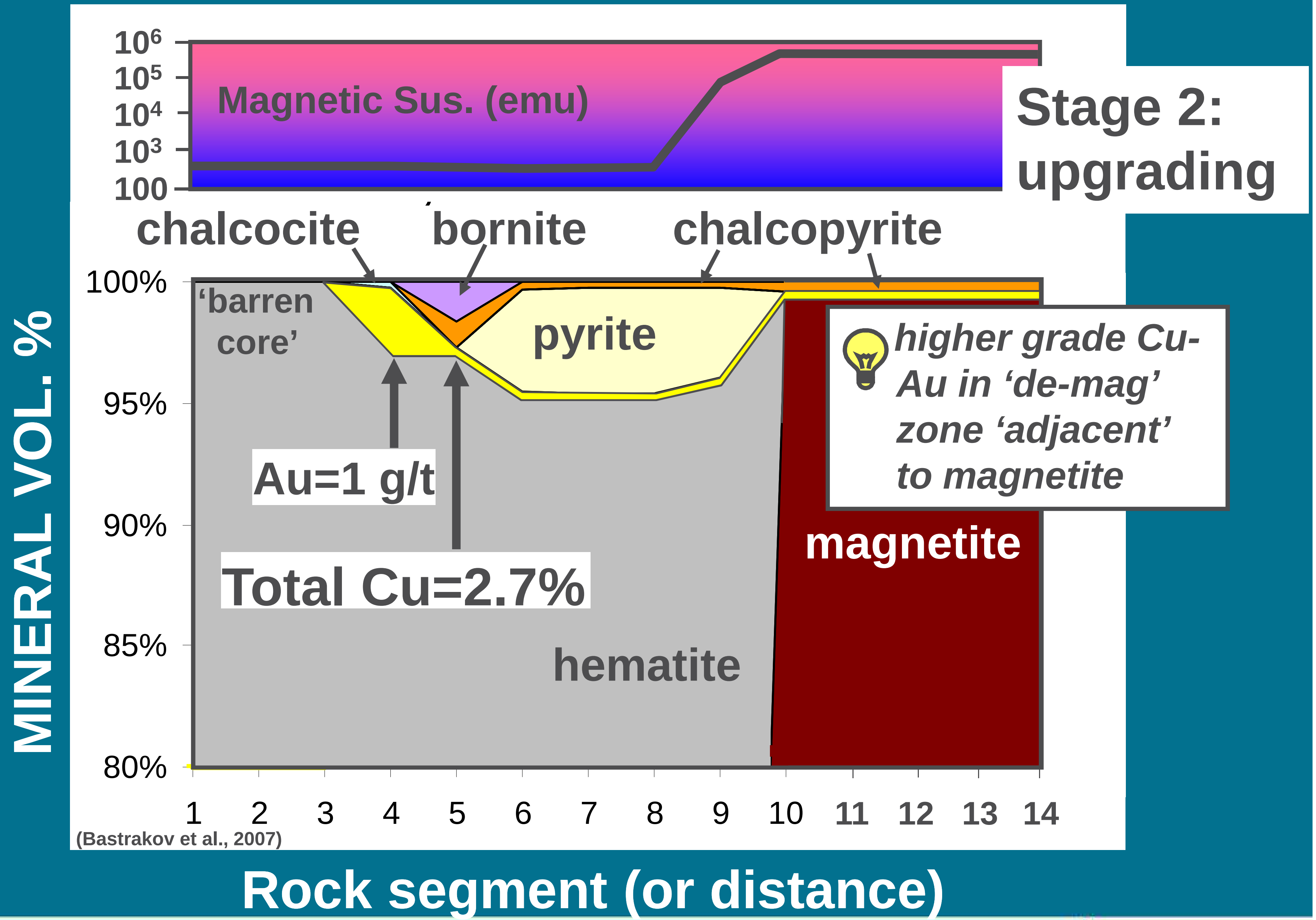
4. IOCG ore depositional gradients:

Search the redox and sulfur gradients!

Chemical modelling of 2-stage IOCG process:
1. 'proto-ore' of magnetite with low grade Cu-Au

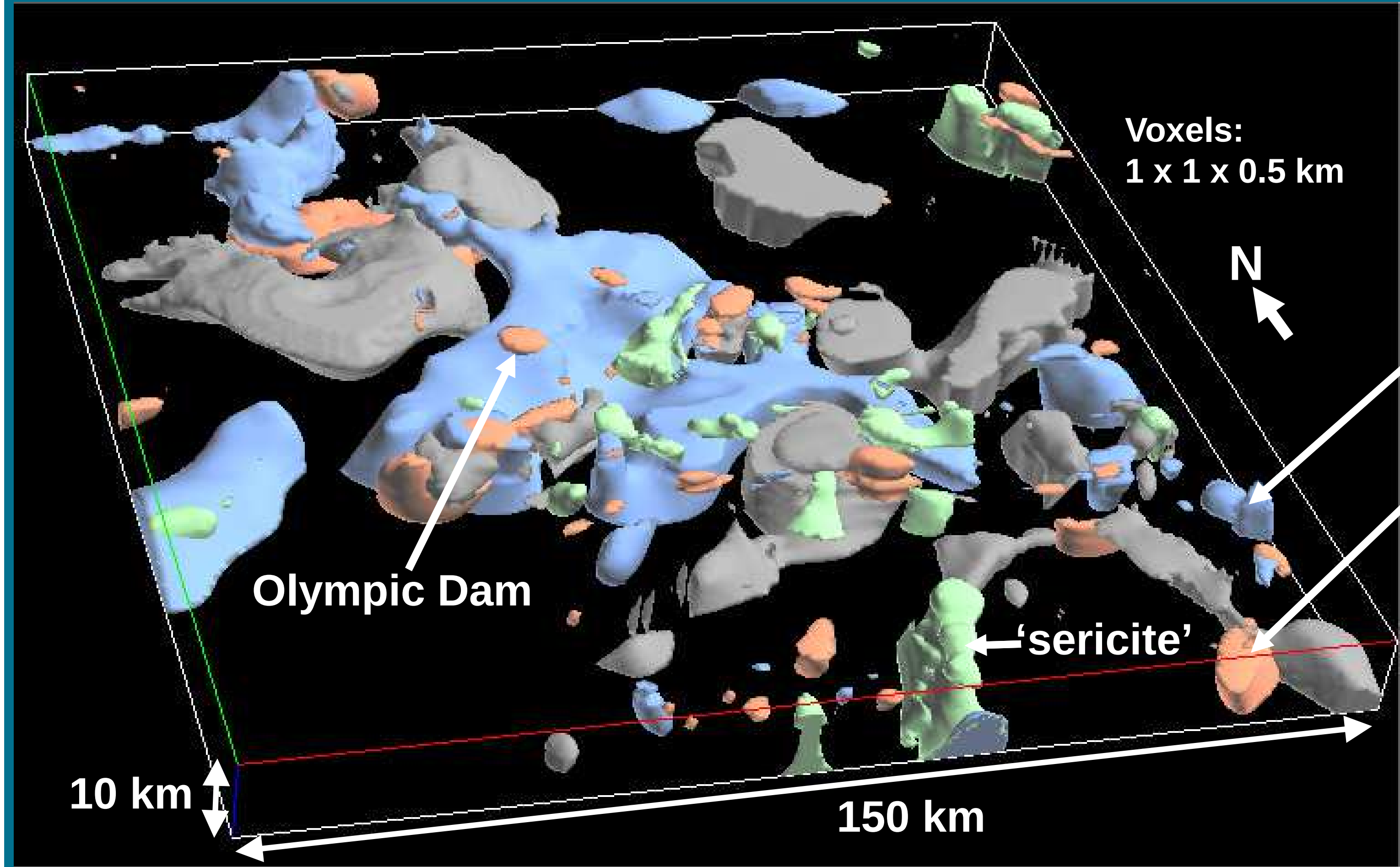


Rock segment (or distance)


Stage 2: upgrading
Magnetic Sus. (emu)
10^6
10^5
10^4
10^3
100
chalcocite
bornite
chalcopyrite
MINERAL VOL. %
100%
95%
90%
85%
80%
'barren core'
pyrite
Au=1 g/t
Total Cu=2.7%
hematite
magnetite
higher grade Cu-Au in 'de-mag' zone 'adjacent' to magnetite
1
2
3
4
5
6
7
8
9
10
11
12
13
14
(Bastrakov et al., 2007)
Rock segment (or distance)

District-scale targeting:
3D mapping of magnetite vs hematite alteration
using joint inversion modelling of gravity & magnetic data

Best Cu-Au(-U) in redox gradients; many untested anomalies



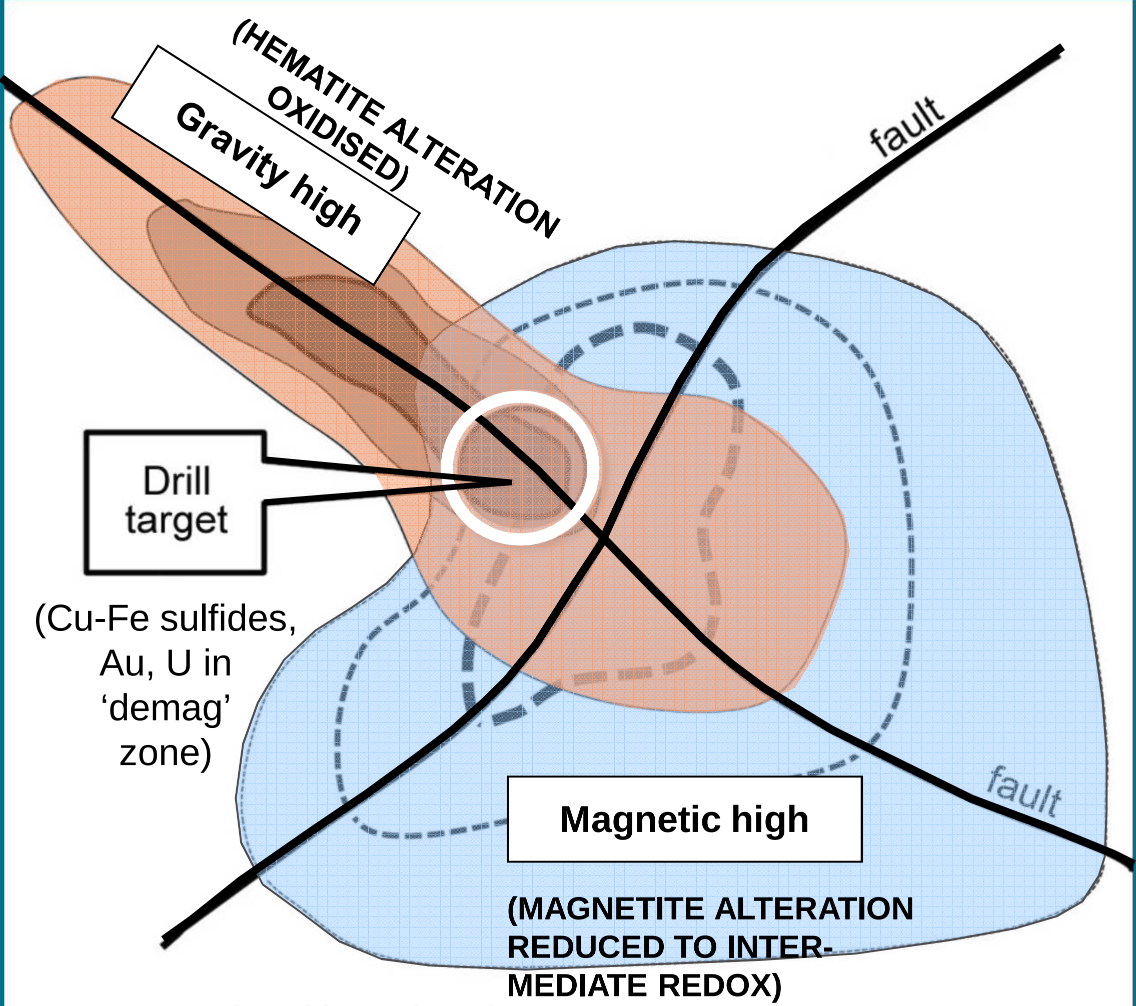
magnetite
>1 vol. %

'hematite'
>0.5 vol.%
(including other dense non-magnetic minerals)

(Richard Lane, Nick Williams, using modified UBC software; updated from Williams et al., 2004)

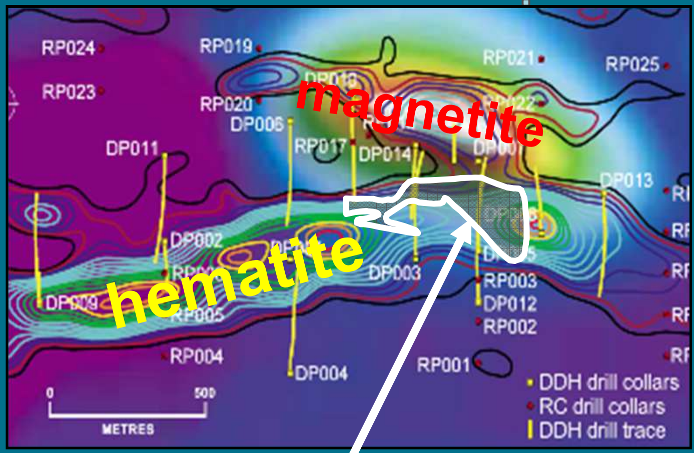
Ore depositional gradients:

Deposit-scale targeting: redox gradients are good!



From Hayward & Skirrow (2011)

PROMINENT HILL
Magnetics (background colour)
+ gravity (contours)



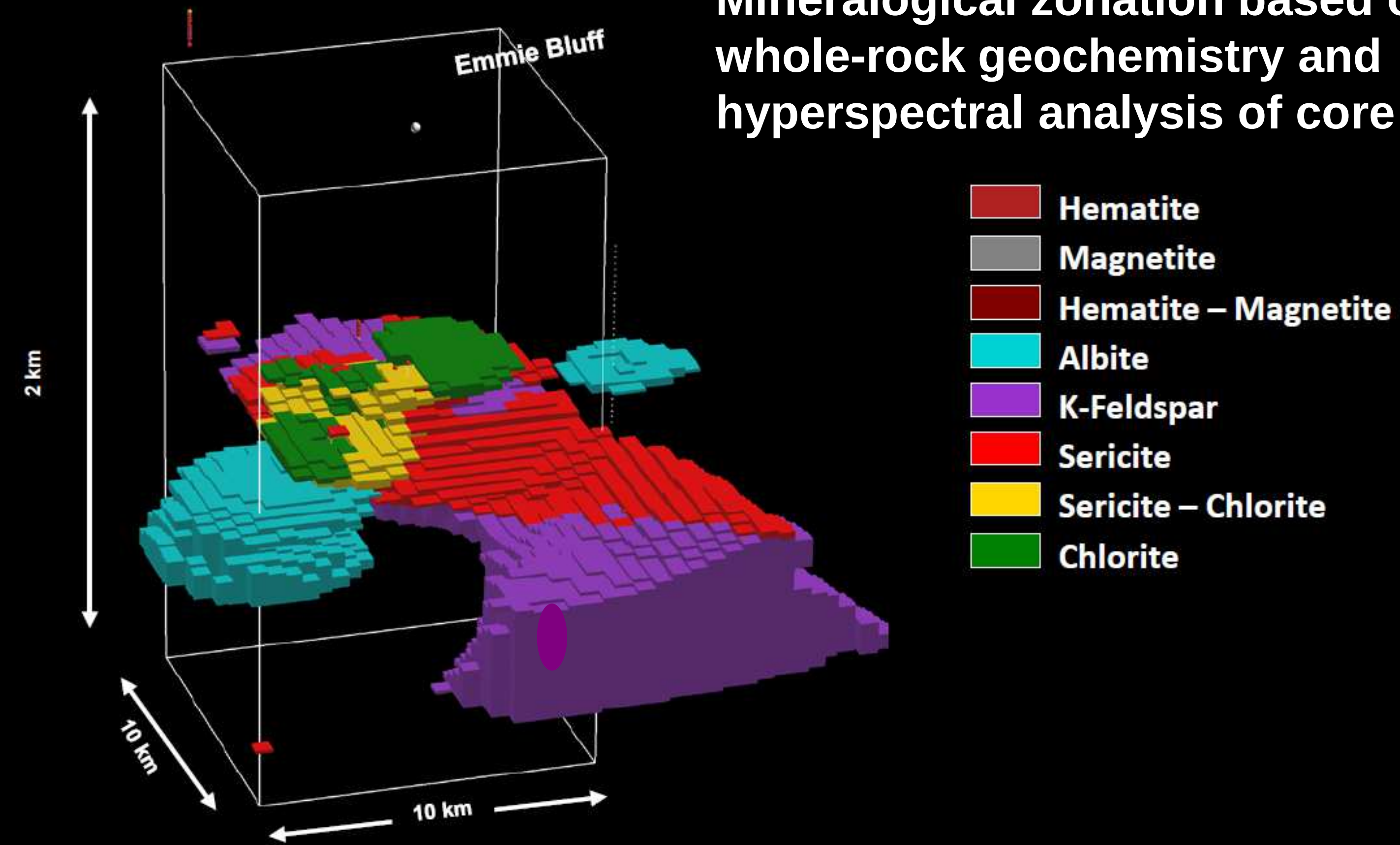
>0.5% Cu, projected to surface

Sources: Minotaur +
MESA Journal (January 2003)

Emmie Bluff 3D Model

New 3D mapping campaign by Geol Survey SA, DET CRC, U of Adelaide:

Mineralogical zonation based on whole-rock geochemistry and hyperspectral analysis of core



Mineralogy: Chemistry+spectral

(Fabris et al., SAREIC 2014)

Four essential components in IOCG ore systems of Olympic Dam type

1. **Crustal architecture**
   - Situated near/above trans-crustal or trans-lithospheric structures
   - Reactivated orogenic architecture at craton margin
2. **Energy sources / drivers of hydrothermal systems**
   - High-temperature A- and I-type felsic and coeval mafic-ultramafic magmatism drove IOCG hydrothermal fluids; mantle driver unclear
3. **Sources of metals & fluids**
   - Nd (and Cu) from mainly mafic sources; U from felsic sources?
   - Two fluids resulting in zoned crustal-scale alteration systems:

     (1) 'deep-sourced' high-temp brine of magmatic-hydrothermal and/or basinal origins

     (2) 'shallow-sourced' lower temp fluids of evolved meteoric origin
4. **Cu-Au (-U) ore depositional gradients**
   - Fluid mixing in major deposits; redox, sulfur and temperature gradients
   - Higher grade Cu-Au(-U) near gradient between magnetite and hematite

For more information, and free national and regional geoscientific datasets, visit:

www.ga.gov.au/minerals

www.geoscience.gov.au/

Olympic Dam breccia

ADDITIONAL SLIDES

What are Iron Oxide Cu-Au (IOCG) deposits?

A descriptive definition

- **Cu, Au, U, LREE, Ag, CO_3, F, P, Ba, Mo association**
- **Cu-Fe sulfides & Au spatially associated with abundant (>10%) low-Ti magnetite and/or hematite**
- **Hydrothermal quartz<<Fe-oxides; sulfides<<Fe-oxides**
- **Local alteration is potassic (Kfs, bt), or hydrolytic (ser, chl), and/or carbonate; regional alteration is Na-Ca (alb, amph)**
- **Epigenetic, structurally-controlled hydrothermal replacements, breccias, vein stockworks**
- **Distal from coeval igneous intrusions; bimodal magmatism**
- **Two fluids: hypersaline, & separate lower salinity brines (± CO_2)**

(based on Hitzman et al., 1992; Hitzman, 2000; Williams et al., 2005; Groves et al., 2010)

Hematite-bornite breccia, Gawler Craton

Classification of IOCG deposits

Deposit type		*EXAMPLES*
Iron Oxide Cu-Au ± U (IOCG deposits)	Hematite-group	Olympic Dam Prominent Hill Manto Verde
	Hematite-magnetite	Raul Condestable Ernest Henry Salobo, Sossego
	Magnetite-group	Candelaria, Peko
Other deposit types (not IOCGs but in some cases in same districts; possibly affiliated)	Fe-oxide -apatite	Kiruna
	Low-Fe-oxide Cu-Au	Pahtohavare, mantos?
	Fe-oxide U (low Cu)	Michelin, Mt Gee
	Co-As Fe-oxide (low Cu)	NICO
	Alkaline-carbonatite -related Cu or REE	Palabora, Bayan Obo

Based on Williams (2008, 2010)

IOCG prospectivity mapping using mineral systems approach

1. Architecture

- Crustal domain boundaries
- Faults
- Volcanic rocks

2. Driver / energy

- A- & high-T I-type igneous rocks
- Mafic igneous rocks
- Breccias in intrusive rocks
- Evidence of high level intr.

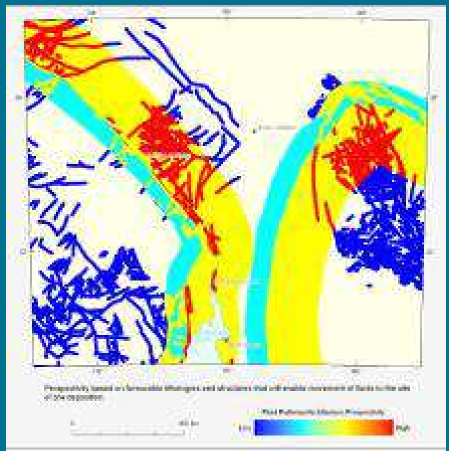
3. Sources: Cu, Au, U, Cl, F, S

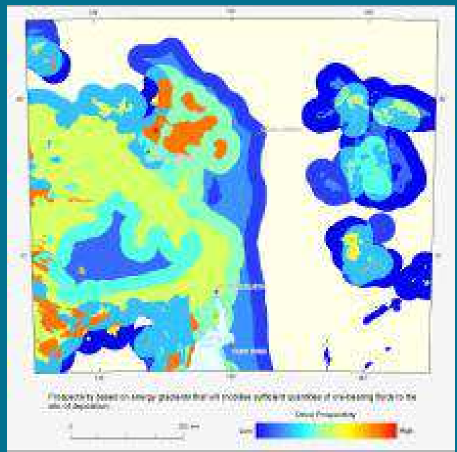
- Rift basin sources (Cl S Fe)
- High-U igneous rocks (U)
- High-T igneous rocks (U)
- Mafic igneous rocks (Cu Au Fe S)
- High-F igneous rocks (F)

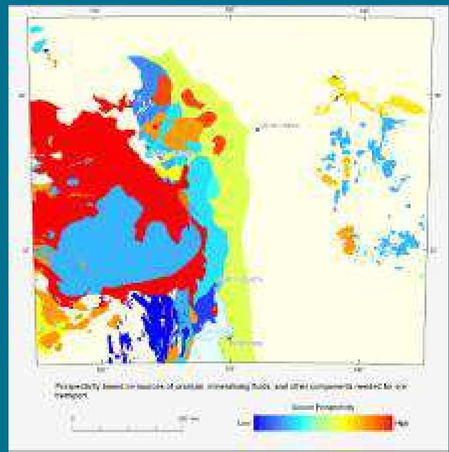
4. Ore depositional gradients

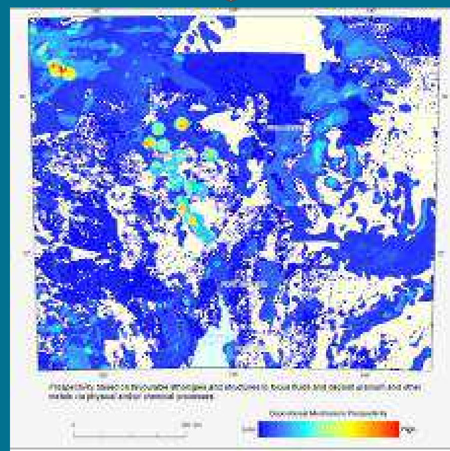
- U^2/Th, 1σ & 2σ above mean
- 'Hematite' from inversions
- 'Magnetite' from inversions
- Ironstones, BIF
- Observed hem-ser-chl alt'n

Mappable criteria



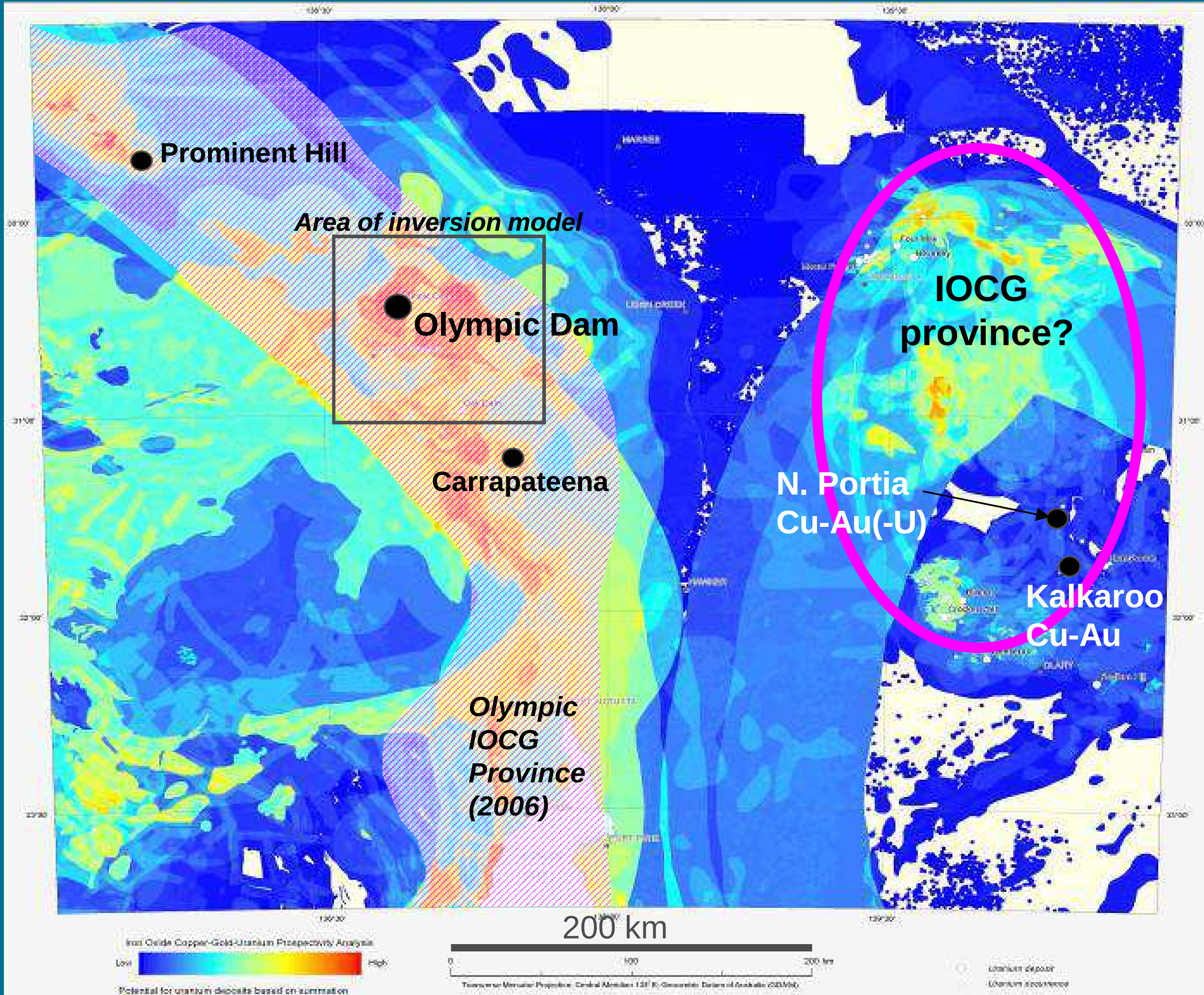






From Skirrow et al. (2011) in Huston (ed.) (2011, GA Record 2011/34)

IOCG(U) prospectivity map of Gawler-Curnamona region



From Skirrow et al. (2011) in Huston (ed.) (2011, GA Record 2011/34)