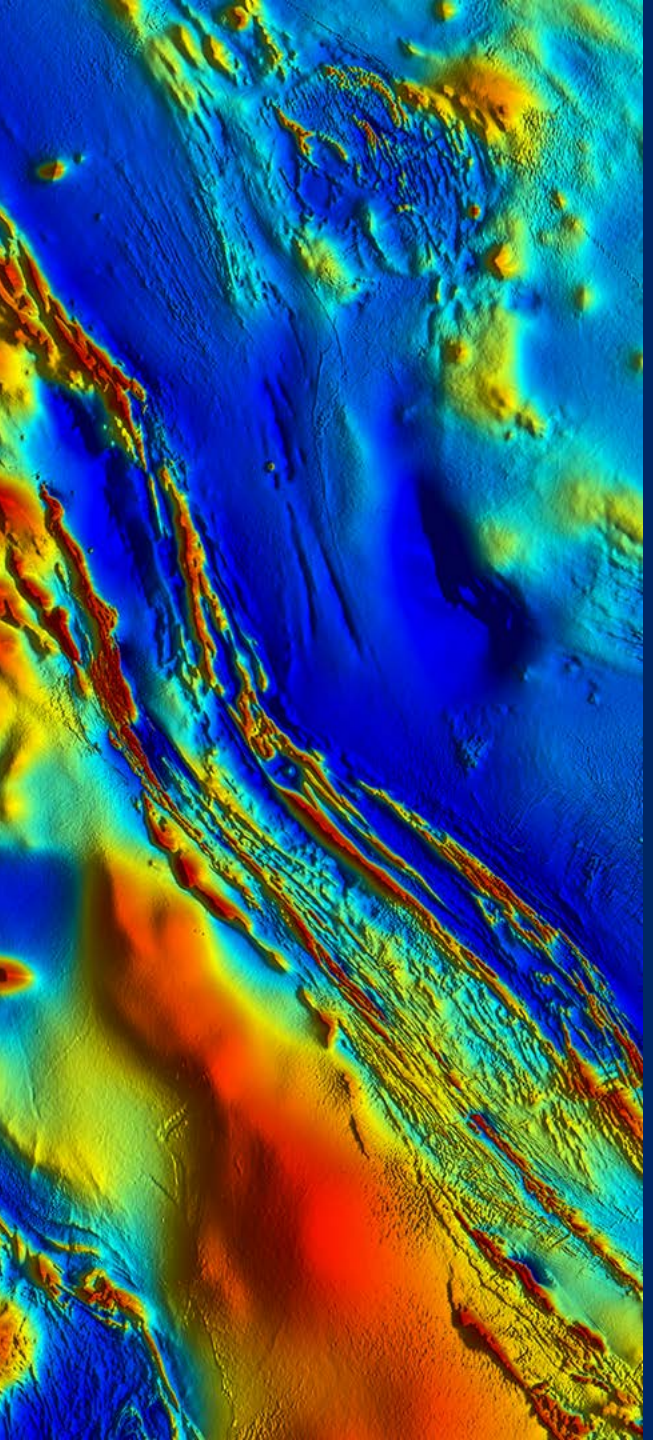


The Macquarie Arc: recycling, evolving, persisting

New geochemical and geochronological evidence

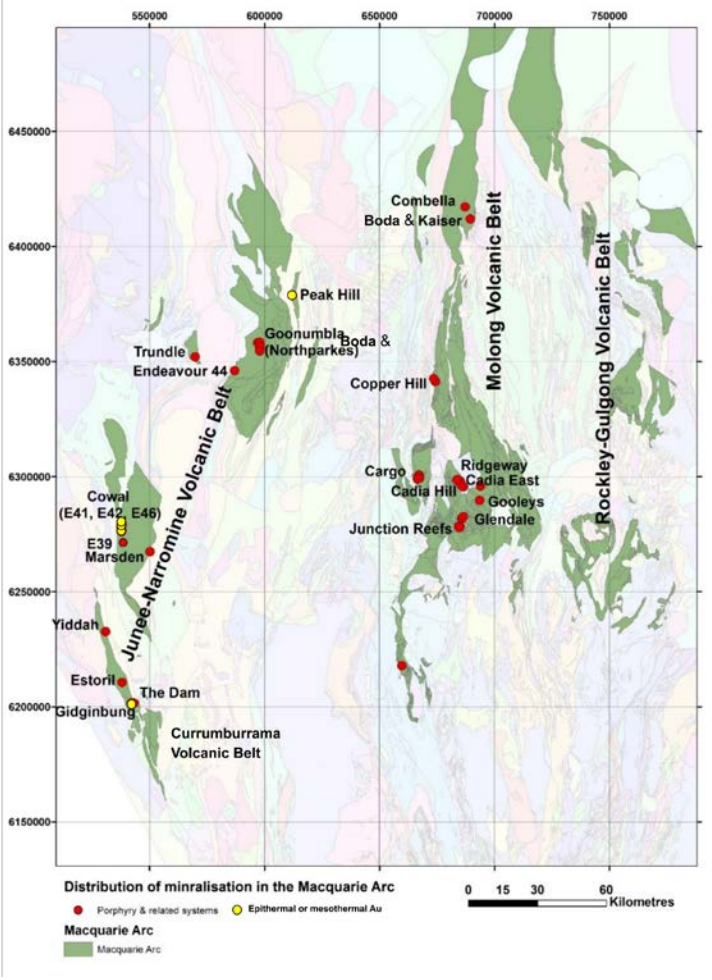
David Forster, Ryan Dwyer, Brenainn Simpson, Phillip Blevin and Huiqing Huang

May 2024

The Macquarie Arc

Background

- Consists of 4 major belts of volcanic and volcano-sedimentary rock packages – each with different age distributions.
- Junee–Narromine Volcanic Belt includes oldest sequence of rocks (Nelungaloo Volcanics) described as including shoshonites by Wyborn et al. (1992) ranging to Early Silurian **(and younger).**
- Molong Volcanic Belt is mainly comprised of Middle Ordovician to Early Silurian rocks.
- Rockley–Gulgong Volcanic Belt is dominated by sedimentary and volcano-sedimentary units – includes intercalation with siliciclastic flysch of the Adaminaby Group.
- Kiandra Volcanic Belt (not shown) has no porphyry-related mineralisation.

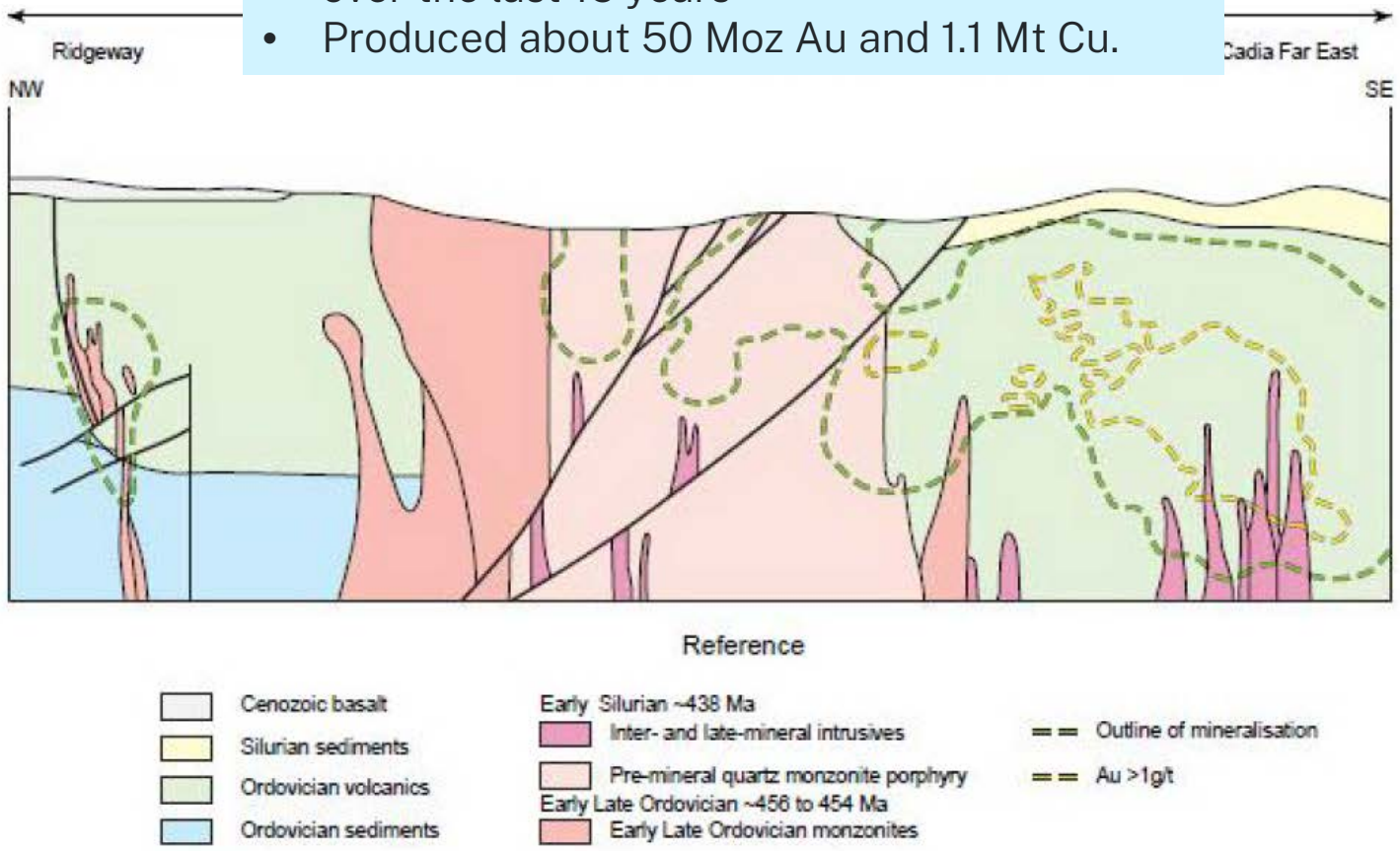


The Macquarie Arc

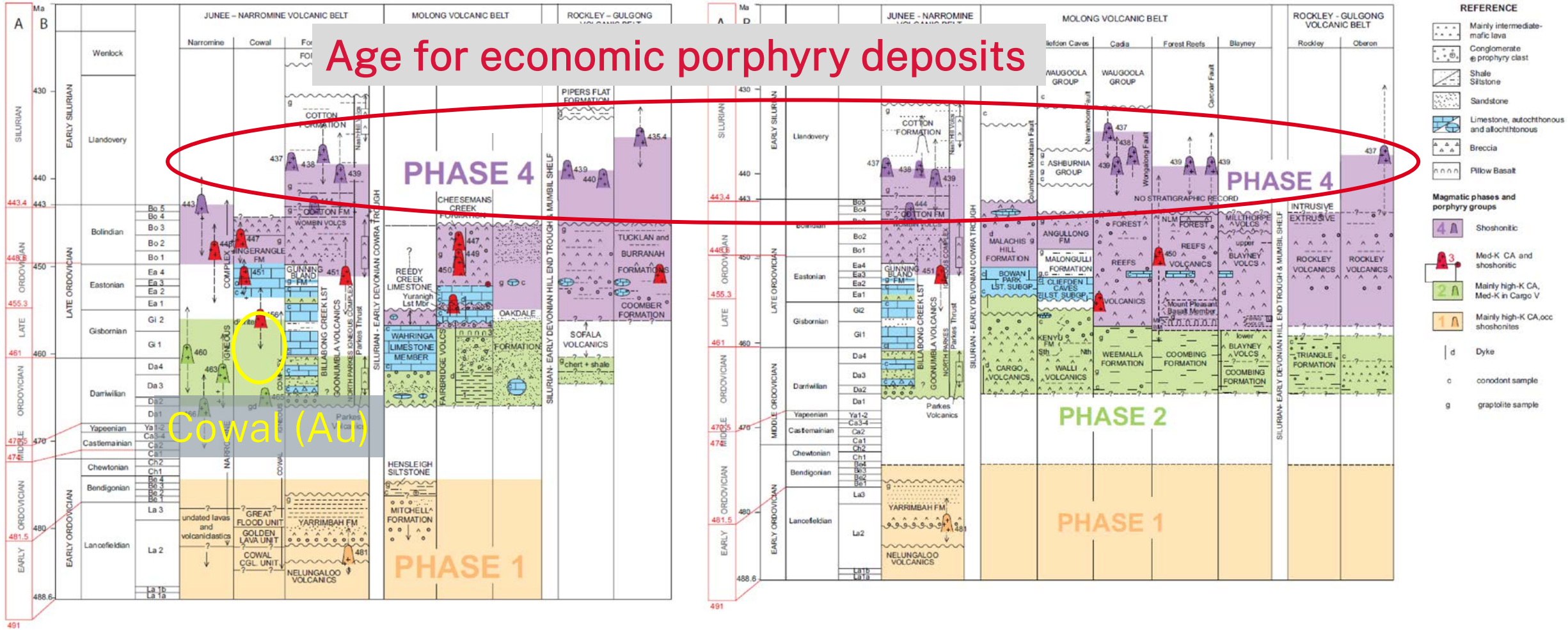
Cadia
- World-class district
- Among top 5 Au-Cu porphyry deposit on Earth.
- 1st or 2nd as Australia's most profitable mine over the last 15 years
- Produced about 50 Moz Au and 1.1 Mt Cu.

Economic significance

- >14 Mt of copper (about 80% of NSW copper endowment) almost entirely hosted by porphyry and related skarn deposits.
- NSW is 2nd nationally in copper resources after South Australia.
- Macquarie Arc hosts >50% of the gold endowment in state (NSW is 3rd nationally).
- 89% of Macquarie Arc gold is hosted by porphyry and related skarns (>65 Moz of gold).



The Macquarie Arc overview

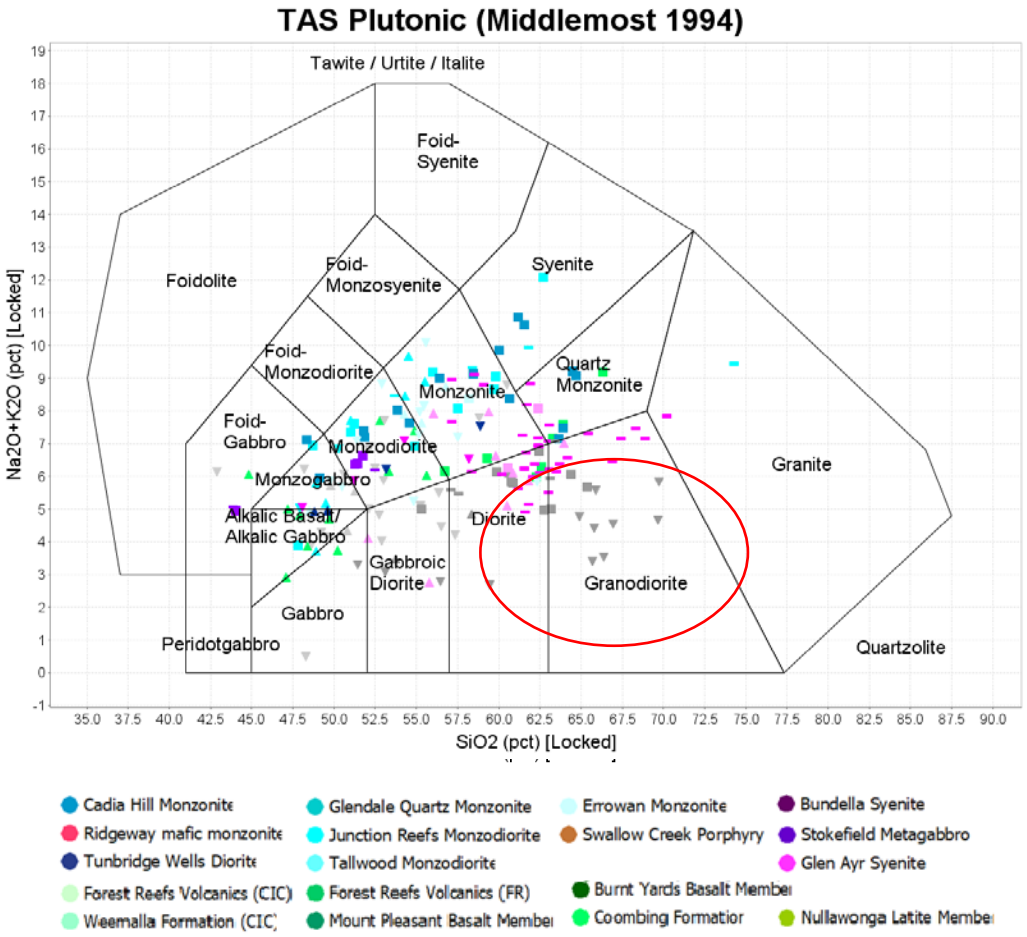


Geochemistry and geochronology problems – old and new

- Wyborn et al. (1992) claimed that much of the Macquarie Arc is 'overwhelming shoshonitic' and hence not consistent with a subduction-related arc.
- Blevin and Morrison (1997) and Glen et al. (1998) – most suites are fundamentally calc-alkaline.
- Why are some of the oldest sequences of the Macquarie Arc LILE-enriched (Sr, Rb, Ba, Th, U, La, Ce) and K+ enriched (from the beginning)?
- What was the role of subduction?
- How were copper and gold enriched and when in various mineralised districts?
- How do 'shoshonites' of the Macquarie Arc compare with other terranes?

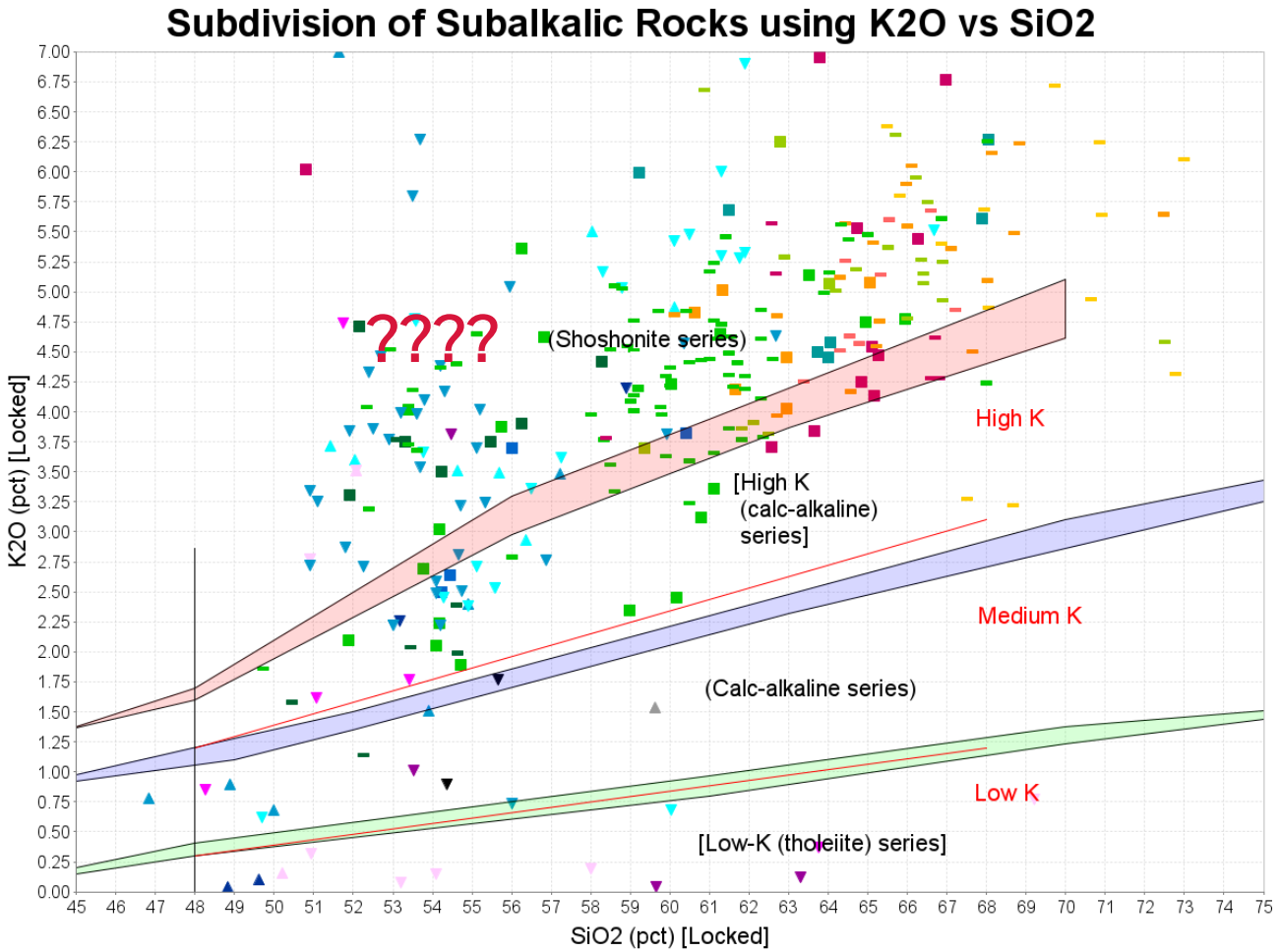
New geochemical, geochronological and isotopic data

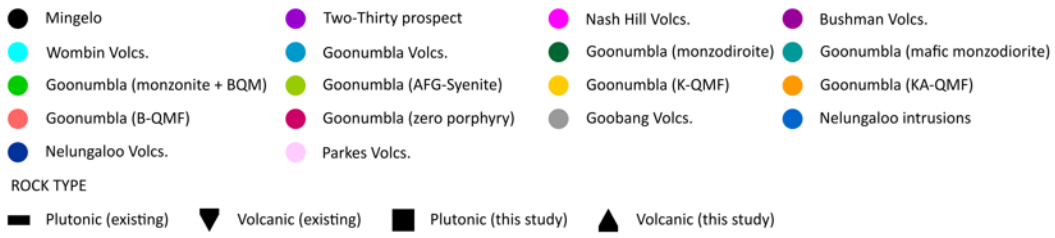
- Cadia – Junction Reefs data.
- Most are moderately K-enriched
- Largely linear compositional trends
- Data for Cadia district include more K-enriched results (including reduced Au skarns – Junction Reefs)
- Trundle Park and Rain Hill are distinctly K-enriched – some of the latter plotting as granodiorites.



New geochemical data – comparisons between suites

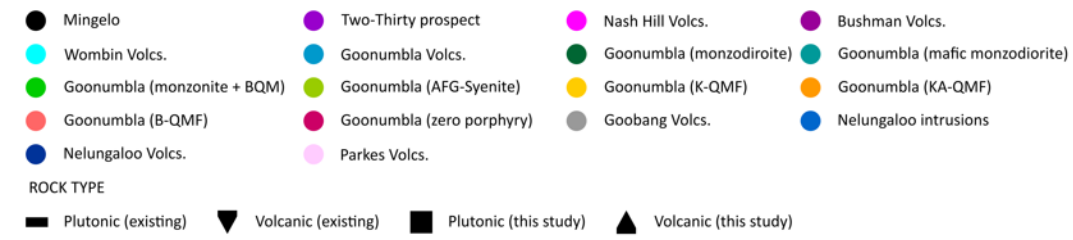
- Basic K_2O vs SiO_2 suggests many suites including Goonumbla rocks and Northparkes intrusions are shoshonitic.

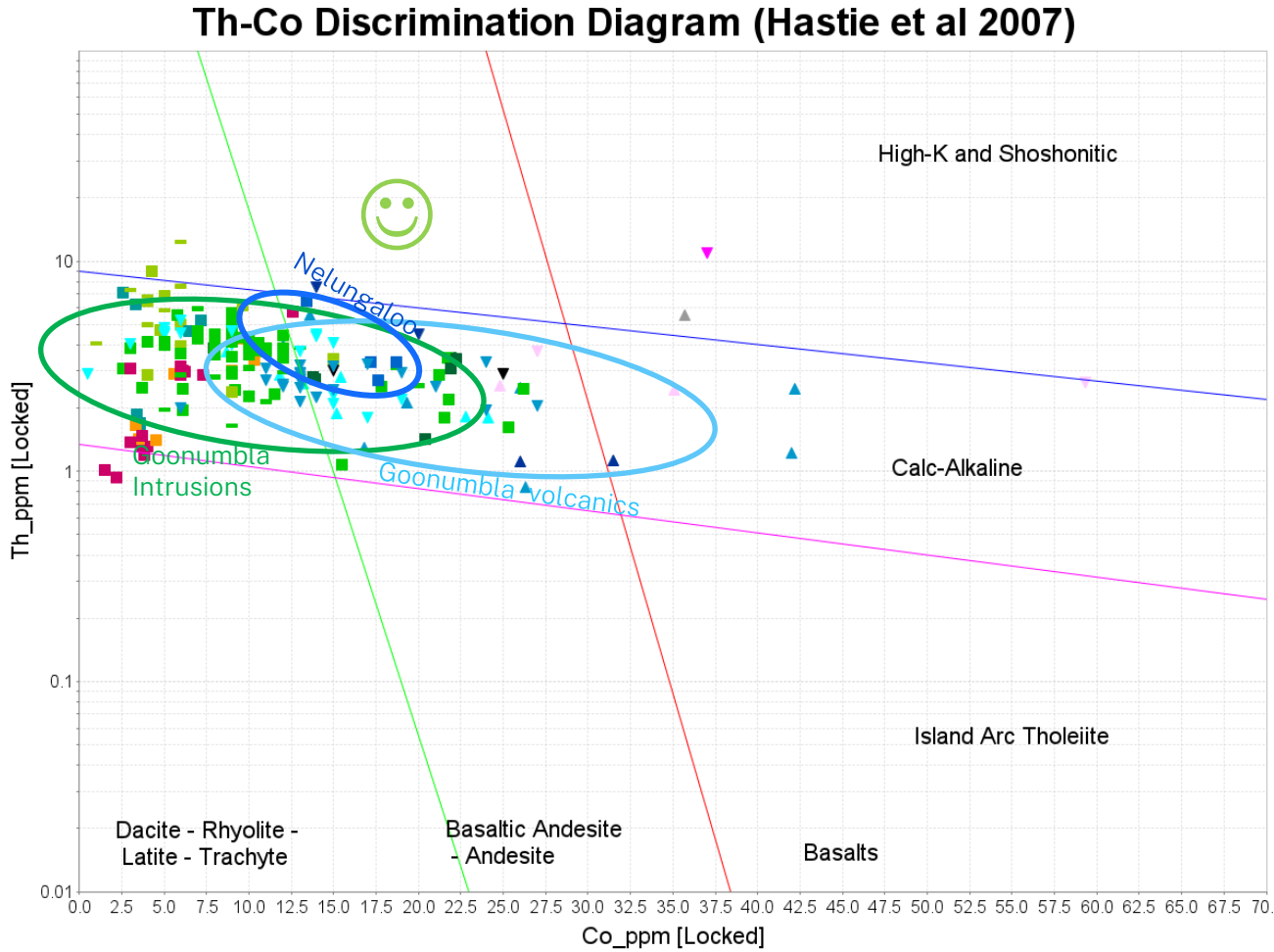




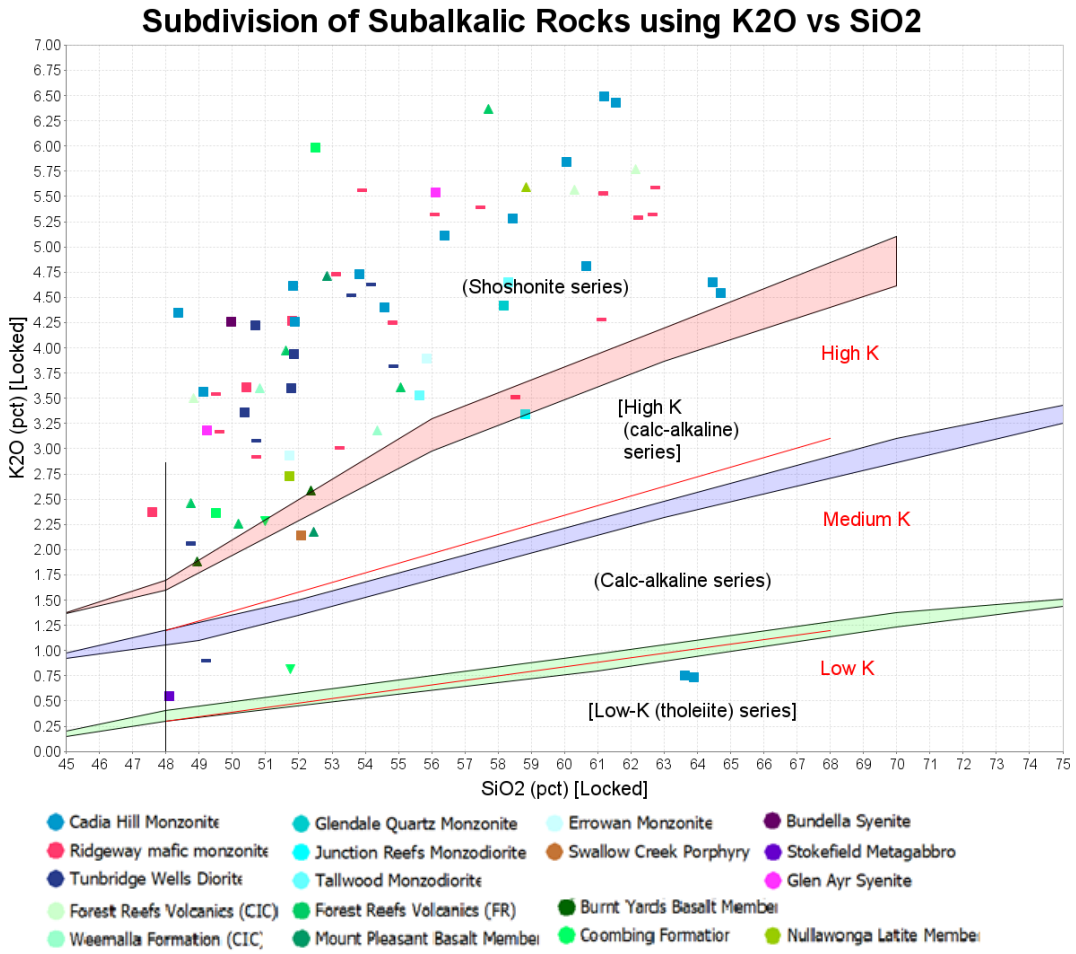
New geochemical data – comparisons between suites

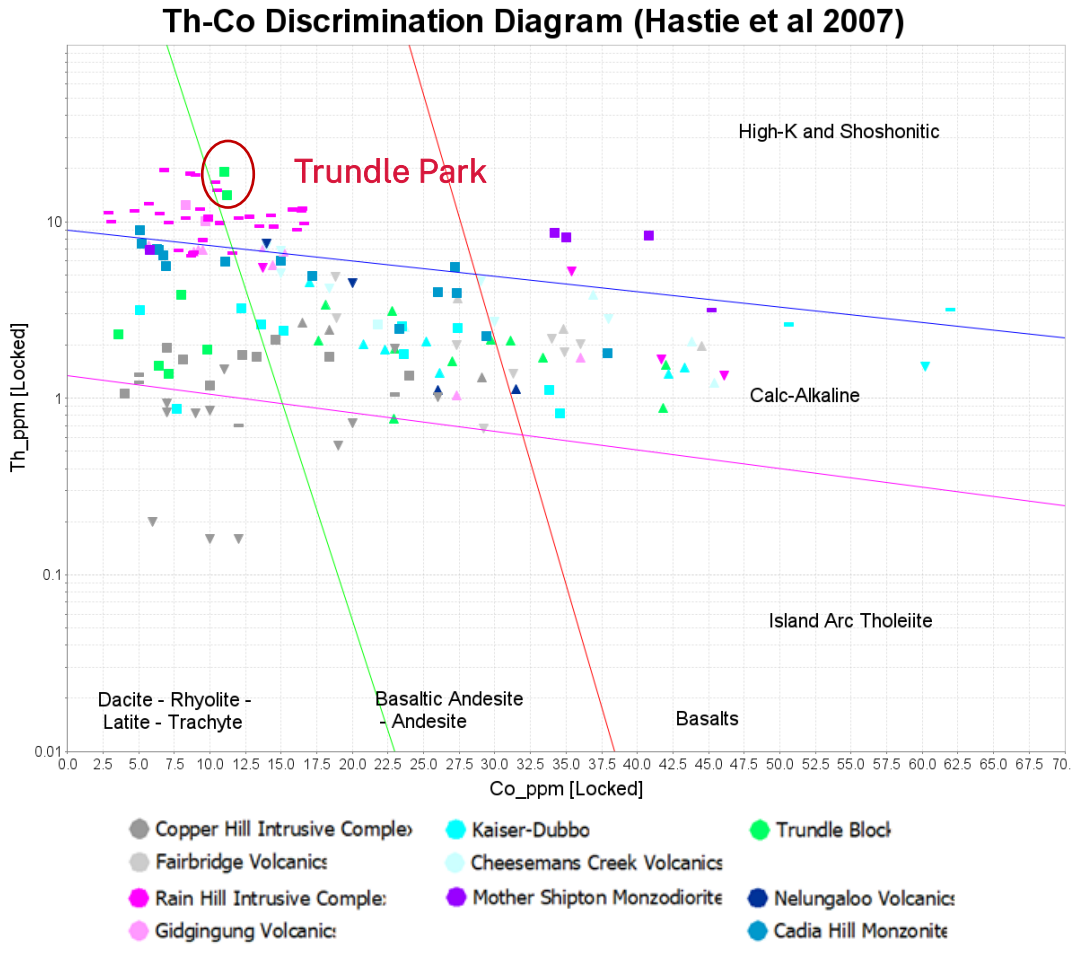
- Conversely, lower mobility trace-element diagram suggests the same rocks are calc-alkaline rocks
- Extra K during alteration/metasomatism? (supported by geochemical alteration modelling)





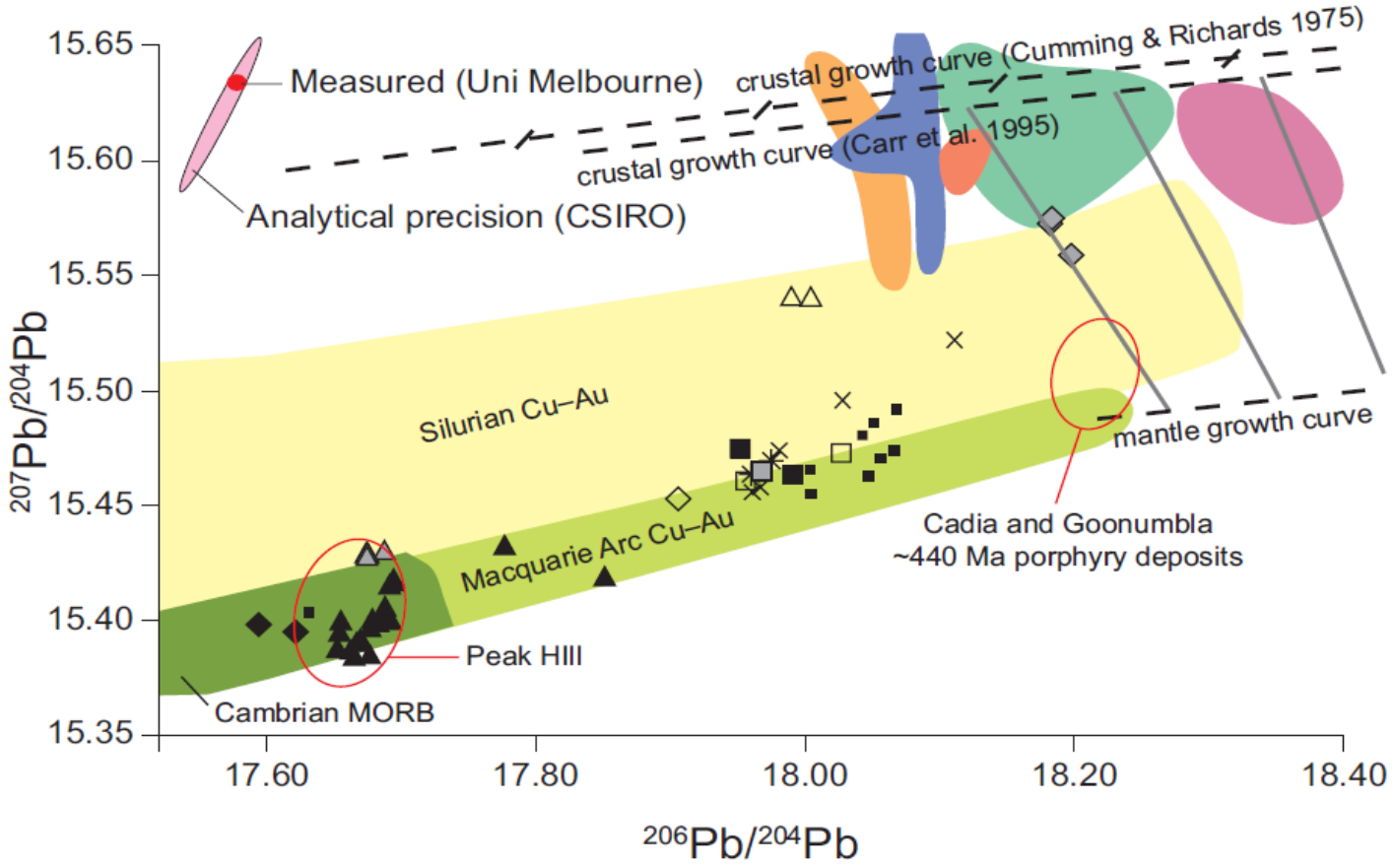
New geochemical data – comparisons between suites





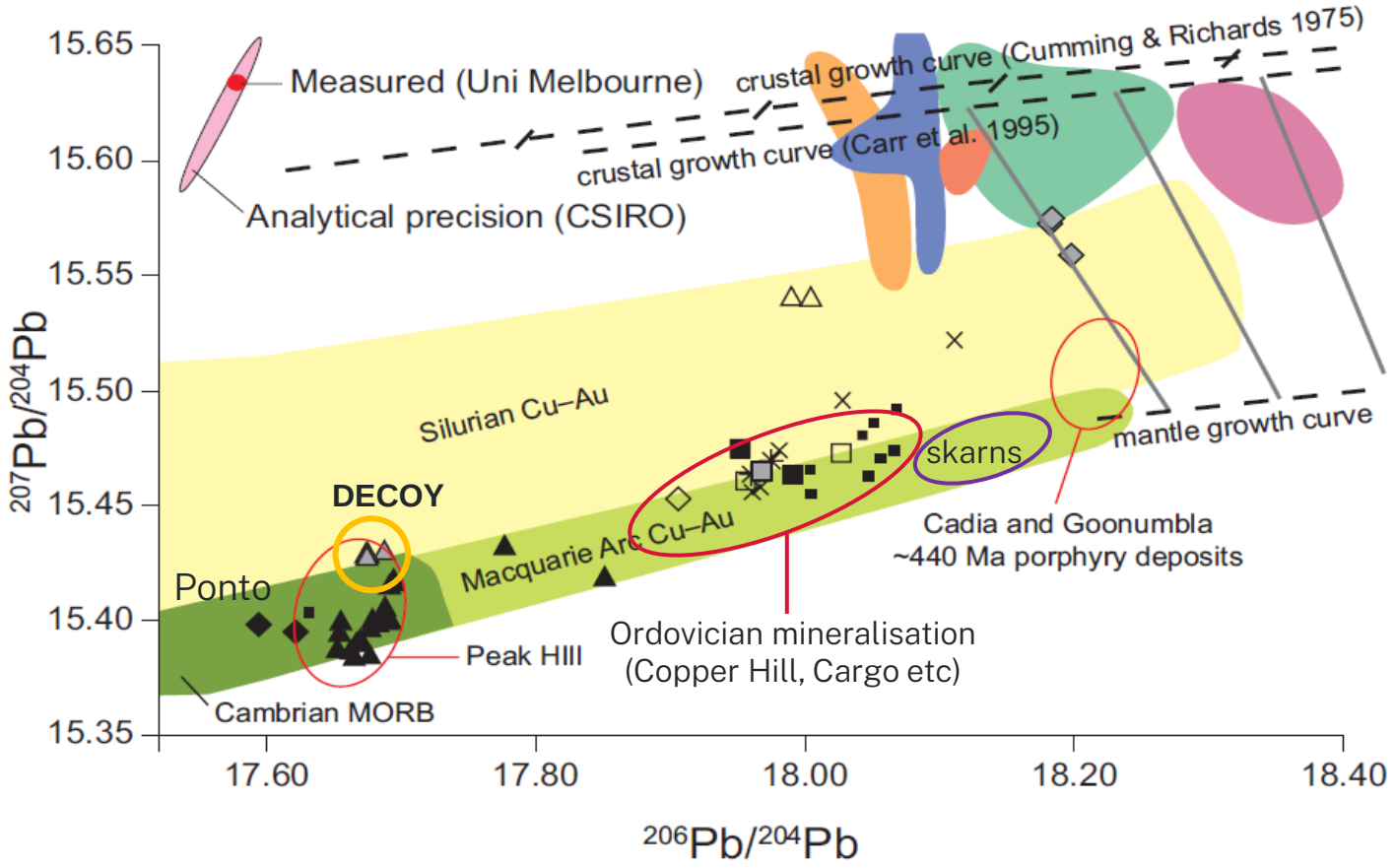
Recycling – old basement - Pb isotopes

- Lead isotopes have linear trends and are mantle-like, providing an excellent tracer for Cu and Au.
- Show correspondence of ^{206}Pb vs ^{204}Pb with age.
- Almost no input from siliclastic 'crustal' sources of Pb for Macquarie Arc deposits.
- Very slight crustal enrichment for Cadia alone (MacArc deposits).
- Any mineralisation in contact with siliciclastic rocks during the Ordovician or younger than Benambran Orogeny is usually markedly contaminated by crustal Pb.

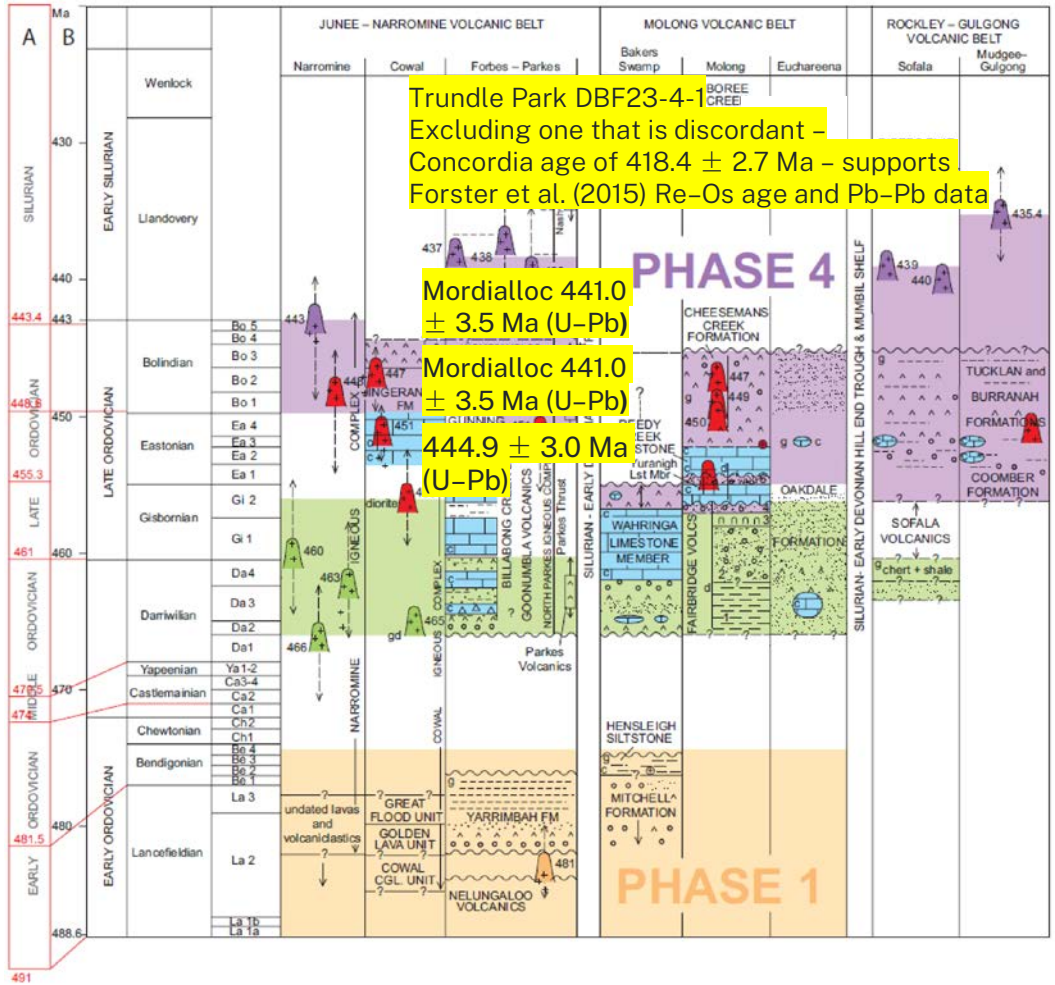


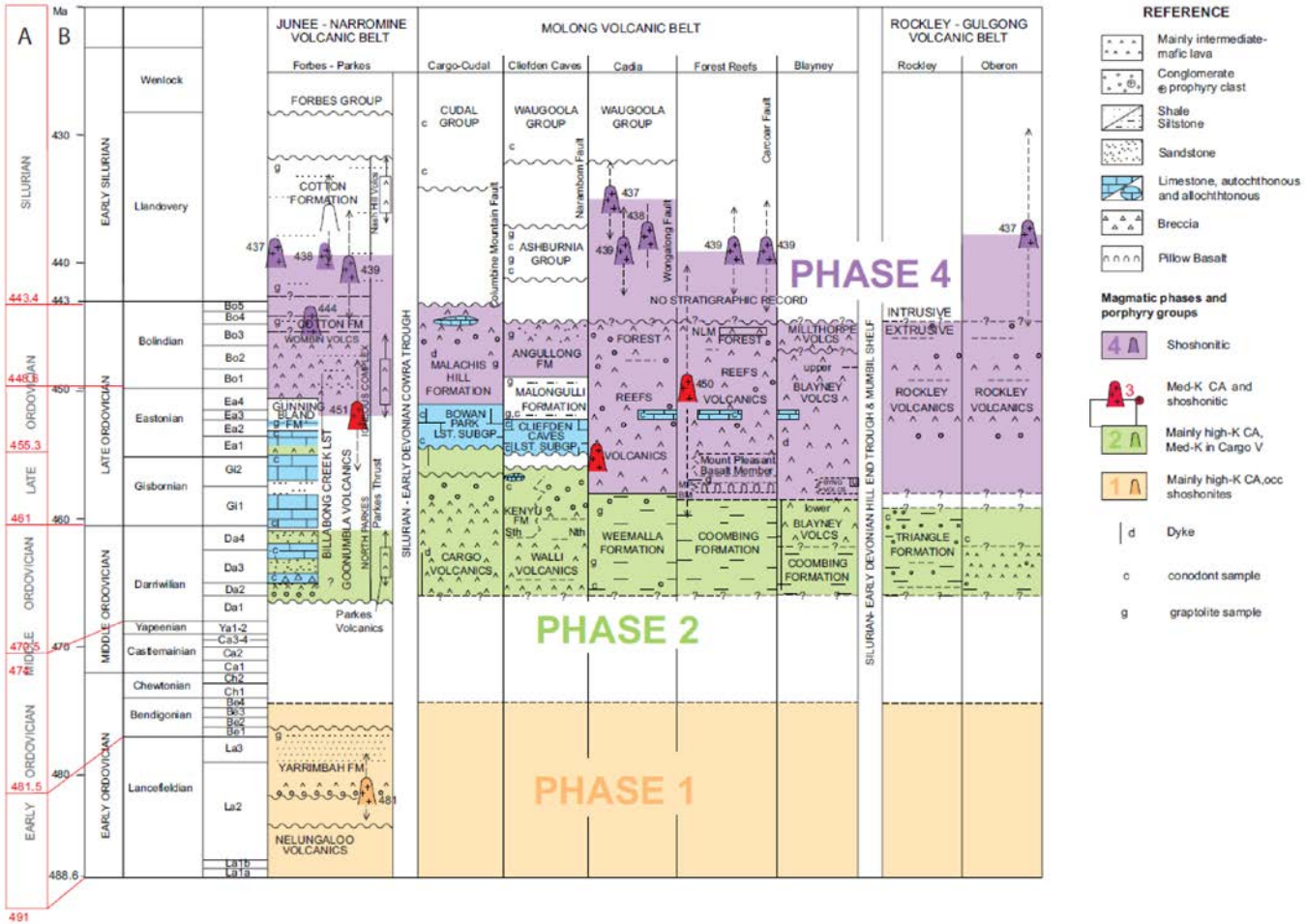
Recycling, evolving – the Macquarie Arc

- Cambrian MORB-like signatures similar to Ponto in the Koonenberry Belt – showed up in previously unexpected places around the Macquarie Arc (e.g. Decoy in the Cowal district).
- Subsequent drilling and geochronology has confirmed Cambrian and early Ordovician substrate to the district.
- Others are proving explicable based on structural/geophysical evidence (e.g. along major fault zones) within deep seated-rift-structures etc.



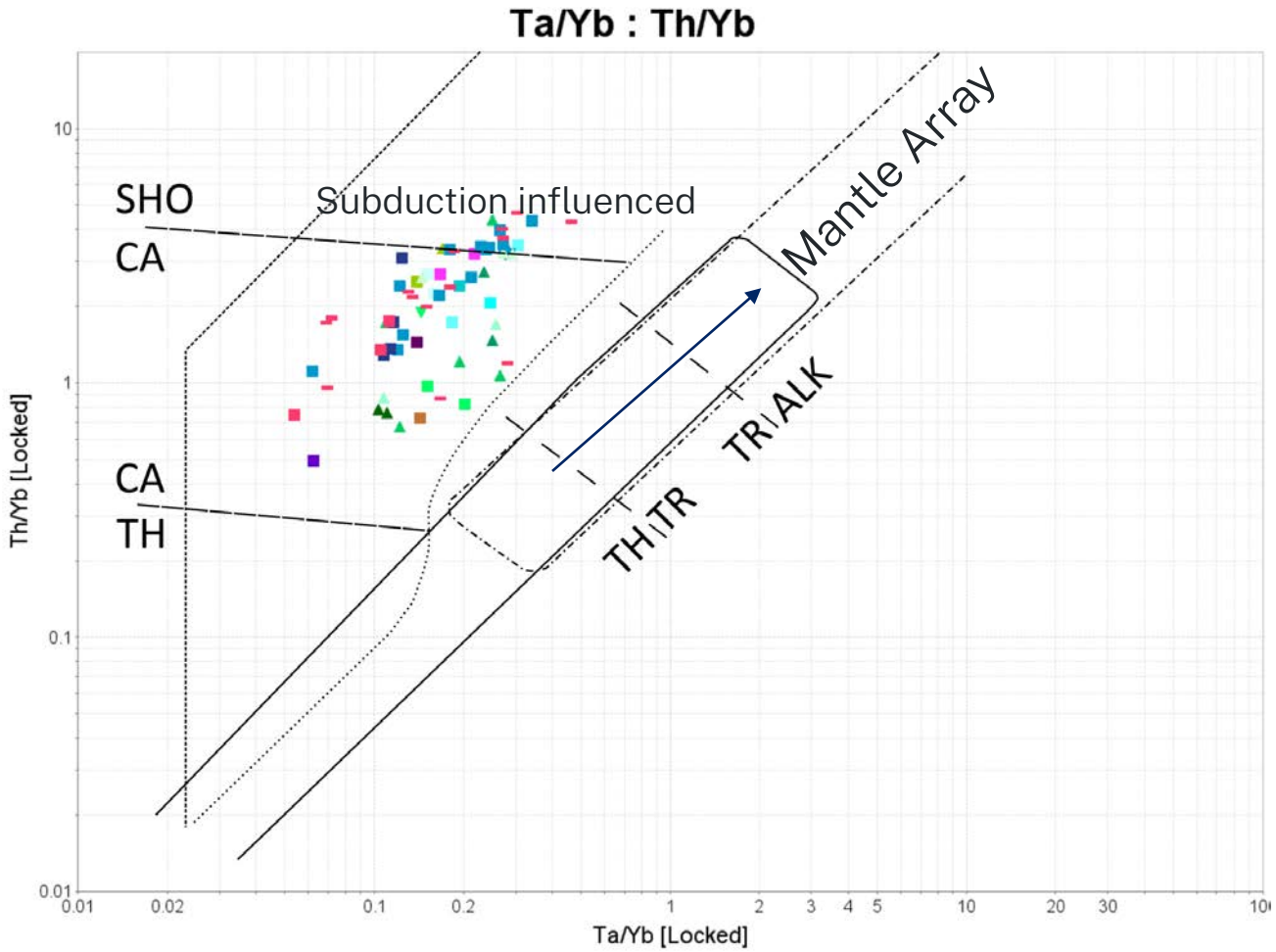
New geochronological data





Evolving – new geochemical, geochronological and isotopic data

- Th/Yb vs Ta/Yb plots provide evidence of compositional evolution away from mantle trends.
- Supports and provides greater resolution while supporting previous Pb–Pb, epsilon Nd and Hf isotope data.



LOCATION

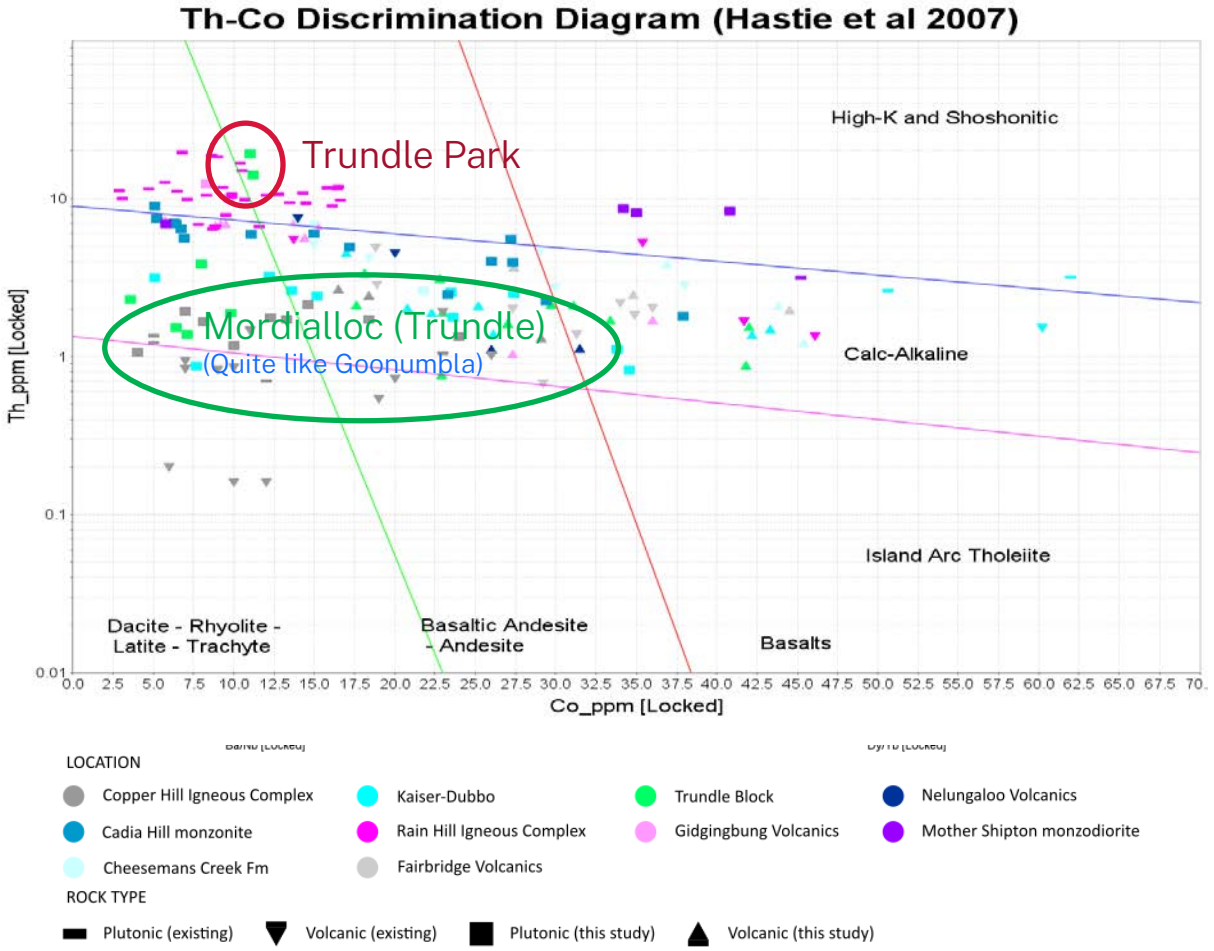
- Cadia Hill monzonite
- Ridgeway mafic monzonite
- Tunbridge Wells diorite
- Bundella syenite
- Forest Reefs Volcs. (within CIC)
- Weemalla Fm. (within CIC)
- Glendale quartz monzonite
- Junction Reefs monzodiorite
- Tallwood monzodiorite
- Errowan monzonite
- Swallow Creek porphyry
- Stokefield Metagabbro
- Glen Ayr syenite
- Forest Reefs Volcs.
- Mount Pleasant Basalt Member
- Burnt Yards Basalt Member
- Coombing Fm.
- Nullawonga Latite Member

ROCK TYPE

- Plutonic (existing)
- Volcanic (existing)
- Plutonic (this study)
- Volcanic (this study)

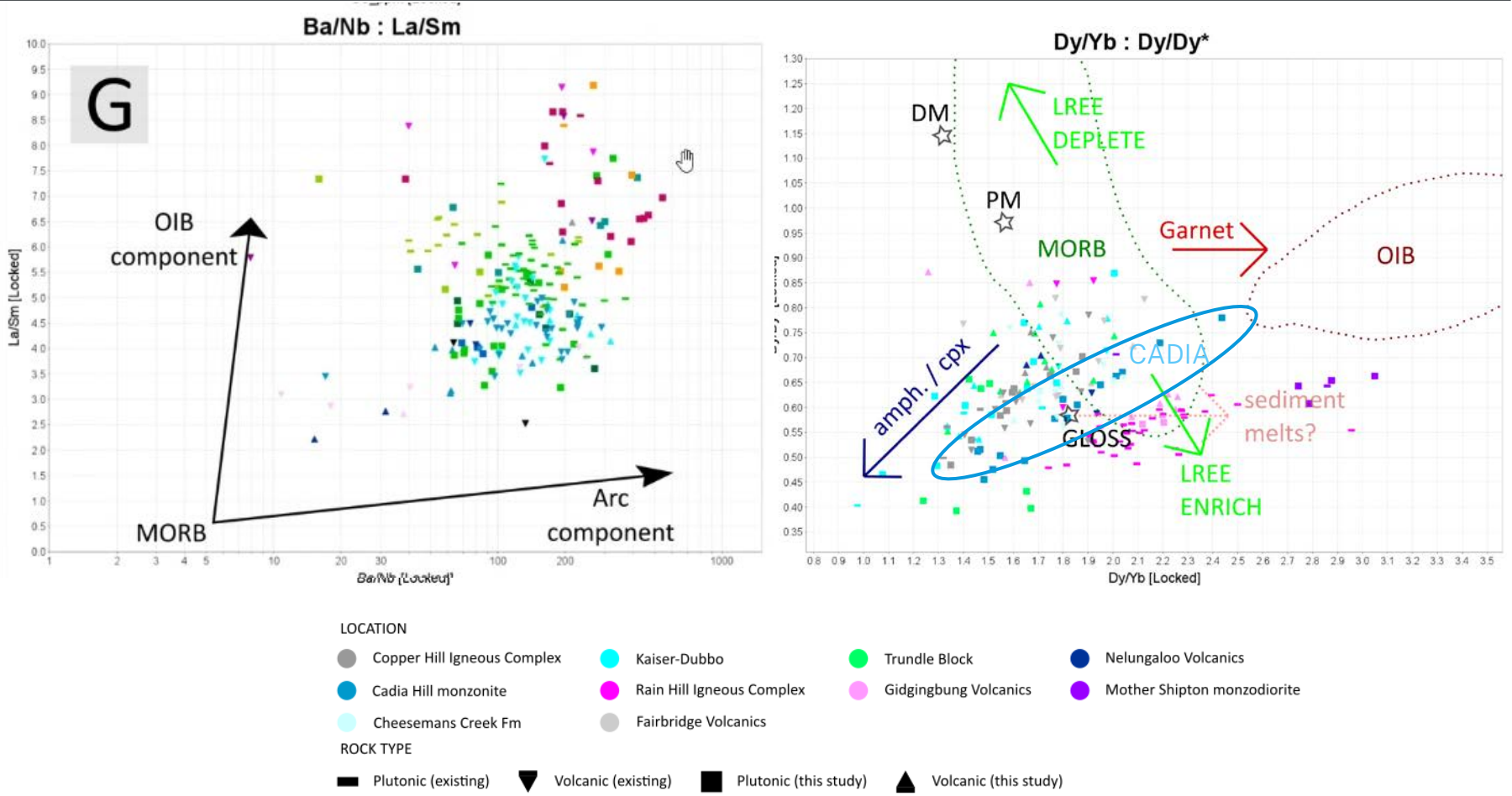
Persisting–new geochemical data beyond the Arc

- Th-Co plot shows Cadia is high-K alkaline to marginally shoshonitic (see Blevin 2002).
- Th-Co plot shows Rain Hill and Trundle Park are shoshonitic.
- Rain Hill is likely crustally contaminated and Trundle Park is younger than MacArc (post-Benambran).
- Trundle Park has formed voluminous Cu-Au mineralisation related to reminiscent looking rocks in the same place as 440 Ma mineralisation – evolving, enriched ex-arc-related sources are still down there.



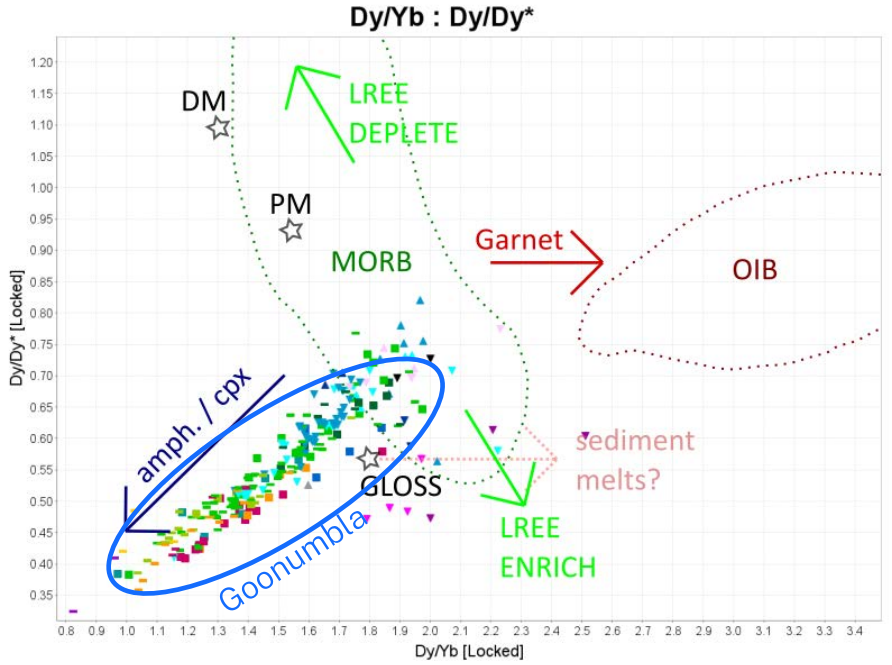
New geochemical data – magma sources

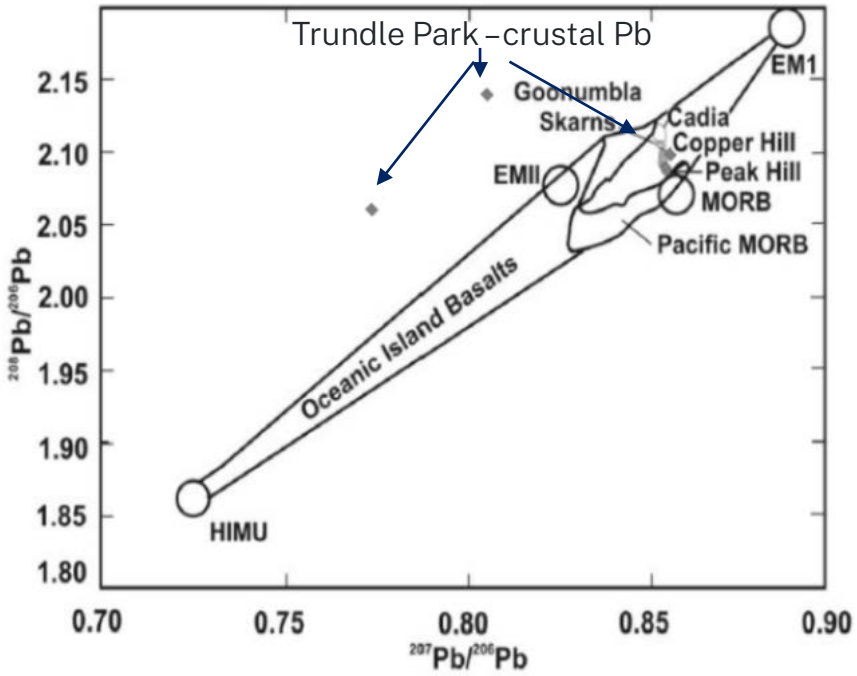
- La/Sm vs Ba/Nb shows influence of OIB component mainly for Trundle Park and Rain Hill – these are likely crustally contaminated.
- Rain Hill is also likely crustally contaminated and Trundle Park is younger than MacArc (post-Benambran).
- Dy/Dy* vs Dy/Yb also shows LREE enrichment for Trundle Park.
- Cadia trends toward OIB possibly suggesting garnet-present melting (high HREE) supported by depth of melting calculations.



New geochemical data – magma sources

- Overall, limited LREE enrichment or depletion-evolution from MORB-like source.
- Strong trend evident – more compositionally evolved and younger data for Goonumbla and Northparkes plot to the left with less evolved MORB-like initial compositions. Probably largely related to pyroxene-amphibole fractionation.
- In detail, cyclicity – probably related to crustal relaxation and limited rifting is evident for Goonumbla district.



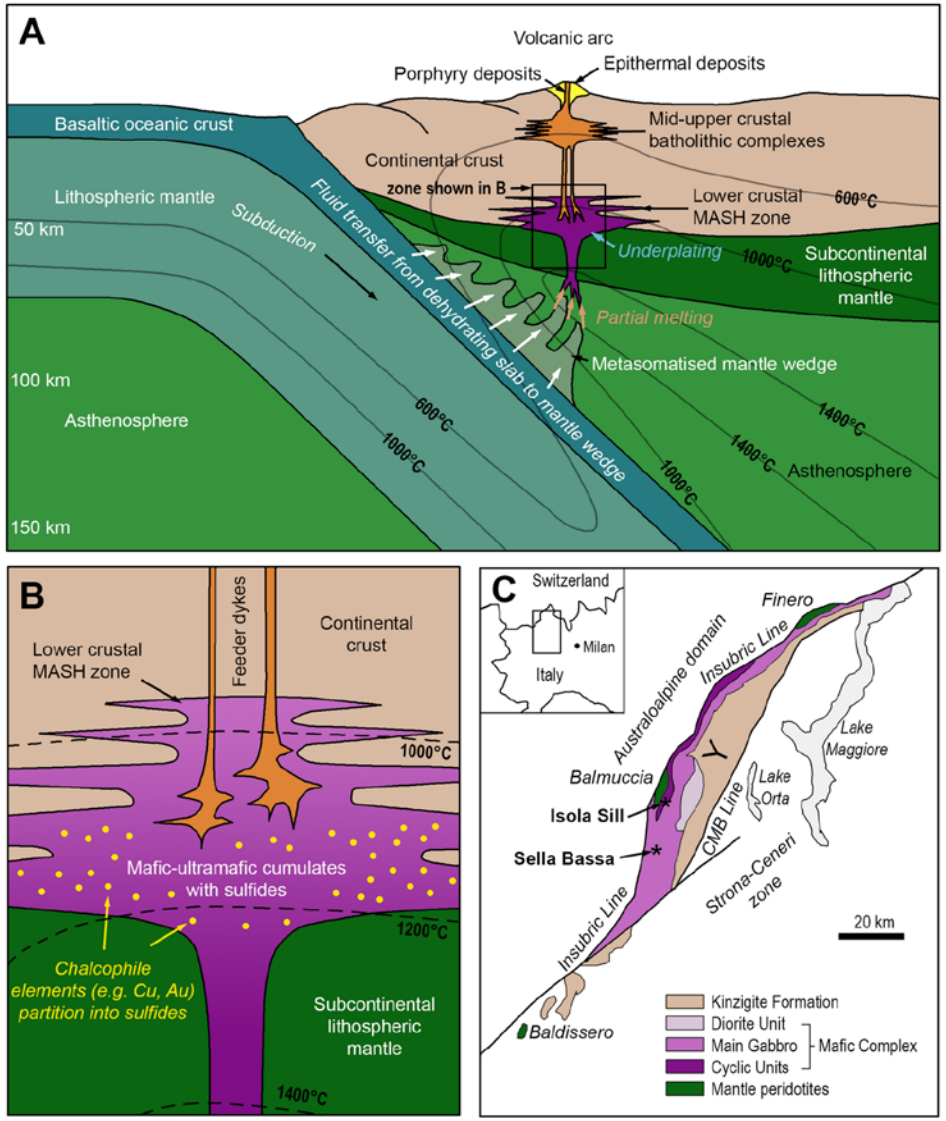


LOCATION

Mingelo	Two-Thirty prospect	Nash Hill Volcs.	Bushman Volcs.
Wombin Volcs.	Goonumbla Volcs.	Goonumbla (monzodiroite)	Goonumbla (mafic monzodiorite)
Goonumbla (monzonite + BQM)	Goonumbla (AFG-Syenite)	Goonumbla (K-QMF)	Goonumbla (KA-QMF)
Goonumbla (B-QMF)	Goonumbla (zero porphyry)	Goobang Volcs.	Nelungaloo intrusions
Nelungaloo Volcs.	Parkes Volcs.		

Legend
EM1 - Enriched Mantle 1
EM2 - Enriched Mantle 2
HIMU - High U/Pb mantle
MORB - Mid ocean ridge basalts

A model for igneous metallogenesis



Subduction-related substrate formed a basement to the Macquarie Arc with LILE enrichment of the sub-arc mantle and lower crust.

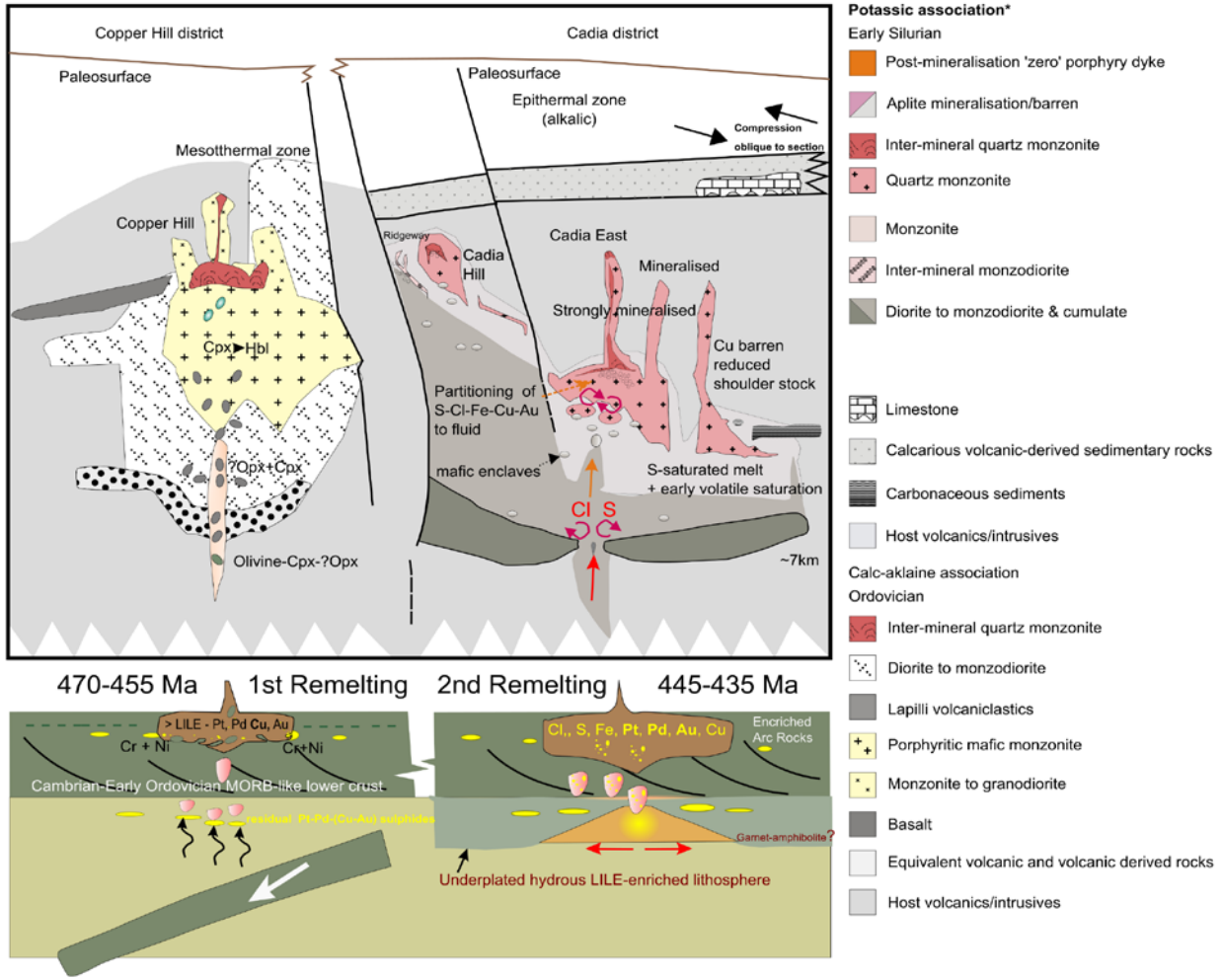
Pt-Pd were partitioned into sulfide phases, whereas Ni-Cr into silicate phases. Both remained in the metasomatised mantle. Some Pt-Pd-bearing olivine symplectites were entrained at Copper Hill (Blevin and Morrison 1998; Blevin 2002). Copper Hill also shows a range of (initial ratio) Pb-Pb isotope results (including being rather primitive).

Holwell et al. 2022 *Nature Communications*

A model for igneous metallogenesis

During the Benambran Orogeny low-percentage partial melting in thickened crust – remobilisation of Fe-Pt-Pd-Au along with Cu occurred in addition to freshly generated batches of melt-derived from aesthenosphere and amphibole ± garnet-bearing sources. Resulting in LILE-enriched, Pt-and Pd elevated and highly Au-enriched parent melts – including at Cadia.

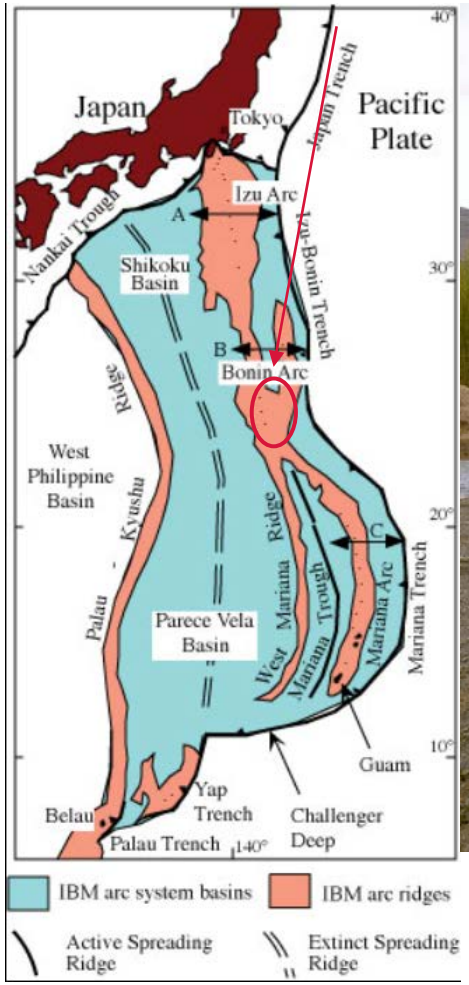
These were probably gold-rich but metal may also have been contributed by pre-existing sulphides and lesser silicates in the source region. All were emplaced in structurally competent architecture.



Analogues – the Izu–Bonin Arc?

Shoshonites

- Shoshonites occur in both low-percentage partial melting zones at depth beneath continental crust and metasomatised mantle in more primitive, subduction-related settings. Deeper generation necessarily requires phlogopite or amphibole-garnet-stable partial melting.
- Shoshonites are developed in thicker, more developed zones undergoing nascent rifting.
- The Izu–Bonin Arc is a reasonable, though imperfect analogue for the Macquarie Arc.
- **Macquarie Arc shoshonites are unlike those described in Tibet** e.g. derived from phlogopite-bearing source regions beneath thick crust.



Conclusions

- New geochronological, geochemical and isotopic data place new constraints on magma sources, which are fundamentally calc-alkaline and porphyry deposits formed mainly in a sediment-starved, subduction-related setting.
- All economic PCDs are associated with ~440 Ma Benambran event and are among the most K and LILE-enriched.
- Some rocks may be classified as shoshonites and suggest that prior LILE and probably enrichment in ore metals occurred from as early as the Late Cambrian.
- Many areas (most notably Goonumbla) show progressive enrichment over time.
- Most shoshonites are akin to those in post-collisional, subduction-related settings.
- Very similar, though more isotopically and compositionally evolved shoshonites are associated with mineralisation some 20 Ma after orogenesis and shutdown of arc magmatism **within the same host rocks**.

Alteration Facies – calc-alkaline deposits (including Copper Hill) vs Cadia