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Treasure maps, sustainable development, and the billion-year stability of cratonic lithosphere

Mark Hoggard, Karol Czarnota,
Fred Richards, David Huston,
Lynton Jaques & Sia Ghelichkhan

1 What are base metals and why do we care?

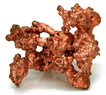
Consumption of base metals over the next ~25 years is set to exceed the total amount produced in human history to date. This trend is driven by global development and the transition to clean energy sources. A growing concern is that the rate of exploitation of existing reserves is outstripping discovery of new deposits.

Despite improvements in recycling efficiency and lower grade deposits becoming more economic, future projections based upon current discovery rates anticipate moderate to severe shortfalls for all four metals.



Nickel

- Catalysts
- Stainless steel
- Batteries & magnets
- Anti-corrosive plating



Copper

- Construction
- Power generation
- Electrics & wiring



Lead

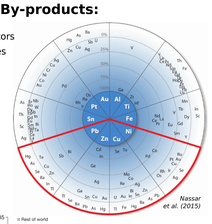
- Batteries & super-capacitors
- High voltage power cables
- Radiation shielding
- Photo-voltaic cells



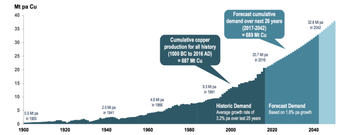
Zinc

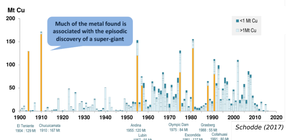
- Galvanisation
- Batteries & paints
- Agricultural fungicides

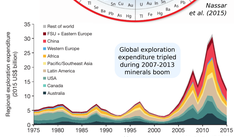
By-products:



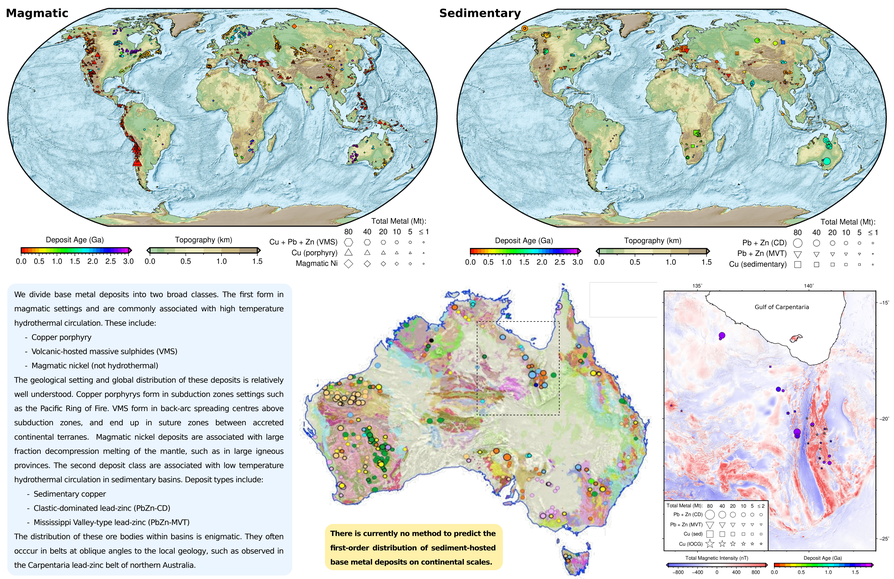
Nassar et al. (2015)







2 Where are base metal deposits located?



We divide base metal deposits into two broad classes. The first form in magmatic settings and are commonly associated with high temperature hydrothermal circulation. These include:

- Copper porphyry
- Volcanic-hosted massive sulphides (VMS)
- Magmatic nickel (not hydrothermal)

The geological setting and global distribution of these deposits is relatively well understood. Copper porphyrys form in subduction zones settings such as the Pacific Ring of Fire. VMS form in back-arc spreading centres above subduction zones, and end up in suture zones between accreted continental terranes. Magmatic nickel deposits are associated with large fraction decompression melting of the mantle, such as in large igneous provinces. The second deposit class are associated with low temperature hydrothermal circulation in sedimentary basins. Deposit types include:

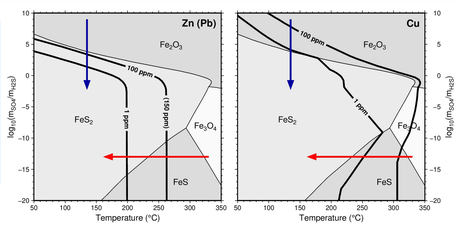
- Sedimentary copper
- Clastic-dominated lead-zinc (PbZn-CD)
- Mississippi Valley-type lead-zinc (PbZn-MVT)

The distribution of these ore bodies within basins is enigmatic. They often occur in belts at oblique angles to the local geology, such as observed in the Carpentaria lead-zinc belt of northern Australia.

There is currently no method to predict the first-order distribution of sediment-hosted base metal deposits on continental scales.

3 How do sediment-hosted deposits form?

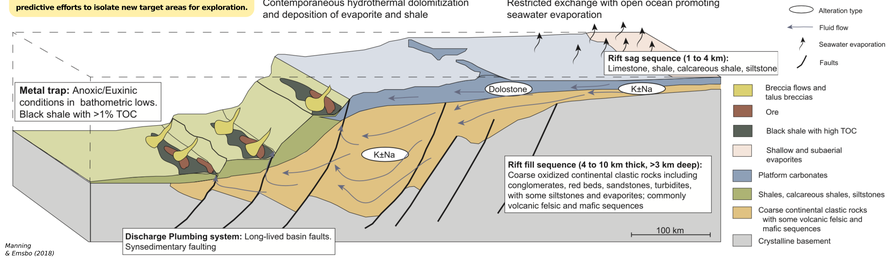
Sedimentary copper and lead-zinc are primarily deposited during rifting of extentional basins and passive margins in sedimentary packages 3 - 15 km thick (Hitzman et al., 2010; Leach et al., 2010). The copper and zinc are sourced from mafic rocks, whilst lead comes from felsic volcanics or arkosic sandstones. These metals are scavenged by basinal brines with moderate-to-high salinity (10 - 30 wt. % NaCl). Palaeomagnetic studies show that these deposits form at low latitudes where conditions for evaporite formation are optimal. In order to dissolve metals from source rocks, these fluids must have moderate temperatures (50 - 250 °C) and be buffered by oxidised terrestrial sediments, limiting the maximum age of deposits to the Great Oxidation Event at 2.4 Ga. Transport along faults focuses these fluids into oxidation-reduction interfaces, such as black shales with high organic carbon content, resulting in precipitation of metal (blue arrows on solubility plots). This reduction mechanism is ineffective at temperatures above 250 °C. Note that in contrast, magmatic deposits are generated by high-temperature hydrothermal circulation and require reducing fluids that cross this precipitation front by travelling down temperature (red arrows on solubility plots).



Sedimentary basins cover ~75% of the continental surface, and these separate mineral systems ingredients are widespread despite the rarity of giant deposits, hampering predictive efforts to isolate new target areas for exploration.

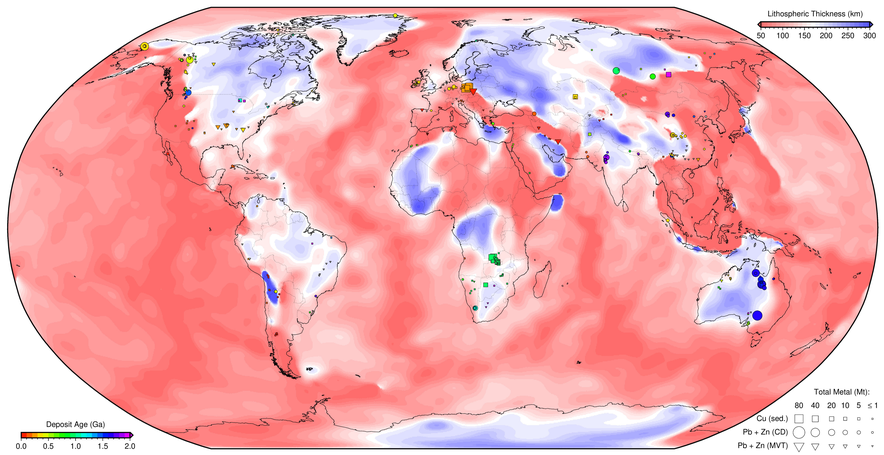
Fluid drive: Density-driven reflux. Contemporaneous hydrothermal dolomitization and deposition of evaporite and shale

Fluid source: Large shallow platform (>10^5 km^2). Restricted exchange with open ocean promoting seawater evaporation



Manning & Emsbo (2018)

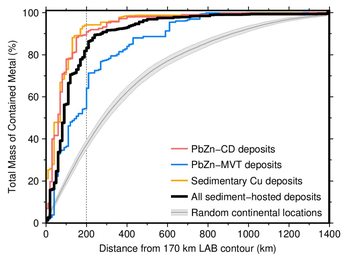
4 Is there a relationship with lithospheric structure?

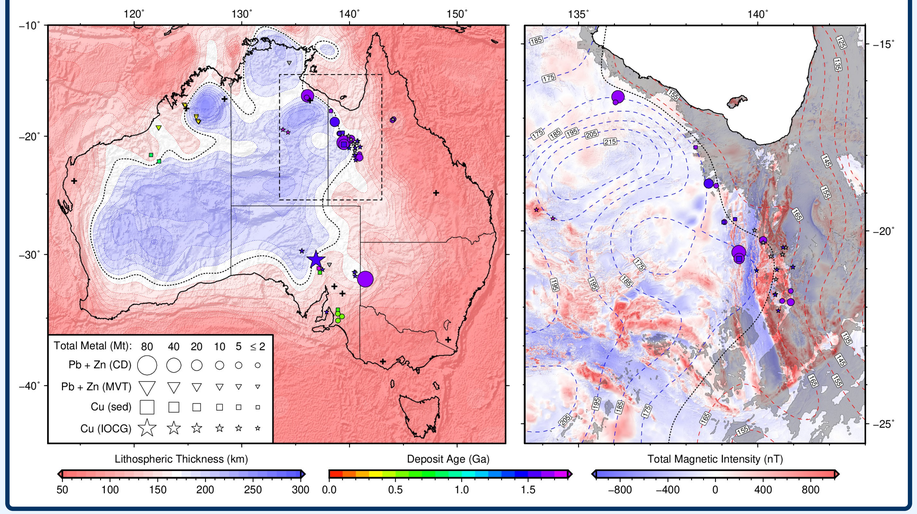


Genesis of sediment-hosted base metal mineral systems involves low-temperature hydrothermal circulation operating in sedimentary basins at shallow crustal levels. Nevertheless, there is a growing recognition that ore deposit locations (particularly magmatic) are fundamentally controlled by large-scale lithospheric structures. We have therefore chosen to investigate the relationship between sediment-hosted mineral systems and the most fundamental lithospheric structure - the lithosphere-asthenosphere boundary (LAB).

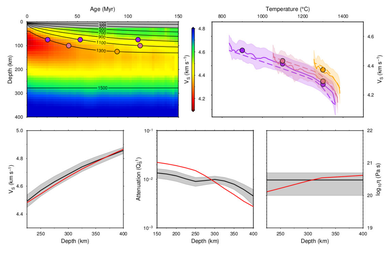
Lithospheric thickness is derived from the SL2013sv seismic tomography model (Schaeffer & Lebedev, 2013) and a calibration for anelasticity at seismic frequencies (see Box 5). There is a strong correlation between the location of giant sediment-hosted base metal deposits and the edges of thick lithosphere, with all deposits containing >10 megatonnes of metal within 200 km of the 170 km LAB contour. The SL2013sv tomography model contains only six seismometers in Australia (fewer than any other continent) and therefore has limited horizontal resolution. Switching to the local FR12 model (Fishwick & Rawlinson, 2012) reveals significantly finer details in lithospheric structure. The 170 km thickness contour passes in the vicinity of all large sediment-hosted base metal deposits, in addition to the Olympic Dam iron-oxide copper gold deposit (world's fourth largest copper and largest uranium deposit, with a value greater than $1 trillion).

Approximately 85% of the world's sediment-hosted base metal is found within 200 km of the present-day 170 km lithospheric thickness contour. This criterion alone narrows the search-space for new deposits by two-thirds. The 2 billion-year age range of these deposits suggests that the majority of thick lithospheric edges are stable on gigayear timescales.

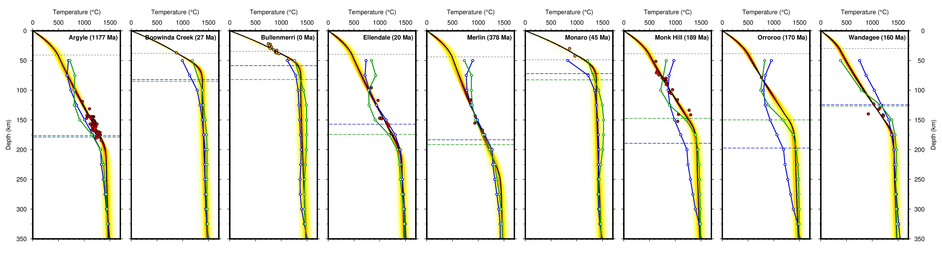




5 Calibrating a V_S to temperature conversion for mapping upper mantle structure



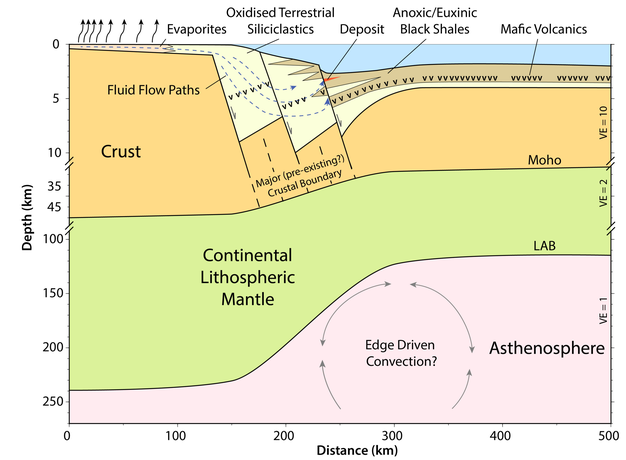
We adopt the parameterisation of Yamauchi & Takei (2016), which includes the effect of anelasticity in the pre-melt region. The global SL2013sv model (red lines) is calibrated using oceanic age-depth stacks and sub-plate adiabaticity, attenuation and bulk viscosity. Lithospheric thickness is obtained from the depth to the 1175 °C isotherm. For the regional FR12 model (Fishwick & Rawlinson, 2012; green lines), we instead fit nine geotherms (located at black crosses on Australia map). These have been constructed using thermobarometry on garnet lherzolite xenoliths and xenocrysts derived from kimberlite pipes and basaltic volcanics. P-T conditions for deeper samples are obtained using Nimis & Taylor (2000) clinopyroxene thermobarometry (blue circles). Shallower samples use the Nickel & Green (1985) barometer and Taylor (1998) thermometer (orange circles). Geotherms are fitted to these data using FITPLOT software (Mather et al., 2011). Note that both tomography models yield surprisingly good fits to the nodule data, despite SL2013sv not being calibrated using these constraints.



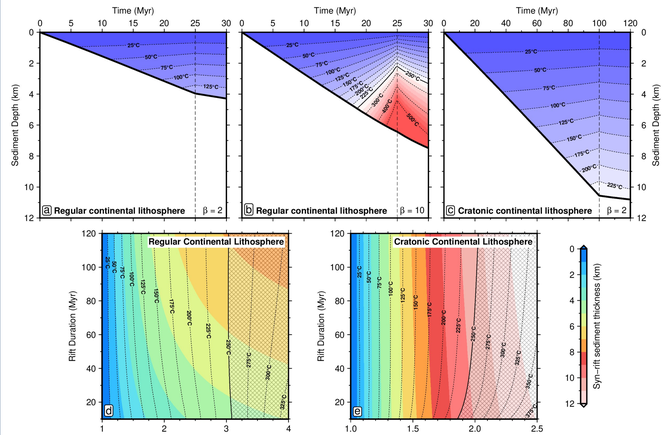
6 Why are giant deposits in cratonic rifts?

Our results indicate that the edges of thick lithosphere place first-order controls on the genesis of these extensional basins and their associated mineral systems. Rifting causes localised thinning and produces a lateral transition from oxidising terrestrial environments into marine settings that provides the optimal juxtaposition of the ingredients necessary for deposit formation. The adjacent unstretched cratons provide a bountiful source of oxidised sediments and extensive low-elevation platforms that enhance evaporite formation. Proximal land masses also promote restricted marine settings that are favourable for euxinic water conditions and deposition of reducing shales high in organic carbon. Thinning of the lithosphere in the centre of the basin causes decompression melting, providing mafic and felsic volcanic rocks from which metals are scavenged. Intercalation of proximal and distal facies components is further modulated by transient vertical motions, generally thought to be associated with edge driven convection across lithospheric steps. Nevertheless, these mineral system components are common to both thick lithospheric rifts and regular passive margins, and the question remains:

What is favourable about rifting cratonic lithosphere for formation of the shallow hydrothermal systems necessary to produce giant deposits?



A key observation is that metal precipitation by the oxidation-reduction mechanism is ineffective when brine temperatures exceed ~250°C. Hydrothermal fluid temperatures are buffered by conditions towards the base of the sediment pile and so the basal temperature of the sediments must not significantly exceed this threshold value. There are three important differences between rifting cratonic lithosphere versus normal continental lithosphere. First, the larger initial thickness results in a lower geothermal gradient and lower basal heat flow spike during rifting. Second, the density of cratonic lithosphere is reduced up to ~60 kg/m^3 as a result of chemical depletion, which increases the amplitude of syn-rift subsidence and provides a larger thickness of sediment and greater probability of containing all of the necessary mineral system ingredients. Third, rifting is slower and can last 50 - 100 Myr, in contrast to standard continental rifts that typically last for ~25 Myr, yielding a more extensive time window for mineralisation. Thus, rifting cratonic lithosphere produces more than twice the volume of mineral system ingredients without exceeding the thermal conditions necessary for successful precipitation, over a duration of time that can be up to a factor of four more extensive. Minor deposits may therefore occur in any extensional setting, but giant deposits requiring the largest volumes of fluid-rock interaction are restricted to rift basins at the margins of the thickest lithosphere.



Rifting of cratons is longer duration, forms thicker syn-rift sediment piles, and is compartively colder than standard continental lithosphere. This increases the likelihood of combining all mineral system ingredients and provides a more extensive operating window to generate giant sediment-hosted base metal deposits.