Minerals on the edge: sediment-hosted base metal endowment above steps in lithospheric thickness

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To meet the rising global demand for base metals – driven primarily by the transition to cleaner-energy sources – declining rates of discovery of new deposits need to be countered by advances in exploration undercover. Here, we report that 85% of the world's sediment-hosted base metals, including all giant deposits (>10 Mt of metal), occur within 200 km of the edge of thick lithosphere, irrespective of the age of mineralisation. This implies long-term craton edge stability, forcing a reconsideration of basin dynamics and the sediment-hosted mineral system. We find that the thermochemical structure of thick lithosphere results in increased basin subsidence rates during rifting, coupled with low geothermal gradients, which ensure favourable metal solubility and precipitation. Sediments in such basins generally contain all necessary lithofacies of the mineral system. These considerations allow establishment of the first-ever national prospectus for sediment-hosted base metal discovery. Conservative estimates place the undiscovered resource of sediment-hosted base metals in Australia to be ~50–200 Mt of metal. Importantly, this work suggests that ~15% of Australia is prospective for giant sediment-hosted deposits; we suggest that exploration efforts should be focused in this area.

The global transition to a cleaner-energy economy is driving demand for base metals (Cu, Pb, Zn and Ni), but significant shortfalls are forecast over the coming decades as discovery rates for new deposits decline (Ali et al., 2017; Schodde, 2017). Australia is not immune, despite hosting many high-quality sediment-hosted Cu, Pb and Zn deposits with companion critical minerals (Mudd et al., 2019). A consensus is emerging that the mineral exploration frontier now lies beneath post-mineralisation cover.

The undercover search space is vast (~80% of Australia) and drastically undersampled. Undercover exploration needs to focus on provinces with the greatest potential for new giant discoveries. The most common approach is to develop a conceptual genetic model of a deposit type largely based on ore deposit studies, and then interrogate spatial databases for key proxies (Hronsky and Groves, 2008). The genesis of sediment-hosted deposits requires oxidised, moderate-temperature (80–250 °C) and moderate- to high-salinity fluids (10–30 wt. % NaCl) that are sourced from evaporites. These brines scavenge metals as they flow through voluminous oxidised terrestrial sediments intercalated with magmatic rocks, before they are focused along faults into oxidation–reduction depositional interfaces such as black shales (Figure 1; Hitzman et al., 2010; Leach et al., 2010). The necessary lithologies for this mineral system can be locally identified in surface geological maps, but have so far been difficult to identify undercover, as systematic subsurface geological maps are in their infancy (Stewart et al., 2020). An alternative approach is to identify fertile basins at the regional scale by screening stacked geological provinces for the presence or absence of these key lithologies using the Australian Stratigraphic Units Database (ASUD; Stewart et al., 2013). These mineral system ingredients are common in many failed rifts and passive margins, so this approach only reduces the search space in Australia to ~60%.

Further reductions in exploration area at the national scale require extensive, homogenous datasets that have mineral system implications (Hronsky and Groves, 2008).

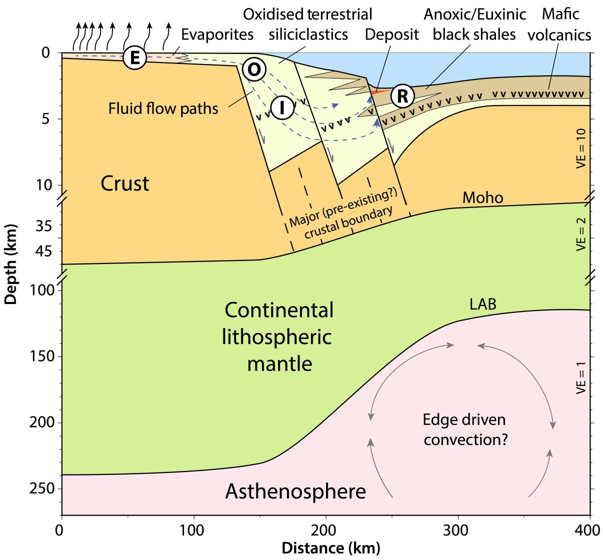

Figure 1 Schematic rift-related lithospheric architecture and four key sediment-hosted base metal mineral system components: (E)vaporitic source of basinal brines that scavenge metals from (O)xidised terrestrial sediments and (I)gneous mafic rocks on route to (R)eduction interfaces, such as black shales, where metals are deposited. Notice variable vertical exaggeration (VE) and prominence of the lithosphere–asthenosphere boundary (LAB) at 1:1 scale. Schematic based on deep reflection seismic profiles across the North Australian Zinc Belt and modelling by Manning and Emsbo (2018). Lithological proxies for the four components are E: Evaporite, Halite, Gypsum, Barite, Scapolite, Cauliflower chert, Sabkha, Stromatolite, Hopper crystals, Oncolite and Anhydrite; O: Dolostone, Dolomite, Dolo, Limestone and Arkose; I: Basalt, Mafic, Tholeiitic, Dolerite, Gabbro, Greenstone, Basic; R: <2 Ga, Black Shale, Carbonaceous.

Among others, seismic tomography techniques are ideal for providing this coverage, as seismic waves sample regions located between sparse seismometer stations (Gorbatov et al., 2020). For almost a decade, seismic tomography has been used to map first-order lithospheric mantle controls on magmatic ore deposits (Griffin et al., 2013). In contrast, deep

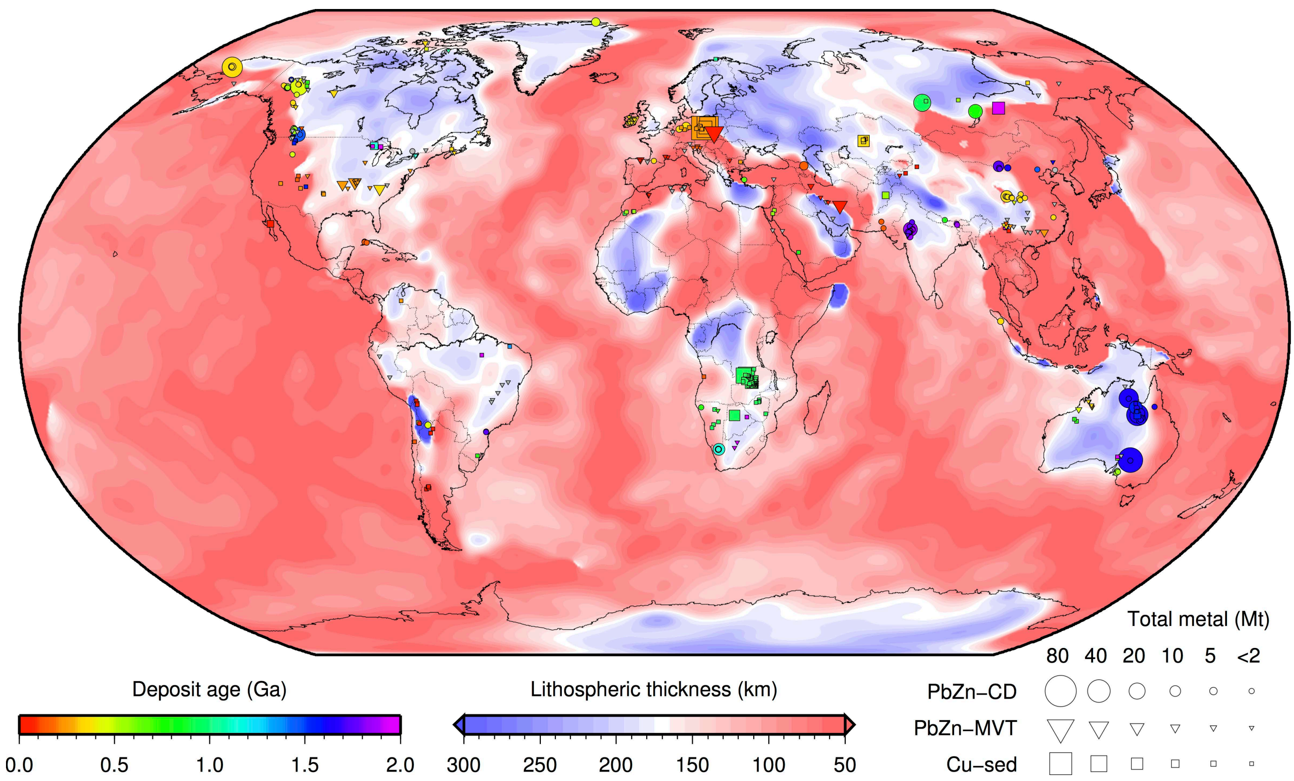

Figure 2: Global distribution of sediment-hosted base metal deposits as a function of lithospheric thickness. LAB derived from SL2013sv tomography model using a calibrated anelasticity parameterisation (Schaeffer and Lebedev, 2013; Yamauchi and Takei, 2016; Richards et al., in press). Symbols show deposit locations, coloured by deposit age (Ga = billion years) and proportional in size to total contained mass of metal (Mt = megatonnes); unknown deposit size is given a 2 Mt symbol; unknown deposit age is plotted in grey; circles are clastic dominated lead-zinc (PbZn-CD); triangles are Mississippi Valley–type lead-zinc (PbZn-MVT); squares are sedimentary copper (Cu-sed).

controls on sediment-hosted mineral systems have been largely overlooked, even though the influence of lithospheric structure on basin genesis is well established (McKenzie, 1978). As part of the Exploring for the Future program, Hoggard et al. (in press) discovered that all giant sediment-hosted mineral deposits (>10 Mt metal) are located above steps in the most fundamental upper mantle structure – the lithosphere–asthenosphere boundary (LAB). Here, we review this finding and the implications for mineral potential in undercover regions of Australia.

Lithospheric control on mineralisation

Given the sporadic distribution of giant mineral deposits, robust linking of geological features to deposit locations is best achieved through a global study. To this end, we compiled a global inventory of six major base metal deposit types from published sources. Three are associated with magmatic process, and three are sediment hosted: sedimentary copper (Cu-sed), clastic-dominated lead-zinc (PbZn-CD, or sedimentary exhalative) and Mississippi Valley–type lead-zinc (PbZn-MVT). Next, we used a method developed by Priestley and McKenzie (2013) of mapping the thermal LAB from seismic tomography, refined by Richards et al. (in press). This method takes into consideration recent laboratory experiments on the effect of anelasticity on shear-wave velocities (Yamauchi and Takei, 2016). We calculated a global LAB using the SL2013sv tomography model, calibrated to the latest thermal structure of cooling oceanic lithosphere (Schaeffer and Lebedev, 2013; Richards et al., 2018). We also calculated a higher-resolution Australian LAB using the FR12 tomography model (Fishwick and Rawlinson, 2012), calibrated using nine local paleogeotherms derived from thermobarometry of mantle xenoliths and xenocrysts.

The global LAB reveals a striking relationship between major sediment-hosted mineral deposits and the edge of thick lithosphere, outlined by the 170 km depth contour (Figure 2). This relationship is even clearer in the higher-resolution model of Australia, with iron-oxide-copper-gold (IOCG) deposits also lying along the same trend, including Olympic Dam (Figure 3a). Unfortunately, ongoing uncertainty in classification schemes of IOCG deposits has hindered our attempt to perform a global assessment of these systems.

To quantify the relationship, we calculated the distance between each sediment-hosted deposit and the 170 km LAB depth contour, and plotted the cumulative distribution function, weighting by the mass of metal within each deposit (Figure 3b). Globally, we find that ~90% of Cu-sed, ~90% of PbZn-CD and ~70% of PbZn-MVT resources are located within 200 km of the 170 km LAB depth contour (Figure 3b). This corridor corresponds to only one-third of continental surface area and encapsulates all giant sediment-hosted deposits. Since the width of this zone is similar to the ~280 km horizontal node spacing in SL2013sv, tighter constraints are only possible with higher-resolution tomography models. Indeed, all giant sediment-hosted and IOCG deposits in our higher-resolution model of Australia are located within 100 km of the 170 km LAB depth contour, illustrating the great benefit of increasing the passive seismic coverage of Australia (Figure 3a). This criterion alone reduces the exploration corridor in Australia to less than one-quarter of the continent (Figure 3c). We tested the significance of the relationship using the two-sample Kolmogorov–Smirnov test, which estimates that the probability of global sediment-hosted deposits representing random continental locations is less than 1 in 10^{12} (Kolmogorov, 1933). Surprisingly, deposit types associated with magmatism do not follow this simple trend. Volcanogenic

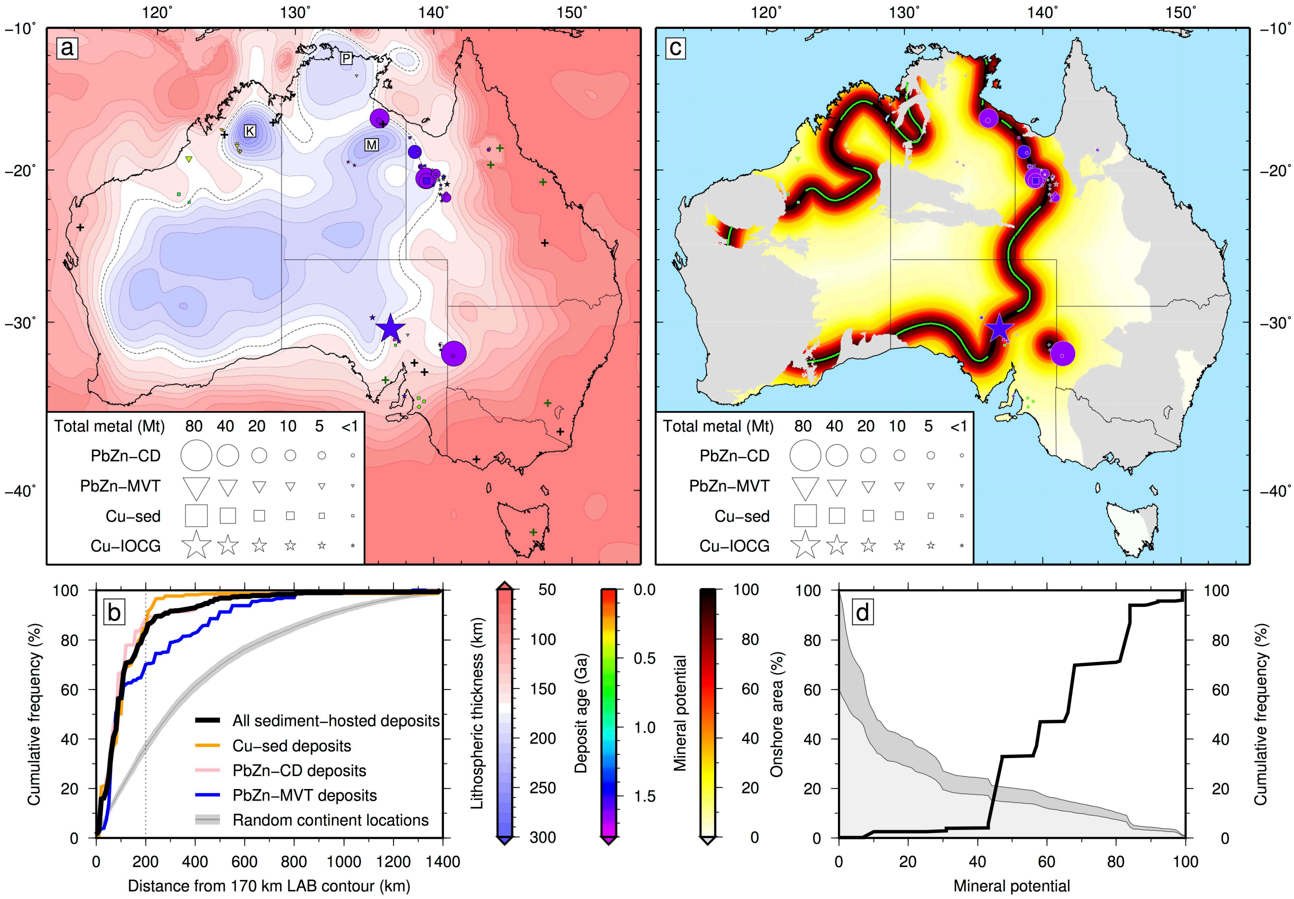

Figure 3 Distribution of sediment-hosted and IOCG deposits as a function of lithospheric thickness. (a) Australian LAB based on FR12 converted to temperature using an anelasticity parameterisation calibrated on local paleogeotherms; black dashed contour = 170 km LAB depth; symbols = deposit locations as in Figure 2, stars = IOCG deposits (largest is the Olympic Dam deposit); black/green crosses = geotherms used as constraints/tests in anelasticity calibration. Newly identified thick lithosphere blocks within northern Australia are named (K)imberley, (P)ine Creek and (M)urphy blocks. (b) Cumulative distribution function (CDF) for global sediment-hosted base metals, mass-weighted for 109 PbZn-CD, 147 PbZn-MVT and 139 Cu-sed deposits, and combination of all three; grey line/bound = mean and standard deviation of 100 sets of equivalent number of randomly drawn continental locations with respect to global LAB enhanced over Australia. (c) Mineral potential heat map based on CDF distance with respect to 170 km LAB contour (a) in areas where stacked geological provinces contain lithological proxies for all four sediment-hosted mineral system components illustrated in Figure 1; green line = underexplored or unexplored portions of the 170 km contour more than 100 km away from known deposits where prospective rocks lie mostly undercover; symbols = deposit locations as in Figure 3. (d) Performance of the mineral potential heat map; solid line = CDF for Australian sediment-hosted base metals, mass weighted; dark grey = percentage of Australian area with ≥ mineral potential value based on distance to LAB contour; light grey = as before but for the clipped coloured region shown in (c).

massive sulfide and porphyry copper deposits are randomly distributed with respect to the LAB edge, while magmatic nickel deposits are concentrated in regions of thicker lithosphere (see supplementary material of Hoggard et al., in press).

Mineral systems implications

This discovery has two important implications. First, the clustering of sediment-hosted base metal deposits on the edge of present-day thick lithosphere, regardless of their age, implies long-term lithospheric stability, spanning at least the last 2 billion years. Major pre- to syn-Paleozoic faults and shear zones of the North Australian Craton wrap around blocks of thick lithosphere, indicating that they have influenced strain partitioning and ore forming processes through multiple tectonic cycles (Figure 3a; Stewart et al., 2020). Other Australian observations that correlate with LAB steps include variations in lead isotopes from Proterozoic galena and pyrite minerals, long-wavelength gravity anomaly gradients, topographic variations, the western extent of Phanerozoic sedimentary basins, and the pattern of surface drainage (Huston et al., 2020; Sandiford et al., 2020). These observations corroborate the longevity of cratonic roots.

Second, this relationship forces a reconsideration of sediment-hosted base metal mineral system models, which to date have not considered the mantle as a first-order control. Hoggard et al. (in press) highlight four important and interlinked factors (Figure 1). (1) Lithospheric thickness steps localise strain during rifting, focusing the optimal juxtaposition of mineral system components. Evaporites and oxidising terrestrial environments are located inboard, whereas restricted marine settings with reduced facies and volcanics derived from shallow decompression melting occur outboard. (2) Rifting of thick lithosphere results in a broader spatial and temporal window for mineralisation. Increased seismogenic thickness results in deeper, longer, more widely spaced normal faults, and a greater lateral extent of sediments deposited within grabens. These faults are also active for longer periods. The entire syn-rift phase of basin formation, generally associated with mineralisation, can last 50–100 Myr, in contrast to standard continental rifts that typically last <25 Myr. (3) Crucially, rifting of cratonic lithosphere results in deeper basins with lower geothermal gradients. Given that thermodynamic considerations limit metal precipitation conditions to less than ~200 °C, these two features together substantially increase the depth extent of the mineral system operating window compared with standard lithosphere. (4) Deformation and exhumation along the edges of thick lithosphere are often mild, with orogenies generally focused in regions of thinner lithosphere. This setting therefore allows exhumation of deposits to the near surface, while increasing preservation potential through subsequent tectonic cycles. Notably, all of these factors contribute to cratonic edges being favourable for formation of giant deposits, but they do not preclude the generation of smaller deposits in standard lithosphere, thereby providing an explanation for minor outliers.

Estimating mineral potential

New predictive power from the LAB relationship can be combined with screening of stacked geological provinces for necessary lithologies. This approach provides a new perspective on the sediment-hosted base metal potential of Australia, reducing the exploration search space to just ~15% of the continent with plenty of opportunities (Figure 3d).

This result highlights frontier exploration areas and allows estimation of undiscovered sediment-hosted base metal resources. Unexplored or underexplored regions along the prospective 170 km LAB contour can be mapped by first projecting known deposits located within 200 km onto the contour, and then excising a 100 km radius around them (making the crude assumption that these regions have been explored). The remaining ~3700 km of the contour provides an indication of the frontier search space in Australia, the majority of which lies undercover (Figure 3c). Globally, ~26% of the contour hosts known deposits, yielding an estimated average endowment of ~55 kt of base metals per kilometre of contour. Applying these values to the length of underexplored contour in Australia suggests that ~50–200 Mt of base metals (worth ~$1 trillion) are still to be discovered in Australian frontier basins. These estimates are equivalent to the known resource in the North Australian Zinc Belt (~130 Mt Pb+Zn+Cu) and the Olympic Dam IOCG deposit (>80 Mt Cu).

Conclusion

The discovery that 85% of sediment-hosted base metals, including all the world's giant deposits, are found within 200 km of the edge of thick lithosphere has (1) forced revision of mineral systems and basin dynamic models within the context of lithospheric stability; (2) provided the first statistical basis for translating mineral system models to mappable proxies on global scales, and a new means of identifying frontier fertile basins; and (3) indicated, in combination with geological proxies, that ~50–200 Mt of base metals and associated critical minerals are likely to be still discovered in Australia. Taken together, these considerations suggest that the discovery of a new world-class sediment-hosted base metal minerals province in undercover Australia is realistic, and enable refocusing of exploration to achieve it.

Datasets

LAB grids can be downloaded from: http://pid.geoscience.gov.au/dataset/ga/132624.

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