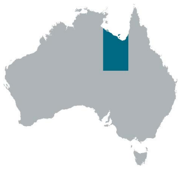

Lithospheric-scale controls on zinc–lead–silver deposits of the North Australian Zinc Belt: evidence from isotopic and geophysical data

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The North Australian Zinc Belt is the largest zinc–lead province in the world, containing 3 of the 10 largest individual deposits known. Despite this pedigree, exploration in this province during the past two decades has not been particularly successful, yielding only one significant deposit (Teena). One of the most important aspects of exploration is to choose regions or provinces that have greatest potential for discovery. Here, we present results from zinc belts in northern Australia and North America, which highlight previously unused datasets for area selection and targeting at the craton to district scale. Lead isotope mapping using analyses of mineralised material has identified gradients in μ ($^{238}U/^{204}Pb$) that coincide closely with many major deposits. Locations of these deposits also coincide with a gradient in the depth of the lithosphere–asthenosphere boundary determined from calibrated surface wave tomography models converted to temperature. In Australia, gradients in upward-continued gravity anomalies and a step in Moho depth corresponding to a pre-existing major crustal boundary are also observed. The change from thicker to thinner lithosphere is interpreted to localise prospective basins for zinc–lead and copper–cobalt mineralisation, and to control the gradient in lead isotope and other geophysical data.

Sediment-dominated basins are by far the largest global source of zinc and lead, containing 54% and 68%, respectively, of the world's pre-mining resources of these metals (D. Huston, B. Eglington [University of Saskatchewan], S. Pehrsson [Geological Survey of Canada] and S. Peircey [Memorial University of Newfoundland], pers. comm.). Because of the giant size of these deposits, they are attractive exploration targets. However, they are difficult to find because they are rarer than other zinc–lead deposits such as volcanic-hosted massive sulfide deposits.

Despite their attractiveness, very few major deposits have been discovered in the past two decades. One possible reason has been a poor understanding of fundamental, large-scale controls on mineralisation. Given that there are hundreds of basins in the world, are there ways to screen more prospective from less prospective basins?

The North Australian Zinc Belt, which is hosted by the Paleo- to Mesoproterozoic North Australian Basin System (Southgate et al., 2000, 2013), is the richest zinc province in the world, containing a total pre-mining resource of 89 Mt Zn and 41 Mt Pb—10% and 13%, respectively, of global pre-mining resources of these metals. As part of the Exploring for the Future program, Geoscience Australia has acquired new datasets and reprocessed old datasets to provide industry with new exploration tools for iron oxide–copper–gold and basin-hosted zinc–lead and copper–cobalt deposits. As part of this program, we have been assessing a range of criteria to identify fertile mineral provinces, including spatial variations in lead isotope, surface wave tomography and other geophysical data. This reassessment has led to some surprising correlations between these datasets and the distribution of basin-hosted zinc–lead deposits. Here, we present the evidence for these correlations and then speculate about their possible reasons.

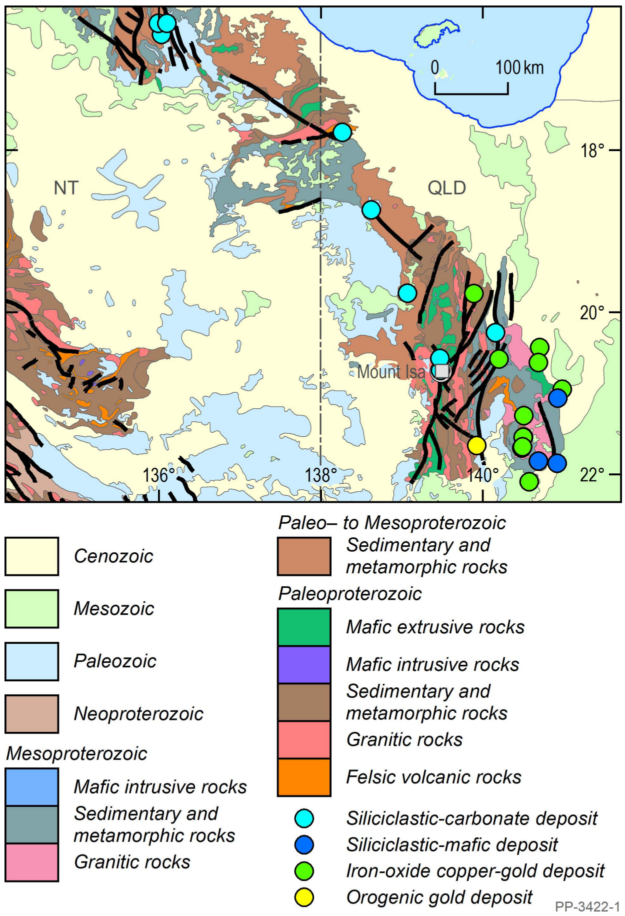

Figure 1 Simplified geological map of the North Australian Zinc Belt, showing the location of sediment-hosted zinc–lead, iron oxide–copper–gold and orogenic gold deposits (from Raymond et al., 2012).

North Australian Zinc Belt

The North Australian Zinc Belt (Figure 1) contains 3 of the 10 largest zinc–lead deposits in the world (McArthur River [HYC], Hilton-George Fisher and Mount Isa), as well as several smaller, but still important, deposits (Century, Dugald River, Teena, Lady Loretta and Cannington). Of these, only Teena is a recent (2013) discovery. In addition, significant copper–cobalt and zinc–lead resources are being defined at the Walford Creek deposit.

Figure 1 shows the surface geology of the North Australian Zinc Belt and the location of sediment-hosted zinc–lead and copper–cobalt deposits, as well as iron oxide–copper–gold and orogenic gold deposits. The North Australian Basin System, which hosts the North Australian Zinc Belt, has been subdivided into three superbasins: the 1780–1740 Ma Leichhardt, the 1730–1640 Ma Calvert and the 1640–1575 Ma Isa superbasins (Gibson et al., 2016). The Leichhardt Superbasin consists of a rift filled with continental tholeiites, fluvial to lacustrine siliciclastic and minor carbonate rocks (Jackson et al., 2000). The Calvert Superbasin consists of shallow-marine siliciclastic and carbonate rocks in the west, but deeper-marine siliciclastic rocks in the east that mostly lack carbonates but contain coeval mafic sills and possible lavas (Jackson et al., 2000; Southgate et al., 2013; Withnall and Hutton, 2013). Deposition of the siliciclastic-dominated succession in the east coincides with erosion and development of an unconformity and emplacement of granitic rocks to the west (Neumann et al., 2009). The uppermost Isa Superbasin consists of fluviatile to deep-marine sandstone, siltstone and dolostone (Southgate et al., 2000).

The North Australian Basin System has been compartmentalised into third- and fourth-order sub-basins by long-lived north-northeast- and northwest-trending faults (Figure 1). The former are steep to subvertical and thought to have been inherited from the underlying ≥1840 Ma crystalline basement (Gibson et al, 2017; Hejrani et al., 2020). The northwest-trending faults mainly formed during formation of the Calvert Superbasin as a right-stepping en echelon array of crustal-scale normal faults along the western margin of the Lawn Hill and Mount Isa regions, where the majority of zinc–lead deposits are located (Figure 1). This array originated during northeast–southwest-directed extension, and broadly marks the western limits of bimodal magmatism and lithospheric thinning during and before formation of the Calvert Superbasin (possibly indicating a craton edge). Along with the older basement faults, these Calvert-age faults were reactivated during later basin-forming events, and strongly influenced the location and distribution of younger, more easterly-trending sub-basins of the Isa Superbasin. Calvert-age faulting and rift-related basaltic magmatism concluded at or before ca. 1655 Ma, to be followed by thermal subsidence, basin inversion and orogenesis from ca. 1650 to ca. 1640 Ma (Riversleigh Event; Withnall and Hutton, 2013; Gibson et al., 2017). Subsequent to this event, extension resumed in a north–south-directed orientation and continued until ca. 1620 Ma when terminated by onset of the Isan Orogeny (e.g. Gibson et al., 2017). Orogenesis and sedimentation in the Isa Superbasin came to a close around 1575 Ma. No basaltic rocks are present in this basin, which, with the exception of minor, but locally abundant, tuff horizons (e.g. Davidson and Dashlooty, 1993) and late ca. 1620 Ma rhyolite sills, was largely amagmatic (Gibson et al., 2018).

The sediment-hosted zinc–lead deposits are hosted by the Calvert and Isa superbasins. The oldest deposits, which include the Cannington and Pegmont deposits, formed at ca. 1680 Ma in the eastern, siliciclastic-dominated part of the Calvert Superbasin (hereafter siliciclastic-mafic deposits). The upper part of the Calvert Superbasin hosts the ca. 1665 to ca. 1645 Ma Dugald River, Mt Isa, Hilton-George Fisher and Lady Loretta deposits, whereas the Isa Superbasin hosts the ca. 1640 Ma McArthur River and Teena deposits, and the ca. 1575 Ma Century deposits further to the north and west. These deposits (hereafter siliciclastic-carbonate deposits) are hosted in dolomitic and carbonaceous siltstone units within successions that contain abundant carbonate but lack significant volcanic rocks. In contrast, the succession that hosts the Cannington and Pegmont deposits lacks carbonate but contains abundant shallow-level mafic sills.

Variations in lead isotope data

Previous studies (Huston et al., 2014, 2016) have shown that variations in parameters such as μ ($^{238}U/^{204}Pb$), as determined from lead isotope data, can indicate spatial controls and fertility of mineral provinces. Figure 2 shows spatial variations in μ (calculated using the Stacey and Kramers [1975] lead isotope evolution model) in the North Australian Zinc Belt, determined mostly from analyses of ore-related galena and Pb-rich pyrite from deposits and prospects. μ increases from northeast to southwest, and most siliciclastic-carbonate zinc–lead and the Tick Hill orogenic gold deposits are localised along a north-northwest-trending break in μ values. Interestingly, these deposits have a relatively consistent spacing of about 140 km along this break. Iron oxide–copper–gold and siliciclastic-mafic zinc–lead deposits are located to the east of this break. Other parameters determined from lead isotope data, including κ ($^{232}Th/^{238}U$) and ω ($^{232}Th/^{204}Pb$), define a similar break. In detail, the break in μ appears to be en echelon, broadly following the trend of the northwest-trending Calvert-age structures, with individual offsets or steps determined by the position of the underlying north-northeast basement structures (Figure 2). As both sets of structures are thought to have been active during formation of the Calvert and Isa superbasins and their sub-basins, it would appear that

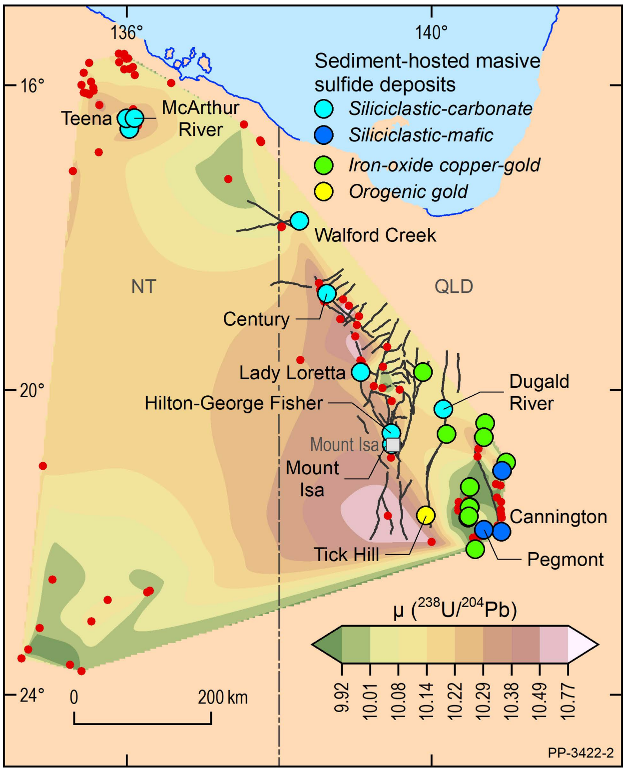

Figure 2 Map showing variations in μ ($^{238}U/^{204}U$) in the North Australian Zinc Belt as determined from galena and pyrite analyses of mineral occurrences and deposits. The Stacey and Kramers (1975) lead evolution model was used to calculate μ. Faults are from Murphy et al. (2011) and differ from those of Raymond et al. (2012) shown in Figure 1.

variations in μ mimic development of these sub-basins along the isotopic break. Although the break in μ appears to be controlled by basement structures, the break itself cuts across the north–south fabric of the surface geology, particularly in the east.

Lithosphere–asthenosphere boundary as defined by surface wave tomography

Figure 3 shows that the locations of major deposits coincide with the transition from thick to thin lithosphere, mapped by converting a surface wave tomography model to temperature and isolating the 1175 °C isotherm (Fishwick and Rawlinson, 2012; Hoggard et al., in press). More specifically, all deposits in the North Australian Zinc Belt—including zinc–lead deposits hosted by carbonate-rich and siliciclastic-dominated succession, and iron oxide–copper–gold deposits—are within 100 km of the 170 km thickness contour. Major deposits are unknown outside this corridor, even though the North Australian Basin System extends well beyond it. Like the lead isotope pattern, the edge of thick lithosphere cuts across the local geological grain in the east (compare Figure 3 with Figure 1), suggesting a more fundamental, deep-seated control on mineralisation.

The first indication that sediment-hosted zinc–lead deposits were associated with regional-scale breaks was the observation by Hobbs et al. (2000) that the major zinc–lead deposits in the North Australian Zinc Belt were aligned along a composite gravity 'worm' or horizontal gradient in gravity data. They found that this horizontal gradient persisted as the gravity data were upward-continued, suggesting that the worm indicated the existence of a major crustal break.

Figure 4 illustrates variations in the Bouguer gravity anomaly (from Geoscience Australia's national gravity grid based on 4–11 km spaced ground gravity data) upward-continued to 100 km. The image indicates that deposits are localised along a gravity gradient that is very similar to the

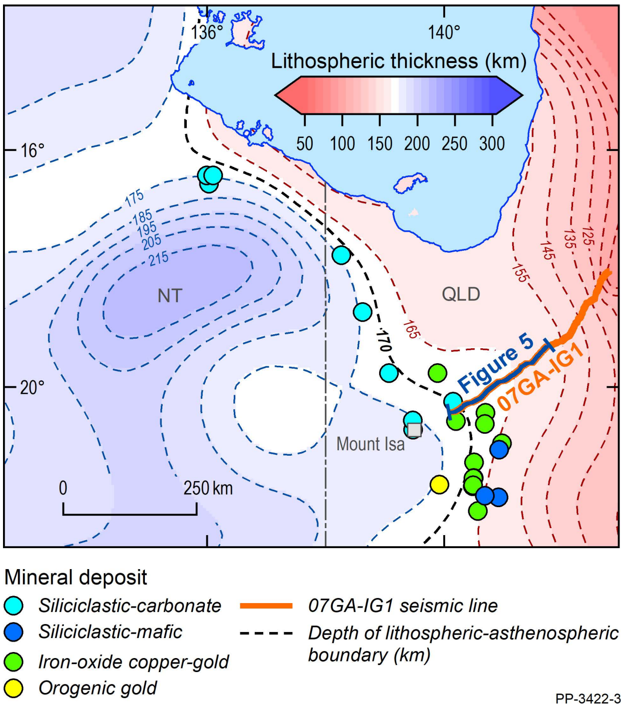

Figure 3 Mineral deposit locations relative to depth of the LAB (Hoggard et al., in press). Contours = LAB depths in km; blue = thick lithosphere; red = thin lithosphere; heavier dashed line = 170 km contour. Symbols are scaled by deposit size and coloured by age. Heavy black line = location of Figure 5.

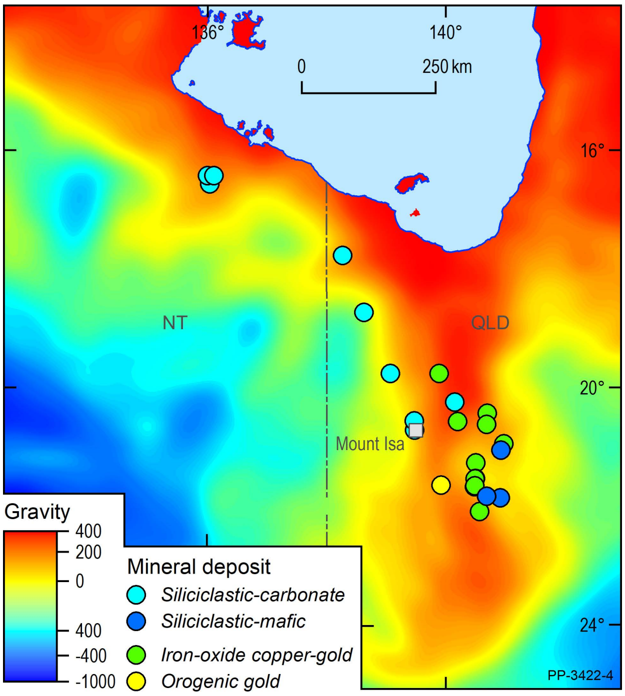

Figure 4 30 km upward-continued Bouguer gravity anomaly map with overlain deposits

170 km lithosphere–asthenosphere boundary (LAB) contour. This gravity gradient separates low-density rocks to the southwest from higher-density rocks to the northeast, most likely at lithospheric mantle depths. Interestingly, the Leichhardt River Trough is positioned over these denser rocks and contains a large thickness of mafic igneous rocks.

Reflection seismic data

In 2007, Geoscience Australia, in collaboration with the Geological Survey of Queensland, collected a series of reflection seismic transects (Korsch et al., 2012), one of which—07-IG1—crossed the gradients in μ, LAB depth and gravity described above. Figure 5 shows a northeast–southwest section that crosses near the Mount Isa deposit, illustrating the variation in crustal architecture and the LAB based on this transect and the LAB model.

As indicated by Figure 5, the 170 km LAB contour corresponds to a change in crustal thickness (cf. Gorbatov et al., 2020) and an interpreted major crustal boundary (Gidyea Suture) that separates two crustal blocks: the thicker Mount Isa Province to the southwest (one-layer crust) and the

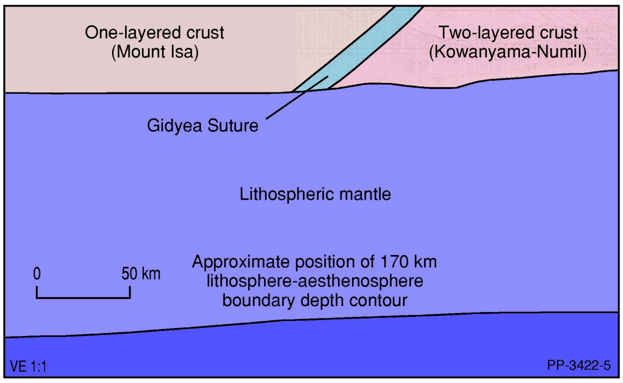

Figure 5 Cross-section across the North Australian Zinc Belt (no vertical exaggeration; location in Figures 1 and 3). Upper mantle and crustal structure based on reflection seismic traverse 07-IG1 (Korsch et al., 2012) and estimates of the depth of the LAB (Hoggard et al., in press).

thinner Kowanyama/Numil Seismic Province (two-layered crust) to the northeast.

Comparison with other sediment-hosted zinc–lead provinces

Data from the North Australian Zinc Belt suggest that most major deposits are localised along isotopic breaks, and along specific contours and corridors defined by geophysical data. Although these relationships are reasonably well defined in the North Australian Zinc Belt, the question is whether these relationships are global and, hence, have broader implications.

Although lead isotope data are relatively limited in the global sense, the availability of large datasets from Alaska (Church et al., 1987) and western Canada (Thorpe, 2008 has allowed construction of a map showing variations in μ for the northern Cordillera of western North America (Figure 6). This region contains two top-10 global zinc–lead deposits (Red Dog and Howards Pass). As in the North Australian Zinc Belt, there is a strong spatial association between sediment-hosted zinc–lead deposits and a gradient in μ.

Figure 6 shows that basin-hosted zinc–lead deposits in the northern Cordillera of western North America also correspond with the 170 km LAB contour derived from surface wave tomography. We have not tested for a

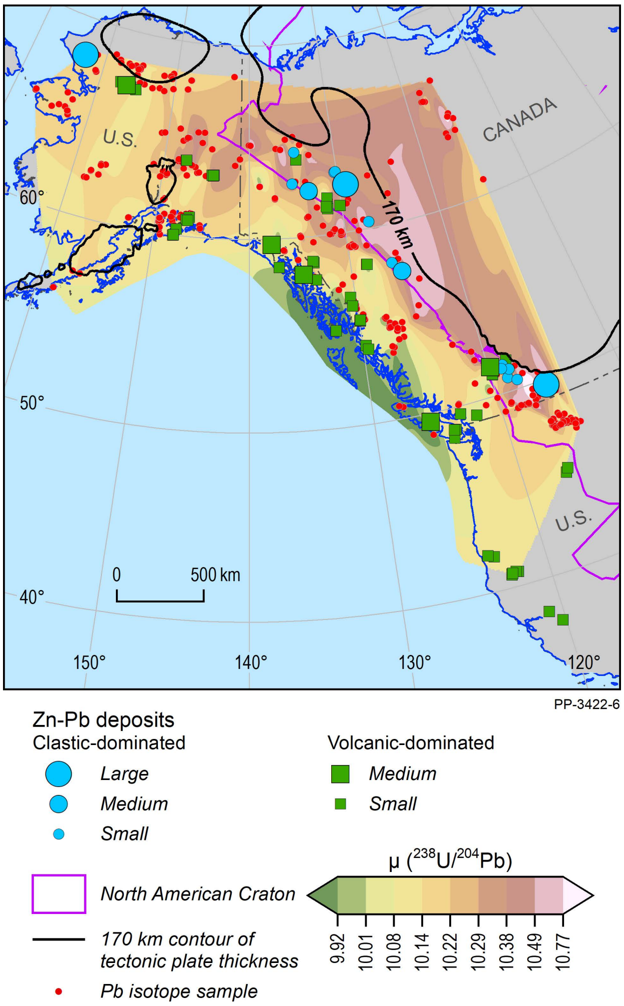

Figure 6 Map of the northern Cordillera of western North America, showing variations in μ. The map also shows the locations of basin-hosted zinc–lead and volcanic-hosted zinc–lead–copper deposits (after Huston, Pehrrson, Eglington and Piercey, unpublished data) and the western margin of the North American Craton (B. Eglington, pers. comm., 2020).

correlation of the deposits with gradients in upward-continued gravity data. Despite this, the location of basin-hosted zinc–lead deposits, the gradient in μ and the 170-km-depth LAB depth contour all correspond to the edge of the North American Craton.

Analysis by Hoggard et al. (in press) of global correlation between LAB depth and the distribution of sediment-hosted deposits showed that 85% of zinc resources and 85% of copper resources were located within 200 km of the 170 km contour. The correlation with the LAB, originally identified in the North Australian Zinc Belt, applies globally, and therefore we suspect that the gradient in μ and gravity do also.

Discussion

Disparate datasets suggest that basin-hosted zinc–lead deposits in the North Australian Zinc Belt and around the world are associated with changes in the isotopic character and thickness of the crust and lithosphere. Data from the North Australian Zinc Belt suggest that these changes correspond to pre-existing breaks between crustal blocks, and data from western North America suggest that deposits there correspond to the western boundary of the North American Craton.

We interpret these correlations to reflect regional- or global-scale controls on the setting of basins that host zinc–lead deposits. In Australia, we showed that gradients in μ, LAB depth and upward-continued gravity are associated with the location of the Gidyea Suture on reflection seismic profile 07-IG1. We infer that this suture acted as a pre-existing weakened zone that localised extension, and the thinning of the crust and lithospheric mantle as the North Australian Basin System evolved. The gradient in μ (which corresponds with a gradient in upward-continued gravity) is likely to reflect the emplacement of dense and juvenile mafic volcanic and subvolcanic rocks in thinned crust to the northeast.

As discussed by Gibson et al. (2016, 2018), sub-basin development in the North Australian Basin System was compartmentalised during northeast–southwest-directed extension. Figure 7, which is oriented northeast–southwest, illustrates this conceptual architecture, with the reactivated Gidyea Suture forming a backstop to developing northeast- and east-dipping extensional faults, some of which are visible on the 07-IG1 seismic traverse (cf. Korsch et al., 2012). This architecture is compatible with the sedimentary facies model proposed by Neumann et al. (2009), which suggests the development of shallow-water shelf-type sedimentary successions inboard (to the southwest) and deeper-water turbiditic successions outboard (to the northeast) at the ramp or shelf edge.

As modelled by Hoggard et al. (in press), changes in crustal and lithospheric thickness inferred from gradients observed in μ, LAB and upward-continued gravity produce different thermal regimes within rift basins and, hence, hydrothermal fluid conditions. Thicker subcontinental lithospheric mantle in effect insulates the overlying basin from hot asthenosphere mantle during mild to moderate rifting, resulting in lower thermal gradients within the rift basins. In addition, thicker basins develop during rifting of the thick, and therefore necessarily buoyant, lithosphere. These two factors combine to produce voluminous sedimentary basis with lower-temperature basinal brines, which, if oxidised, can be highly efficient at transporting base metals (Huston et al. 2016).

Other data bearing on basin fertility

Global reviews on the characteristics and temporal distribution of basin-hosted zinc–lead deposits (Leach et al., 2005, 2010) provide additional information on important

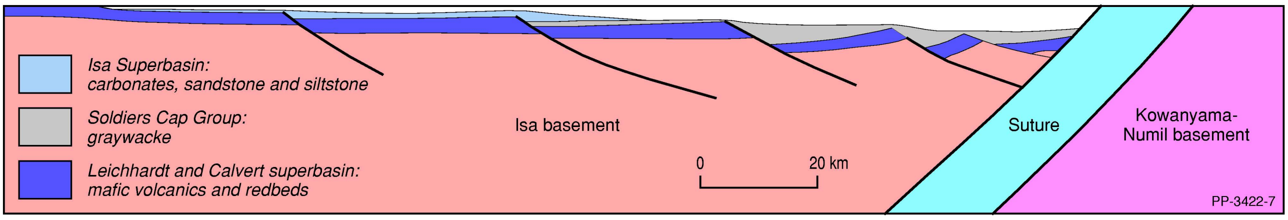

Figure 7 Conceptual northeast–southwest transect of the upper crust, showing the hypothesised basin architecture of the North Australian Zinc Belt

controls of these deposits. The oldest major basin-hosted zinc–lead deposit has an age of ca. 1850 Ma, and there is a major cluster, including deposits from the North Australian Zinc Belt, at ca. 1850 to ca. 1490 Ma. This cluster followed the development of an oxidised, upper layer of the ocean (Farquhar et al., 2010), which allowed, for the first time, the development of oxidised fluids essential for hydrothermal transport in cool basins formed over thickened lithosphere. Hence, a basin age younger than ca. 1900 Ma can be used as an additional criterion to define more prospective basins.

Information on paleo-environment at the time of mineralisation can also refine the search space. Based on Phanerozoic deposits, Leach et al. (2005) suggested that virtually all basin-hosted zinc–lead deposits formed within 30° of the equator, with most 10–30° from the equator, the equivalent of modern desert belts. Paleomagnetic data suggest that the North Australian Zinc Belt was within 40° of the equator at the time of mineralisation (Idnurm, 2000). These data indicate that an arid littoral environment, which is critical to form evaporative brines, is essential to form basin-hosted zinc–lead deposits. In addition to paleomagnetic data, the presence of evaporites, evaporitic textures, evaporitic minerals, or mineral or textural pseudomorphs within the host succession may also indicate favourable basins (Czarnota et al., 2020).

Cooke et al. (1998) and Champion et al. (2020) have demonstrated that zinc and copper in some basaltic rocks from the Leichhardt and Calvert superbasins have been depleted in association with regional chlorite-, K-feldspar- and/or hematite-bearing alteration assemblages. Preliminary data suggest that the copper leaching may be associated with demagnetisation of the basalt (Champion et al., 2020).The presence of such rocks at deep levels may be an additional characteristic of a fertile basin.

All significant silicilastic-carbonate deposits in the North Australian Zinc Belt are hosted by carbonaceous and dolomitic siltstone lenses within carbonate- and/or sandstone-rich successions (Large et al., 2005; Czarnota et al., 2020). These fine-grained units most likely formed in restricted, deeper-water depocentres, and acted as redox traps to deposit metals from oxidised ore fluids either diagenetically in the shallow subsurface (Williams, 1978) or syngenetically at the sea floor (Large et al., 2005). The presence of these fine-grained rocks enhances the fertility of basins for siliciclastic-carbonate zinc–lead deposits (although not for some other basin-hosted deposits), and identification of the spatial and temporal positions of these depocentres can further constrain the search space.

Idnurm (2000) showed that many of the major siliciclastic-carbonate zinc–lead deposits in the North Australian Zinc Belt are temporally associated with bends in the apparent polar wander path of the North Australian Craton. The 1635–1645 Ma McArthur River and Lady Loretta deposits correspond in time not only to a major bend, but also to the Liebig Orogeny (Scrimgeour et al., 2005) on the southern margin of the North Australian Craton and the Riversleigh Tectonic Event. Hence, the trigger of fluid flow in the North Australian Zinc Belt may be local or out-of-area structural–tectonic events that are apparent in the paleomagnetic and/or structural history of the North Australian Craton. This information may provide time constraints that can further refine the exploration search space.

Conclusions

Although cartoon-like diagrams of basin-hosted mineral systems (e.g. Leach et al., 2005; Huston et al., 2016) have long suggested that these deposits form along the edges of continental blocks on passive margins, this study has shown that data such as ore lead isotope analyses, surface wave tomography converted to temperature and upward-continued gravity can map the distribution of these cratonic margins, even if the margins have been involved in later collisional events. The surface wave tomography data, in particular, suggest that continental margins are associated with thicker lithosphere, and seismic reflection data suggest that the formation of the passive margins might be localised along pre-existing crustal boundaries. These features appear to be a first-order control on basins that are fertile for basin-hosted mineral deposits and can be used as exploration guides in area selection.

Modelling of this architecture suggests that thick lithosphere insulates the overlying basins from the asthenospheric mantle, leading to thicker and cooler basins (Hoggard et al., in press). This architecture, in combination with the oxidation of the upper ocean, allowed, for the first time, the development of large volumes of low-temperature, oxidised basinal brines, which are potent ore fluids capable of carrying high concentrations of zinc, lead and copper. Mafic volcanic rocks, present towards the base of the North Australian Basin System, are potential source rocks that appear to have lost copper, zinc and lead, at least at the local scale (Cooke et al., 1998; Champion et al., 2020).

Fluid flow may have been triggered by local or out-of-area tectonic or structural events, and metal deposits have been localised in depocentres characterised by thickened intervals of carbonaceous and dolomitic siltstone. Czarnota et al. (2020) have undertaken preliminary studies assessing the fertility of basins across Australia using many of these criteria.

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