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LETTER

A crucial role for slab break-off in the generation of major mineral deposits: insights from central and eastern Australia

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Abstract In the Lachlan Fold Belt of southeastern Australia, major orogenic gold and porphyry gold–copper deposits formed simultaneously within distinct tectonic settings during a very short time interval at ca. 440 Ma. The driving mechanism that controlled the temporal coincidence of these deposits remains largely unexplained. A review of contemporaneous metallogenic, tectonic, magmatic and sedimentological events in central and eastern Australia reveals that a change in subduction dynamics along the Australian sector of the Early Palaeozoic circum–Gondwana mega-subduction system could have influenced lithospheric stress conditions far inboard of the subduction margin. The magnitude of ore formation and the spatial extent of related events are proposed in this paper to have been controlled by the interplay of mantle processes and lithospheric changes that followed slab break-off along a portion of the mega-subduction system surrounding Gondwana at that time. Slab break-off after subduction lock-up caused mantle upwelling that, in turn, provided an instantaneous heat supply for magmatic and hydrothermal events. Coincident reorganisation of lithospheric stress conditions far inboard of the proto-Pacific margin of Australia controlled reactivation of deep-lithospheric fault structures. These fault systems provided a pathway for fluids and heat fuelled by mantle upwelling into the upper lithosphere and caused the deposition of ~440 Ma gold deposits in the Lachlan Fold Belt, as well as a range of metallogenic, tectonic and sedimentary changes elsewhere in central and eastern Australia.

Keywords Lachlan Orogen · Ore deposits · 440 Ma · Slab break-off · Mantle upwelling

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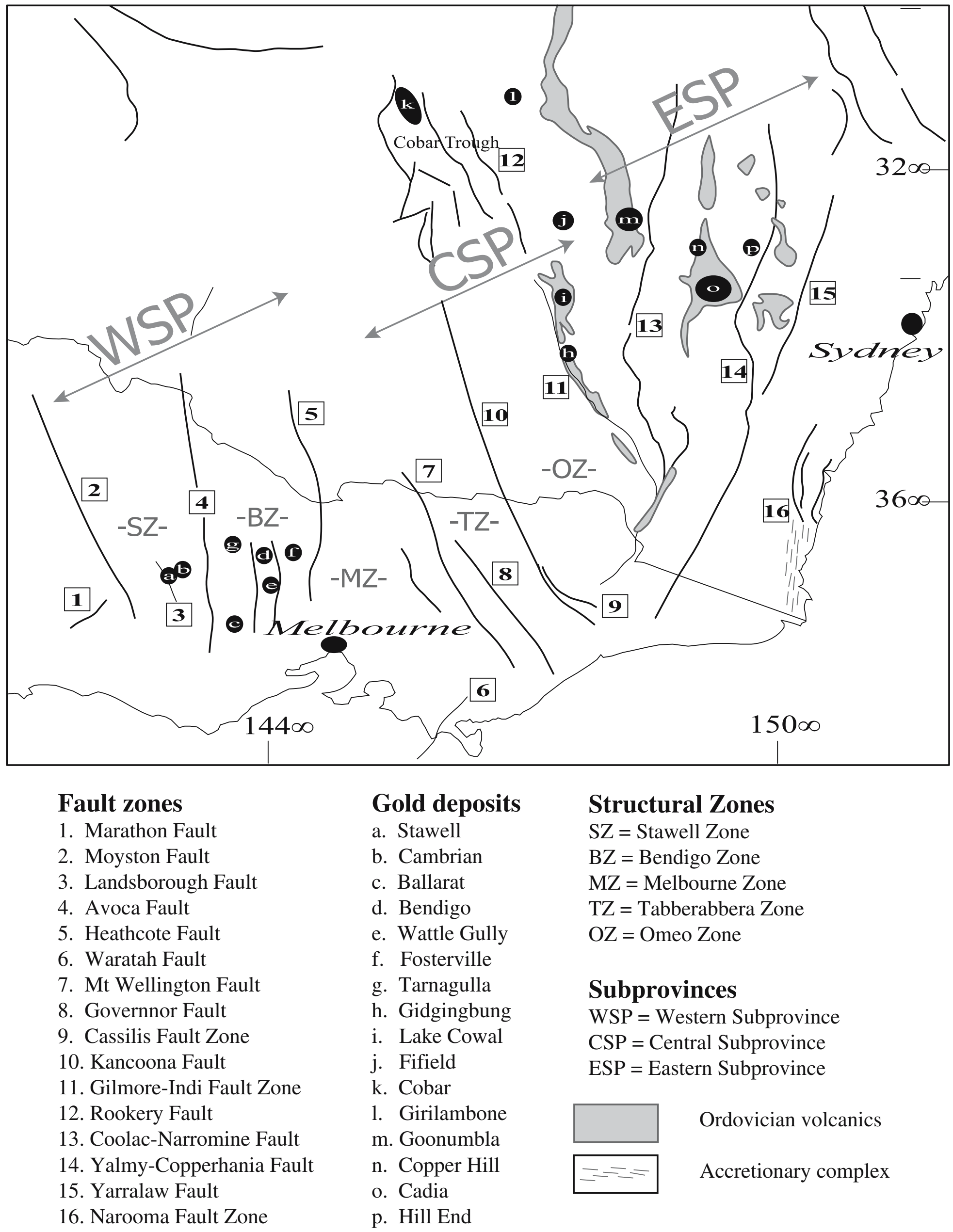
Introduction

An extraordinary large number of mineralisation ages for gold deposits in the Lachlan Orogen in southeastern Australia (Fig. 1) concentrate around 440 Ma (Perkins et al. 1995; Foster et al. 1998; Bierlein et al. 2002). These deposits reflect distinct mineralisation styles that include orogenic gold deposits formed in fore-arc- to back-arc-like settings in the western subprovince of the Orogen and porphyry gold–copper deposits that formed in an intra-arc setting in the eastern subprovince (Bierlein et al. 2002; Gray et al. 2002). Contemporaneous with the generation of these gold deposits, metallogenic, tectonic and magmatic events occurred in central and eastern Australia (e.g. Mawby et al. 1999; Vandenberg et al. 2000; Elburg et al. 2003; Groves et al. 2003).

Fig. 1 Geological element map of the Lachlan Orogen (modified after Gray et al. 2002) indicating fault structures and major ~440 Ma gold deposits in the western, central and eastern subprovinces



Several authors have considered mechanisms to explain some of these ca. 440 Ma events. Wang and White (1993) suggested that extensional orogenic collapse controlled the development of structures and mineral deposits in the western subprovince of the Lachlan Orogen. Elburg et al. (2003) proposed that simultaneous hydrothermal-magmatic activity in central Australia and mineralisation in central and eastern Australia at ca. 440 Ma were controlled by the global redistribution of tectonic plates after the Taconian Orogeny. Squire and Miller (2003) inferred that the generation of major gold deposits at ~440 Ma across the Lachlan Orogen could be attributed to slab rollback and mantle upwelling along the margin of Gondwana. However, the existence and nature of a driving force behind the occurrence of contemporaneous events across an area far greater than the accretion–subduction system of the Lachlan Orogen remains unresolved. In this paper, we invoke a unifying, lithospheric-scale driving mechanism that can rationalise the coincidence of ca. 440 Ma metallogenic, magmatic and tectonic events in spatially separated, distinct tectonic settings. Furthermore, we postulate that the interplay of slab break-off along a portion of a 'mega-subduction' system and mantle upwelling might be an important driving force for the generation of major mineral deposits.

The ~440 Ma event in central and eastern Australia

Several metallogenic, tectonic, magmatic and sedimentological events occurred simultaneously at ca. 440 Ma across wide regions in central and eastern Australia (Elburg et al. 2003; Figs. 2 and 3):

1. Gold mineralisation in the western subprovince of the Lachlan Orogen (Fig. 1), including the genesis of world-class (i.e. >100 tonnes of Au) orogenic gold deposits at Bendigo, Stawell and Ballarat, during and shortly after the culmination of deformation and peak metamorphic conditions in an episodically eastward stepping subduction–accretion system (Foster et al. 1998; Bierlein et al. 2001).
2. Formation of several major porphyry-style gold–copper deposits (>50 tonnes Au; Cadia, Northparkes) in the Macquarie Volcanic Arc in the eastern subprovince of the Lachlan Orogen (Fig. 1), during the final stages of distinct K-rich (shoshonitic) arc magmatism (Heithersay and Walshe 1995; Perkins et al. 1995; Glen et al. 1998)
3. Rapid changes from shale- to more sand-dominated turbidite sedimentation simultaneously with a change from overall contraction to partial contraction and basin formation throughout the Lachlan Orogen (Vandenberg et al. 2000; Vos et al. 2003; Fig. 3).
4. Magmatic-hydrothermal events in the Mt. Painter Inlier in South Australia (Figs. 2 and 3), including emplacement of the I/S-type British Empire Granite in the north of the inlier, quartz-hematite and uranium mineralisation in the Mt. Gee area, and the formation of numerous diopside–titanite veins throughout the inlier (Elburg et al. 2003).
5. Zinc–lead mineralisation in the Beltana region in the northwestern part of the Adelaide Fold Belt (Figs. 2 and 3), including coronadite ($MnPbMn_6O_{14}$) and willemite (Zn_2SiO_4) deposits derived from a low to moderate temperature hydrothermal system (50–170°C) spatially associated with inverted growth faults (Groves et al. 2003).
6. Large-scale geodynamic changes from regional extensional deformation to compression in the Palaeoproterozoic to Palaeozoic Arunta Inlier in Central Australia (Fig. 2), based on U-Pb and Sm-Nd age dating from major mid-crustal upper amphibolite facies (>650°C, 6 kbar) mylonite zones in the Harts Ranges (Hand et al. 1999; Mawby et al. 1999; Scrimgeour and Raith 2001a)
7. Zircon growth associated with shear zone movement in the Strangways Metamorphic Complex (Figs. 2 and 3) at 443±6 Ma (Möller et al. 1999).
8. Major depocentre shifts in basins surrounding the Arunta Inlier, a marked decrease in sediment influx and a change from mostly marine to non-marine sedimentation conditions associated with the disruption of the Larapintine Seaway from ca. 450 Ma onwards, indicative of exhumation of the region (Haines et al. 2001; Scrimgeour and Raith 2001b). Exhumation is also supported by 445–435 Ma ages obtained from amphibolite grade shears along the Delny–Mt. Sainthill Fault Zone and Entire Point Faults together with Silurian cooling ages from the northern Harts Range (Scrimgeour and Raith 2001a).

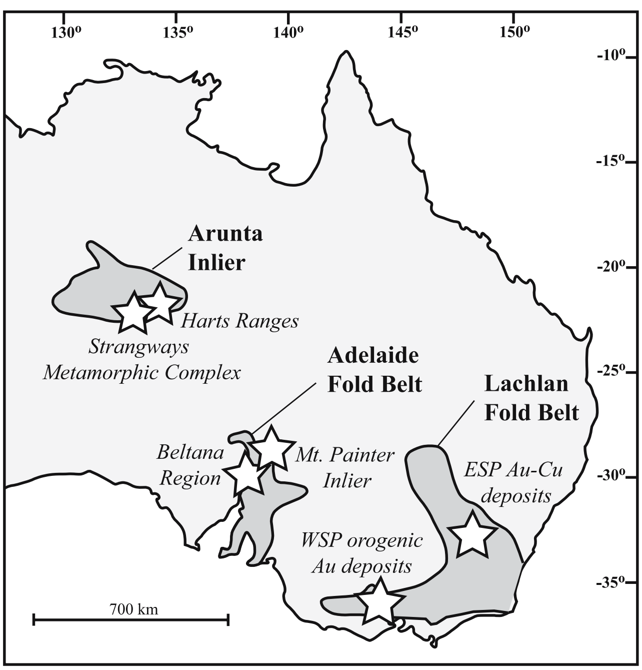


Fig. 2 Location and distribution of ~440 Ma events in central and eastern Australia. *WSP*/*ESP* Western/eastern subprovince of the Lachlan Orogen

Slab break-off: a possible driving mechanism?

Slab detachment is not a new concept in lithosphere dynamics and is well recognised in the Mediterranean region (e.g. Wortel and Spakman 2000), where a close relationship to mineralisation has been proposed (De Boorder et al. 1998). Wong et al. (1997) suggested that the arrival of buoyant fragments, such as continental lithospheric material, at the trench of a subduction zone could initiate the process of slab detachment. Wortel and Spakman (2000) further suggested that the arrival of any weakness zone (e.g. transform fault, spreading ridge segment) might initiate slab detachment. Slab break-off is generally considered to occur at depths as shallow as 50 km, with asthenospheric material rising to fill the newly formed gap and providing an advective-type heat source or

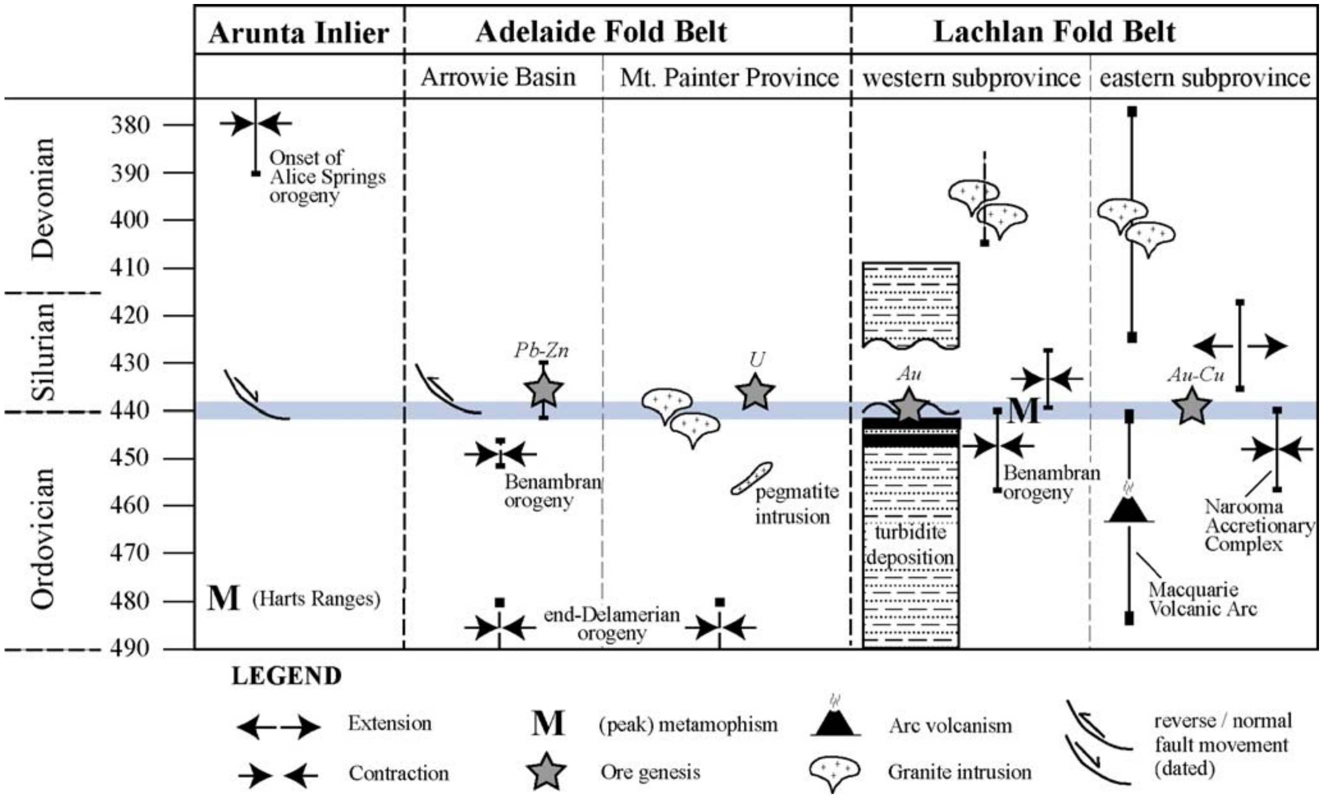


Fig. 3 Time–space diagram indicating the culmination of ~440 Ma metallogenic, tectonic, magmatic and sedimentological events in central and eastern Australia. See text for references

thermal anomaly of a transient nature (Davies and von Blanckenburg 1995; Wortel and Spakman 2000). Besides the termination of subduction with slab break-off, other implications of slab detachment and final break-off include magmatism, metamorphism, major tectonic activity including fault movement and variations in the stress field, mineralisation and rapid uplift of the overlying lithosphere associated with major unconformities in the sedimentary record (Wortel and Spakman 2000).

Throughout most of the Neoproterozoic to Mesozoic, Australia was situated on the margin of Gondwana inboard of a mega-subduction system that virtually surrounded the entire supercontinent (e.g. Foster and Gray 2000; Cawood 2005; Fig. 4). Previous studies have proposed a model that focussed on subduction lock-up at ca. 455 Ma—as indicated by, for example, the cessation of accretion along the proto-Pacific margin in the Narooma Fault Zone (Miller and Gray 1996; Glen et al. 2004; Fig. 2)—after the arrival of a buoyant seamount or ridge along the southeast Australian portion of this subduction system (Glen et al. 1998; Squire and Miller 2003). Arrival of such positively buoyant fragments in a subduction system is likely to trigger changes in subduction dynamics that could, in turn, lead to slab break-off (Davies and von Blanckenburg 1995; Haeussler et al. 1995; Wortel and Spakman 2000). Thus, resistance to subduction after the arrival of a buoyant seamount at the mega-subduction zone outboard of southeastern Australia could have initiated slab detachment that eventually led to break-off of a portion of the subducted circum–Gondwana oceanic slab at ca. 440 Ma. The process of lateral migration of a slab tear, which is generally considered to precede slab break-off (Wortel and Spakman 2000), and this tearing thus could have occurred between 455 and 440 Ma (Fig. 5).

The occurrence of slab break-off along the southeast Australian subduction margin is likely to have initiated mantle upwelling and anomalous thermal conditions (cf. Wortel and Spakman 2000), and it is these interrelated processes that could account for the range of ca. 440 Ma tectono-magmatic and metallogenic events in central and eastern Australia outlined in the previous section. Of note are also mantle isotopic signatures associated with magmatic-hydrothermal events in the Mt. Painter Inlier (Elburg et al. 2003), cessation of arc magmatism in the intra-oceanic Macquarie Arc (Perkins et al. 1995), synchronous gold–copper, orogenic gold and zinc–lead deposition along a decreasing temperature gradient away from the Early Palaeozoic proto-Pacific subduction margin, rapid uplift as indicated by erosional unconformities in central and eastern Australia (Vandenberg et al. 2000; Haines et al. 2001), possibly reflecting isostatic rebound of the overlying lithosphere after slab break-off and associated mantle heat release (Davies and von Blanckenburg

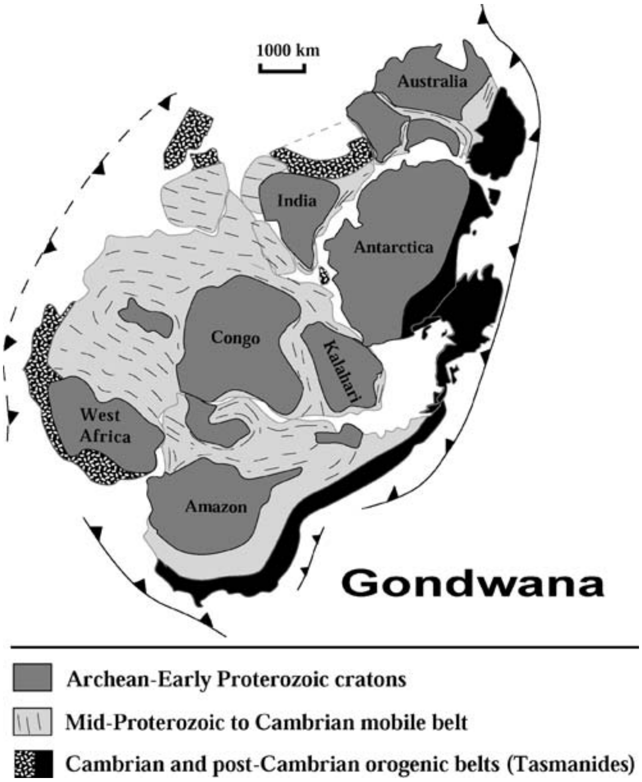


Fig. 4 Schematic reconstruction of Early Palaeozoic Gondwana and the circum–Gondwana subduction system controlling the evolution of the Tasmanides (in *black*). Figure modified from Foster and Gray (2000)

1995; Buiter et al. 2002) and melting of the Early Palaeozoic turbidite pile at mid-crustal levels providing the onset of ca. 435 Ma granite magmatism in the Wagga–Omeo Zone of the Lachlan Orogen (e.g. Foster and Gray 2000; Fig. 1).

Responses in lithospheric stress conditions and anomalous temperature conditions due to slab break-off are difficult to distinguish from lithospheric delamination, and these processes commonly compliment one another (cf. Wortel and Spakman 2000; Lips 2002). Lithospheric delamination has been proposed as an important driving mechanism in the evolution of the Lachlan Orogen by Wang and White (1993) and Collins (1994). Although delamination of lithospheric mantle may indeed explain the observed ca. 440 Ma events throughout the Lachlan Orogen, it fails to provide an explanation for the occurrence of ca. 440 Ma events across an area in central and eastern Australia far greater than the Lachlan Orogen. Unlike lithospheric delamination, slab break-off can trigger tectonic mode switches as well as supplying the heat source required for magmatism and metallogenesis at different lithospheric levels, which, in turn, lead to the concomitant formation of distinct deposit types in a range of tectonic settings (Lips 2002). Similarly, slab rollback as proposed by Squire and Miller (2003) is inadequate to account for the observed temporal coincidence of magmatic, metallogenic and tectonic events across more than 1 million km^2 in central and eastern Australia. Although slab rollback would generate thermo-mechanical responses of the lithosphere comparable to slab break-off, the two processes differ considerably in their temporal and spatial characteristics (e.g. Wong et al. 1997; Lips 2002). This

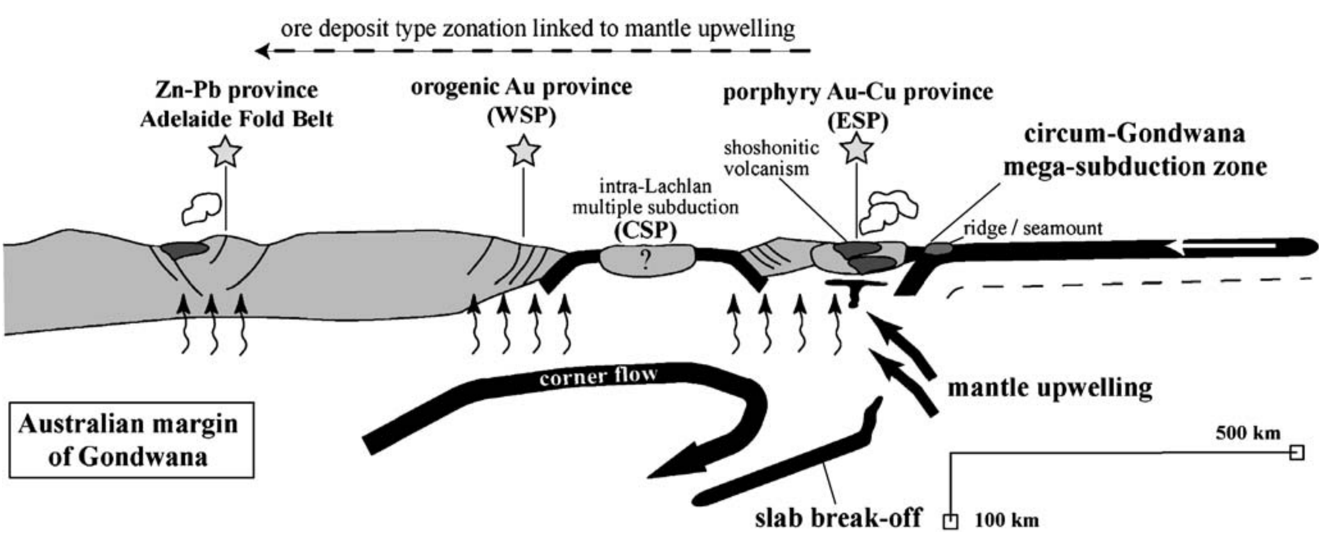


Fig. 5 Schematic cross-section of southeastern Australia around 440 Ma, illustrating break-off of a portion of the mega-subduction zone on the margin of Gondwana. Slab break-off triggers tectonic activity and mantle upwelling, which provides heat (±metals) to the upper lithosphere (as indicated by *small arrows*) for the simultaneous generation of world-class gold provinces in the eastern and western Lachlan Orogen (*ESP* and *WSP*, respectively) and zinc–lead deposits far inboard of the subduction margin. Data from Veevers et al. (2000) and references cited in text. Intra-Lachlan Orogen geodynamics (*CSP* central subprovince), which include the presence of multiple subduction zones, are only schematically represented in this figure and the reader is referred to Fergusson (2003) and Spaggiari et al. (2004) for a comprehensive overview

includes a unilateral spread of mineralisation ages in the case of slab rollback (e.g. Sillitoe 1991). Unilateral propagation is clearly at odds with the punctuated ca. 440 Ma mineralisation and magmatic and tectonic events documented in central and eastern Australia.

We recognise that due to data resolution, slab break-off remains a *suggested* explanation for a range of observed phenomena at ca. 440 Ma in central and eastern Australia. Nonetheless, such a mechanism is in agreement with all available data and thus should be considered in future research.

The role of slab break-off in the genesis of major mineral deposits

The effects of slab break-off and associated mantle upwelling in a supercontinent–mega-subduction zone setting resembling the Palaeozoic circum–Gondwana subduction system (Fig. 3) are poorly understood. It has been argued previously that the insulating effects of large continental masses can develop hot regions at shallow levels in the mantle during periods of subduction (e.g. Busse 1978; Anderson 1981; Ballard and Pollack 1987; Anderson et al. 1992). Lithospheric characteristics, such as the presence of trans-crustal fault systems, localise the effects of mantle upwelling (e.g. Sawkins 1976; Sykes 1978), which suggests that a feedback mechanism exists between plate tectonics, lithospheric stress conditions and mantle upwelling (Anderson et al. 1992). This implies that the presence of hot regions in the shallow mantle underneath supercontinents can amplify the effects of mantle upwelling associated with slab break-off.

In view of this geodynamic relationship, we speculate that the combination of amplified heat build-up as a consequence of long-lived subduction and slab break-off along the southeast Australian sector of the circum–Gondwana mega-subduction system may have triggered an extraordinary mantle upwelling event. In turn, this may have governed the formation of exceptionally large ca. 440 Ma gold deposits in southeastern Australia compared to other gold deposits generated at any other time during the Palaeozoic evolution of eastern Australia (e.g. Goldfarb et al. 2001; Bierlein et al. 2006). The decreasing temperature gradient observed in metal deposits from east to central Australia away from the proposed locus of slab break-off supports the notion of an extraordinary mantle upwelling event, as its effects were recorded more than 1,000 km inboard of the proto-Pacific subduction margin. We emphasise that although short-lived, multiple subduction zones may have existed inboard of the proto-Pacific mega-subduction zone during the evolution of the Lachlan Orogen, these are considered secondary to the long-lived circum–Gondwana subduction system (Cawood 2005). We do note, however, that these short-lived subduction systems, as well as additional factors that operate at the terrane-scale, may have augmented the fertility of particular regions in the Lachlan Orogen (e.g. Bierlein et al. 2002, 2006; Gray et al. 2002; Fergusson 2003; Spaggiari et al. 2004).

Conclusions

The simultaneous occurrence of metallogenic, tectonic, magmatic and sedimentological events in wide regions across central and eastern Australia, in particular the genesis of major copper–gold and orogenic gold deposits in the Lachlan Orogen, can be explained satisfactorily by slab break-off along a portion of the circum–Gondwana mega-subduction zone system at ca. 440 Ma. In this scenario, slab detachment may have been initiated by the arrival of a buoyant seamount chain, ridge or oceanic plateau along the subduction system outboard southeast Australia at ca. 455 Ma and culminated in slab break-off and termination of subduction at ca. 440 Ma. The interplay of slab break-off and mantle upwelling caused rapid uplift as well as changes in lithospheric stress conditions far inboard of the proto-Pacific subduction margin. These changes led to the reactivation of large-scale fault systems and disturbance of sedimentation patterns throughout central and eastern Australia. Deep-seated fault systems channelled and transported substantial quantities of heat and metal-bearing fluids to the upper lithosphere, thus enabling the genesis of ore deposits in distinct tectonic settings along a decreasing temperature gradient away from the locus of slab break-off. In addition to highlighting the well-known importance of long-lived and extensive convergent margins in the generation of fertile areas for mineralisation, supercontinent–mega-subduction zone settings potentially also play a crucial role in increasing the magnitude of ore deposition as a result of amplified mantle upwelling. The recognition of slab break-off and mantle upwelling along parts of long-lived subduction systems as a driving mechanism for major ore deposit genesis is of relevance for conceptual exploration models targeting giant ore deposits and may also explain the punctuated genesis of major ore deposits in similar settings worldwide as previously suggested by De Boorder et al. (1998) and Qiu and Groves (1999).

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