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ARTICLE

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A review of the metallogeny and tectonics of the Lachlan Orogen

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Abstract Future mineral exploration within eastern Australia will be enhanced by resolving the tectonic evolution of the Lachlan Orogen to establish the spatial and temporal terrane distribution of the various mineral deposits. The Lachlan Orogen, from north-eastern Tasmania through to central and eastern New South Wales, is host to a number of major mineral deposit styles—including orogenic gold (e.g. Stawell, Ballarat, Bendigo), volcanic-hosted massive sulphide (e.g. Woodlawn, Currawong), sediment-hosted Cu–Au (e.g. Cobar Basin deposits), porphyry Au–Cu (e.g. Cadia, Parkes, Cowal) and granite-related Sn (e.g. Ardlethan, Beechworth). Each of these mineral deposit styles is a sensitive and diagnostic indicator of the prevalent tectonic environment during their formation. In this review, we briefly summarise the deposit- to large-scale factors that define the diverse metallogenic evolution of the Lachlan Orogen. This overview is intended to "set the scene" for subsequent specialist papers published in this thematic issue on the metallogeny and tectonics of the Lachlan Orogen in south-east Australia.

Keywords Lachlan Orogen · Tasman Orogen · Metallogenys · Structural control · Australia

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Introduction

The Lachlan Orogen (Fig. 1a,b) is one of five Palaeozoic orogenic belts that together form the greater Tasmanides of eastern Australia (Scheibner 1978; Wellman 1995) and comprises three differing thrust systems—the western, central and eastern Lachlan orogens (Gray and Foster 2004). In this paper, we review the relationship between tectonics and metallogenesis of the five major deposit types of the Lachlan Orogen, in the context of the tectonic evolution of the region. In addition to previous work, this review builds on recent publications on the metallogeny and tectonic evolution of the Lachlan Orogen, specifically those by Bierlein et al. (2002) and Gray and Foster (2004). The correlations between metallogenic deposit types and tectonic settings made by Bierlein et al. (2002) will be explored in greater detail with regard to the comprehensive review by Gray and Foster (2004) on all aspects of the evolution of the Lachlan Orogen.

The Lachlan Orogen is a highly endowed metallogenic province (Walshe et al. 1995a; Bierlein et al. 2002; Gray et al. 2002a; Jaques et al. 2002), hosting a large number of major mineral deposits (Figs. 1b and 2) belonging to at least five main ore deposit types, including orogenic gold (e.g. Bendigo, Ballarat, Stawell), volcanic-hosted massive sulphide (VHMS) (e.g. Woodlawn, Currawong), sediment-hosted Cu–Au and Pb–Zn (e.g. Cobar Basin deposits), porphyry Au–Cu (e.g. Cadia, Parkes, Cowal) and granite-related Sn (e.g. Ardlethan, Beechworth).

The Lachlan Orogen, especially in regards to orogenic gold deposits, is comparable to other Phanerozoic orogens that formed by accretion of continental crust along the complex subduction zone of Gondwana, e.g. New Zealand and South America (Goldfarb et al. 2001; Bierlein and Maher 2001). To put the Lachlan Orogen in a global context, the Bendigo and Ballarat goldfields are listed within the world's top 30 Phanerozoic orogenic gold deposits, having produced more than 220 t Au (Phillips and Hughes 1996), and the Cadia porphyry Au–Cu district is one of the world's top ten porphyry gold deposits (Large et al. 2002). The spatial distribution of the deposit types of the

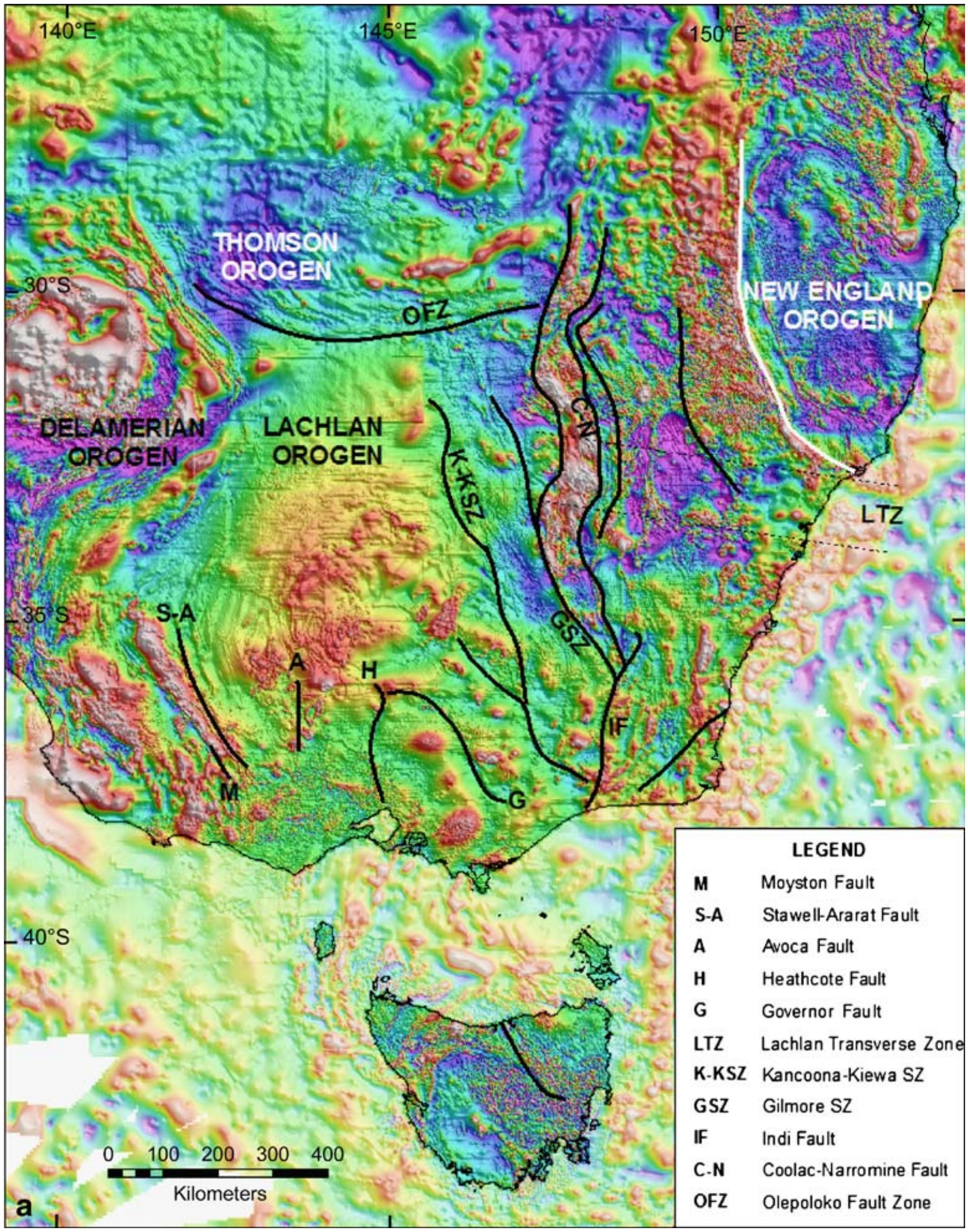


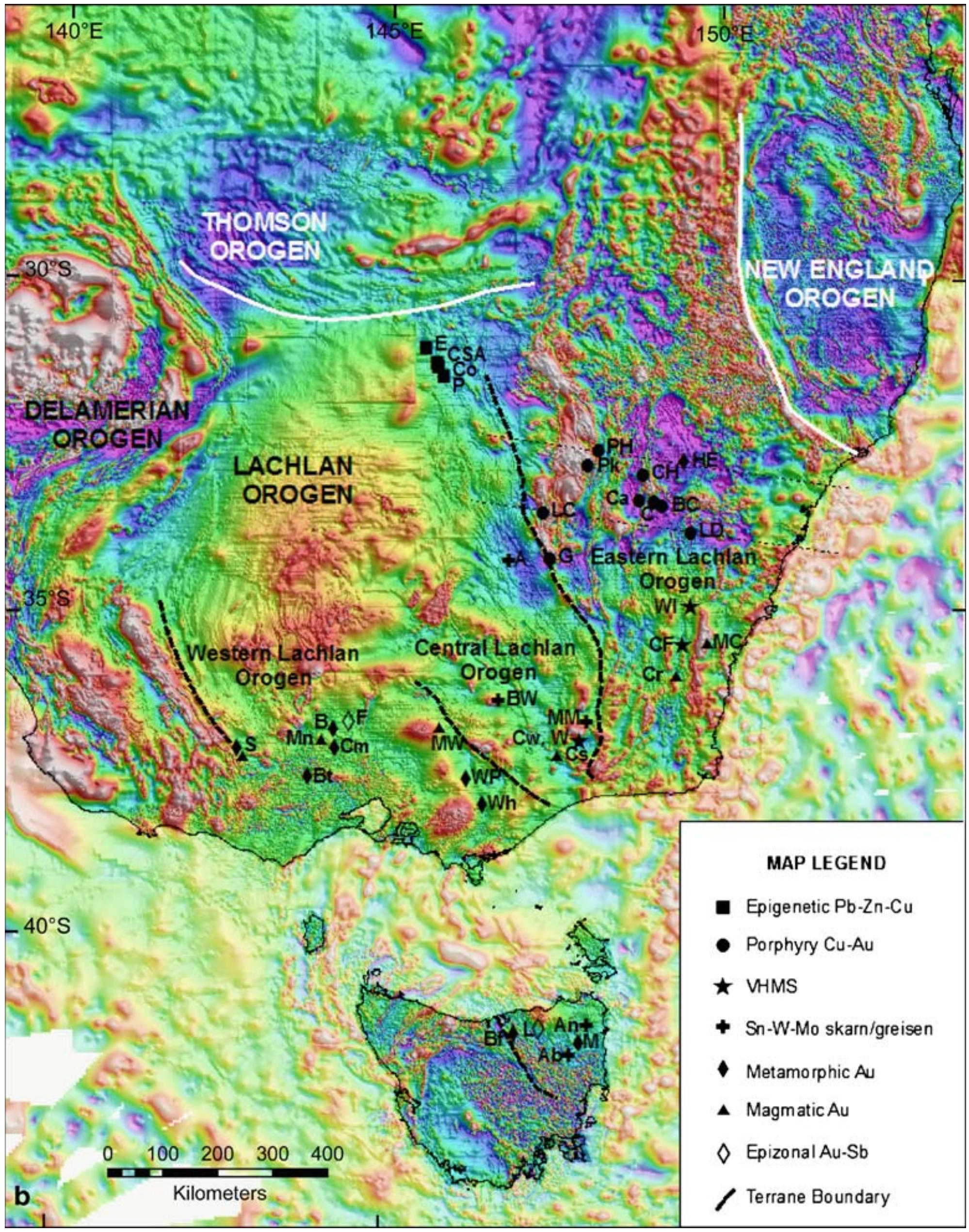
Fig. 1 **a** Location of significant faults and shear zones within the Lachlan Orogen. Sub-divisions of the Lachlan Orogen include the western Lachlan Orogen (*WLO*), central Lachlan Orogen (*CLO*) and eastern Lachlan Orogen (*ELO*) (Gray and Foster 2004). **b** Location of significant mineral deposits and sub-divisions within the Lachlan Orogen. Deposits include: Ardlethan (*A*), Beaconsfield (*BF*), Bendigo (*B*), Browns Creek (*BC*), Ballarat (*BT*), Beechworth (*BW*), Castlemaine (*CM*), Cobar (*CO*), Cadia (*CA*), Captains Flat (*CF*), Cargo (*C*), Copper Hill (*CH*), *CSA*, Cassilis (*CS*), Currawong (*CW*), Cowarra (*CR*), Elura (*E*), Fosterville (*F*), Gidginbung (*G*), Hill End (*HE*), Lake Cowal (*LC*), Lisle (*L*), Lucky Draw (*LD*), Maldon (*MN*), Mathinna (*M*), Mt Murphy (*MM*), Mt Wills (*MW*), Majors Creek (*MC*), Peak (*P*), North Parkes (*PK*), Peak Hill (*PH*), Stawell (*S*), Walhalla (*WH*), Wilga (*W*), Woodlawn (*WL*), Woods Point (*WP*). *Map backdrop*: magnetic anomaly images of the Australian region (image from http://www.ga.gov.au/gadds/)

Lachlan Orogen undoubtedly relates to their formation within a unique tectonic framework, which, in turn, provides important clues regarding the metallogenesis of these deposits.

Gold was first officially recorded within the Lachlan Orogen in 1823, east of Bathurst in New South Wales. Prior to 1851, gold rushes were impeded, as all precious metal discoveries at the time belonged to the Crown. The first goldfield was found and promoted by Edward Hargaves near Ophir in New South Wales in May 1851 (Blainey 2003). Due to the rush of men to the goldfield, and with the fear of violence and lawlessness, the Government decided to sanction and regulate the gold rush by introducing a licencing system. Soon, goldfields throughout the Lachlan Orogen were discovered, especially in Victoria, such as Clunes, Daylesford, Warrandyte, Buninyong and finally, Ballarat (Blainey 2003). Lead and copper were first discovered in South Australia prior to 1845, although the first copper deposit within the Lachlan Orogen was discovered in Cobar (New South Wales) in 1859, followed by tin at Mt Bischoff (Tasmania) and Iverall (New South Wales) in 1871. The Captains Flat Pb–Zn–Cu orebody was first mined in 1882. Unfortunately, the remoteness of the copper deposits and the erratic nature of tin deposits in New South Wales did not encourage mining booms.

As mineral discoveries continued and geological understanding of the links between plate tectonics, orogenesis and metallogenesis evolved, the Lachlan Orogen was compared with northern hemisphere orogenic belts, such as the northern American Cordillera (Ramsay and VandenBerg 1986), the Scandinavian Caledonides and Palaeozoic fold belts of China (Sun 1991), and in relation to the circum-

Fig. 1 (continued)

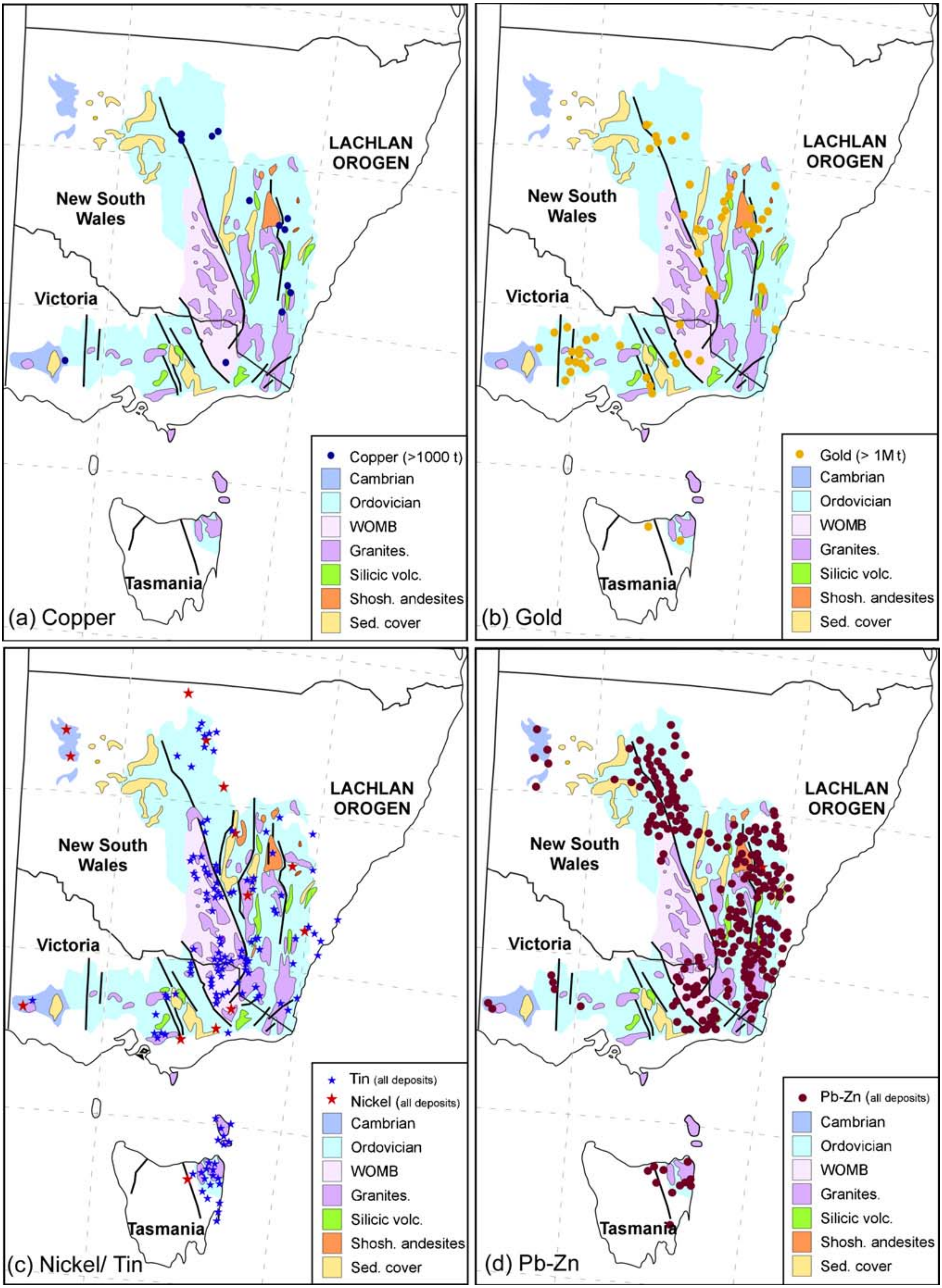


Pacific and the Early Palaeozoic terranes of New Zealand (Coney 1992). By the mid-1980s, the Tasmanides were recognised as a composite orogenic belt of polyphase terrane accretion with the mineral deposits understood in the context of pre-, syn- and post-terrane accretion events (Ramsay and VandenBerg 1986).

More recently, the metallogeny of the eastern Lachlan Orogen, and in particular the porphyry Au–Cu deposits of New South Wales, and, to a lesser degree, orogenic gold and VHMS deposits, were addressed in the context of regional and crustal-scale processes of the major mineral provinces of the Lachlan Orogen with minor references to their links with tectonics (Walshe et al. 1995b).

The Lachlan Orogen

The Lachlan Orogen is commonly discussed in the context of the geographic boundaries of the Australian mainland State divisions, with the Palaeozoic in Tasmania generally ignored. This review looks at the entire Lachlan Orogen (Fig. 1a), from the east-vergent thrust system of the western Lachlan (cratonisation at 450–420 Ma) in north-eastern Tasmania and western-central Victoria, to the south-west vergent thrust system linked to the fault bounded Wagga-Omeo metamorphic complex in the central Lachlan (440–420 Ma) of eastern Victoria and south-west New South Wales, and to the east-vergent thrust system in the eastern


LACHLAN OROGEN
New South Wales
Victoria
Tasmania
(a) Copper
Copper (>1000 t)
Cambrian
Ordovician
WOMB
Granites.
Silicic volc.
Shosh. andesites
Sed. cover
(b) Gold
Gold (> 1M t)
(c) Nickel/ Tin
Tin (all deposits)
Nickel (all deposits)
(d) Pb-Zn
Pb-Zn (all deposits)

◀ **Fig. 2** Lithological maps with mineral occurrences within the Lachlan Orogen. Lithologies, including the Wagga-Omeo metamorphic complex (*WOMB*), modified from Gray and Foster (2004). Mineral occurrences modified from Evans and Jaireth (2001) and Ratajkoski et al. (2005a–c). Note that, for visual clarity, only copper and gold occurrences with a recorded production of 1,000 and 1 t, respectively, are shown in **a** and **b**

Lachlan (430–340 Ma) of central and eastern New South Wales (Gray et al. 1988; Gray and Willman 1991; Gray 1997; Fergusson 2003; Gray and Foster 2004).

The three differing thrust systems of the Lachlan Orogen preserve the evolving stages of the subduction system, which resulted in Ordovician to Carboniferous stepwise accretion, deformation and metamorphism along the eastern passive margin of Gondwana (Gray and Willman 1991; Gray and Foster 1998, 2004). Various authors have categorised the deformation history of the Lachlan Orogen in terms of episodic orogenic cycles, such as the Tyennan (510–490 Ma), Benambran (490–440 Ma), Bindian (418–410 Ma), Tabberaberan (430–380 Ma) and Kanimblan (380–320 Ma) (Taylor and Cayley 2005; Cayley et al. 2002; VandenBerg et al. 2000; Glen 2005). However, the time periods for these orogenic cycles are approximate only, and vary in age and extent across different sections of the Lachlan Orogen. We therefore prefer to use absolute ages (wherever possible) when comparing tectonic and metallogenic events throughout the Lachlan Orogen.

The major lithologies of the Lachlan Orogen

The lithological units across the Lachlan Orogen (Fig. 2) include deep marine turbidites, shallow marine to sub-areal sediments (Talent 1965; Crook et al. 1973; Powell 1984; Fergusson and VandenBerg 2003), extensive granite bodies (White et al. 1974; Collins 1998) and volcano-intrusive complexes (Wyborn 1992; Glen et al. 1998). Deep marine turbidite deposition commenced in the Ordovician, becoming predominantly shallow marine and sub-areal in the Devonian (Cas et al. 1983) in the extensional basins of the eastern Lachlan Orogen. Sediments of the Lachlan Orogen were generally sourced from the Ross-Delamarian Orogen of the Gondwana craton to the west (Fergusson and Tye 1999), with the exception of westward sedimentation from palaeo-highs recognised in some of the structural zones (e.g. Tabberabbera Zone; VandenBerg 2000).

The western Lachlan Orogen in Victoria is dominated by Cambrian to Ordovician turbidites deposited in deep submarine fans (Cas and VandenBerg 1988; VandenBerg et al. 2000). Two periods of magmatism resulted in bimodal volcanism in minor rift basins and the intrusion of granites at 405–400 Ma, and silicic cauldron complexes, granite plutons and dyke swarms at 370–365 Ma (VandenBerg et al. 2000). The post-tectonic and essentially undeformed granites throughout Victoria were emplaced at levels of less than 3 km and vary widely in composition and mineralogy (Hergt et al. 2002; White 2002). The most common igneous sub-types are metaluminous hornblende–biotite granite (I-type), peraluminous cordierite-bearing granite (S-type) and some extrusive equivalents and weakly peraluminous biotite granite (I-type) (Chappell and White 1974; White 2002). Unlike comparable granites elsewhere in the Lachlan Orogen, the Devonian granites across the central Victorian gold province are relatively reduced and characterised by comparatively high Ba values that commonly exceed 1,000 parts per million. The western Lachlan Orogen in north-eastern Tasmania is also dominated by Cambrian to Ordovician turbidites (Powell et al. 1993) which have been intruded by Devonian alkali feldspar granites that host numerous Sn–W deposits (e.g. Anchor).

Sedimentation within the central Lachlan Orogen lasted from the Cambrian to the Silurian in a deep marine environment (Powell 1983; Gray and Foster 2004). The low-P/high-T Wagga-Omeo metamorphic complex, which was exhumed during the Early Devonian, dominates the central Lachlan Orogen (Morand 1992). This complex is the highest-grade metamorphic zone within the entire Lachlan Orogen and is centred around numerous elongate syntectonic, and invariably deformed, Silurian granite bodies with north-north-west trends, sub-parallel to the structural grain of the central Lachlan. The more highly fractionated granites of the central Lachlan also host Sn–W deposits (e.g. Ardlethan).

The eastern Lachlan Orogen comprises forearc sediments and slices of oceanic crust (Powell 1984; Gray et al. 2002c; Fergusson and VandenBerg 2003), abundant Silurian to Devonian syntectonic granites and volcano-intrusive complexes. The Silurian Narooma accretionary complex on the eastern coast of New South Wales comprises interbedded sandstone and mudstone deposited in a distal fan environment. Late Silurian to Early Devonian granites (405–400 Ma) of the eastern Lachlan are predominantly I-type granites and have a northerly trend, sub-parallel to the structural grain of the eastern Lachlan Orogen (Collins 1998). The volcanic belts include Silurian to Devonian silicic volcanics and Ordovician shoshonitic andesites (Heithersay and Walshe 1995; Glen et al. 1998).

The structural zones of the Lachlan Orogen

Structural intensity and vergence varies across the Lachlan Orogen (Gray 1997; Foster and Gray 2000). In addition, the western, central and eastern provinces are all separated by major north–south trending crustal structures (Gray et al. 1988; Gray and Willman 1991; VandenBerg et al. 2000). These structures dip steeply at the surface but become listric at midcrustal detachments (Fig. 1a). Surface mapping of the fault geometries revealed a complex history of contraction, extension and stike-slip movement (Gray and Foster 1998).

The western Lachlan Orogen is dominated by an imbricated, chevron-folded sequence, which outcrops in western-central Victoria and north-eastern Tasmania. It includes the Stawell Zone, Bendigo Zone, Melbourne Zone and the laterally equivalent auriferous eastern Tasmanian

Terrane (Reed 2001b). In Victoria, the western Lachlan Orogen is bounded by the Moyston Fault to the west and Governor Fault/Mt Wellington Fault (Fig. 1a) to the east, which may continue undercover into New South Wales. The east-vergent thrust system of the western Lachlan Orogen (Gray and Foster 2004) has zones of alternating north-west and north-trending structures (Cox et al. 1991; Gray and Willman 1991).

The central Lachlan Orogen consists of the Tabberaberan Zone, an Ordovician to Silurian fold-thrust belt in Victoria, and the Wagga-Omeo Zone that straddles the Victoria/New South Wales border (Glen 1992; Gray and Foster 2004). The central Lachlan is dominated by north-west-trending structures, and is bounded by the Governor Fault to the west and the Indi Fault, the Jam Tin Fault and the Lucas Point Fault in the east in Victoria (Fig. 1a). The east-bounding faults merge to form the Gilmore Fault in New South Wales.

The eastern Lachlan Orogen consists of the Deddick, Kuark and Mallacoota Zones in Victoria and the Canberra-Buchan Zone, which traverses the Victoria/New South Wales border (Glen 1992; Gray and Foster 2004). East-directed thrusting inverted the extensional basins in the west (Glen 1992), whereas in the south and east of the eastern Lachlan, an east vergent thrust system overrides an older subduction-related accretionary complex (Fergusson and VandenBerg 1990; Miller and Gray 1996, 1997; Offler et al. 1998).

Major crustal stuctures of the Lachlan Orogen

The inherent connection between large ore-forming systems and major crustal structures (Figs. 1b and 2) is well recognised (Kerrich et al. 2000; Cooke and Pongratz 2002). In the Lachlan Orogen, ore deposits such as gold, tin and copper–gold porphyry are spatially associated with first- and second-order fault systems of major deep-seated faults (Walshe et al. 1995a; Bierlein et al. 2004). The ca. 410–390 Ma Governor Fault/Mt Wellington Fault Zone (Foster and Gray 1998) that separates the western and central Lachlan Orogen is up to 2 km wide and was formed as a result of terminal collision of the two orogenic segments. The Walhalla–Woods Point Goldfield lies parallel to this major fault zone, approximately 30 km to the west.

Gold deposits in north-eastern Tasmania have also been linked to deep fault structures in the Tamar Valley. Reed (2001a) suggested thrust faults in the Tamar Valley could penetrate to a depth of greater than 20 km and, therefore, source hydrothermal fluids. Williams (1978) interpreted the Tamar Fracture System (Fig. 1a) to be a Late Devonian sinistral wrench fault based on the north-trending foliations of the north-eastern Tasmanian granites. The fault system appears to separate the pre-Silurian basement of Tasmania, although it is now suggested to be a west-vergent thrust system (Powell and Baillie 1992) or west-vergent subduction zone (Bierlein et al. 2005) laterally equivalent to the subduction zone bounding the Melbourne Zone.

The Gilmore-Indi Fault Zone (Fig. 1a) is approximately 6 km wide and is Late Silurian to Mid-Devonian in age. It is considered to be a steeply dipping major transform fault (Cook et al. 1998) and divides the Au–Cu and Sn metallogenic provinces of the eastern Lachlan. The fault acted as a regional focussing structure for mantle fluids, controlling the emplacement of granites and the location of Sn deposits (Walshe et al. 1995b).

Within the eastern Lachlan Orogen, several belts of mafic to intermediate volcanic, intrusive and volcanoclastic sequences are separated by north–south- and north-north-west-trending fault structures that host a number of copper–gold porphyry deposits, such as North Parkes, Peak Hill and Tomingley (Walshe et al. 1995a,b). The fault structures are thought to be either thrust faults of opposing vergence or major strike-slip faults. Chalmers et al. (2004) have suggested that the volcanic belts once formed the Macquarie Arc, an oceanic island arc volcano-sedimentary wedge, now cut by major thrust faults. In addition, Walshe et al. (1995b) and Cooke et al. (2004) recognised the subtle west-north-west structural trends of the Lachlan Transverse Zone (Fig. 1a) within the eastern Lachlan Orogen that controls the distribution of the major mineral provinces of the Fifield deposit and in the Goonumbla and Cadia complexes of the Macquarie Arc. The Lachlan Transverse Zone has influenced the structural evolution of the Lachlan Orogen since the Ordovician, as it follows Proterozoic structural trends (Glen and Walshe 1999).

Tectonic evolution of the Lachlan Orogen

Models of the complex tectonic evolution of the Lachlan Orogen have been developed to explain the differing geology and metallogeny of the western, central and eastern provinces in the context of plate tectonic settings (Scheibner 1973; Crook 1980; Powell 1983). There are currently two popular schools of thought as to the tectonic evolution of the Lachlan Orogen: (1) the intraplate convergence model: initial passive margin and backarc basin setting with episodic deformation due to convergence between the Australian Craton and microcontinental fragments (Powell 1983, 1984; Fergusson and Coney 1992a,b; VandenBerg 1999; Cayley et al. 2002); and (2) the double divergent subduction model: oceanic setting involving complex interactions of multiple subduction/accretion systems (Gray and Foster 1997, 1998; Gray et al. 1997, 2002c). Model constraints include the source(s) of magmatism, the nature of the crustal fault structures and the metallogeny of the orogen.

The earlier studies of the Lachlan Orogen proposed an intraplate back arc setting behind a long-lived subduction zone (Powell 1983, 1984; Fergusson and Coney 1992a,b) analogous to a Japan Sea-type back-arc basin or a Philippine Sea-type basin (Gray and Foster 2004). The intraplate model is still a valid debate (Li and Powell 2001; Willman et al. 2002; Squire and Miller 2003; Braun and Pauselli 2004). Braun and Pauselli (2004) recently developed a thermo-mechanical finite element model to test their hypothesis on the tectonic evolution of the Lachlan Orogen during the Mid-Palaeozoic, suggesting a continuous subduction event along a single subduction zone. Prevailing models of the Lachlan Orogen, however, involve more complex multiple subduction systems in a marginal ocean setting behind a major long-lived subduction system (Gray 1997; Soesoo et al. 1997; Collins 1998; Foster and Gray 2000; Fergusson 2003; Spaggiari et al. 2003b). The concept of a multiple subduction system was proposed by Gray and Foster (1997) to explain underthrusting, the north-west granitoid elongation of the Wagga-Omeo metamorphic complex in the central Lachlan Orogen, the north–south trend of the eastern Lachlan Orogen magmatic belt, a low geothermal gradient inferred from phengites in the turbidites, the presence of serpentinite-matrix mélange in major fault zones and the presence of the Narooma accretionary complex in the eastern Lachlan Orogen (Gray and Foster 2004). Bierlein et al. (2002) proposed that the Lachlan Orogen formed by the interactions between several microplates and three accretionary complexes in an oceanic back-arc setting.

Evidence of serpentinite matrix mélanges with blueschist blocks, as well as the presence of dismembered ophiolite slivers along major fault zones in the western Lachlan Orogen (e.g. Heathcote and Governor faults; Spaggiari et al. 2003a), suggests the possible location of subduction zones during the tectonic evolution of the western and central Lachlan Orogen (Gray and Foster 2004). The Cordilleran-type occurrence of off-scraped ophiolite slices within turbidite wedges, suggesting subduction rather than obduction, is characteristic of Pacific-Rim accretionary terranes (Spaggiari et al. 2004).

In contrast, Fergusson and Glen (1992) observed that the Lachlan Orogen lacked key features of a collisional orogen, specifically, a high-grade metamorphic hinterland, foreland thrust belt and a peripheral foreland basin, and more recently, Collins (2001) suggested evidence of tectonic switching from shortening to extension, in which short-lived contractional events form localised orogenic belts and emplacement of granites, whereas the extensional periods produce rift basins and asthenospheric magma upwelling. This suggestion fits well with the evolution of the eastern Lachlan Orogen only.

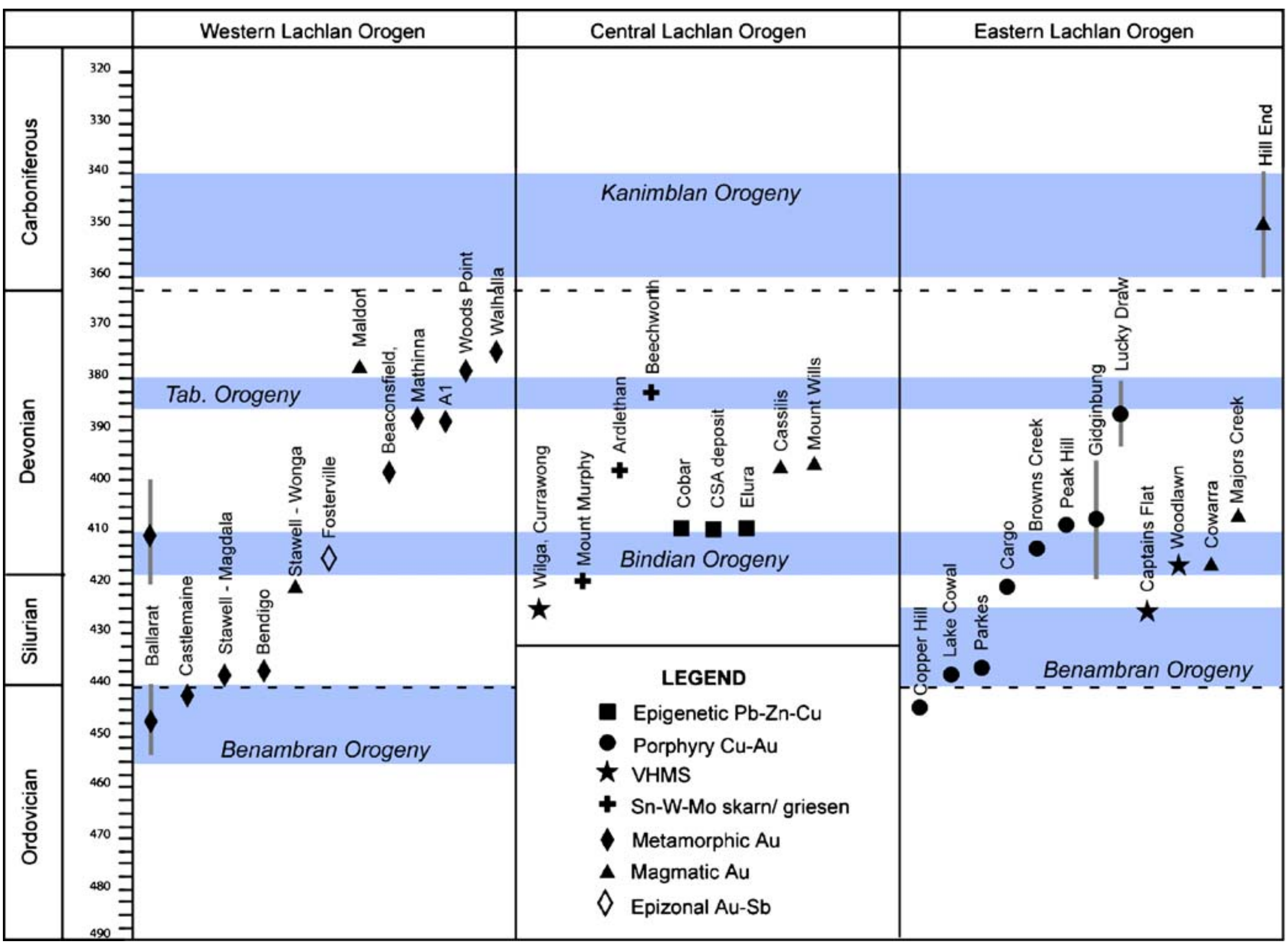


Fig. 3 Time–space diagram of significant mineral deposits of the Lachlan Orogen referred to in Fig. 1. Dates of mineral deposits from Gray and Foster (2004) and Bierlein et al. (2002)

Metallogeny of the Lachlan Orogen

The Lachlan Orogen is host to more than 22 mineral commodities (Walshe et al. 1995a,b; Bierlein et al. 2001; Gray et al. 2002a), including a number of major deposits such as the gold deposits at Ballarat and Bendigo (Victoria), the Tasmania Reef in Beaconsfield (Tasmania) and the Cobar copper–gold deposits (New South Wales). The majority of these deposits are concentrated in highly endowed metallogenic provinces and formed at discrete intervals during globally recognised metallogenic epochs (Figs. 2 and 3) (Jaques et al. 2002).

Walshe et al. (1995b) suggested that the metallogeny of the Lachlan Orogen needed to be understood in terms of source(s), system (transport) and trap in the evolving accretionary terrane on the eastern edge of Gondwana, concentrating on the nature of magmatism and the nature of the large-scale faults and fracture systems of the orogen. More recently, Bierlein et al. (2002) and Gray et al. (2002a) reconstructed the metallogenic evolution of the Lachlan Orogen by using the ore deposits as "tectonic fingerprints" to constrain their architectural setting, reservoirs and depositional mechanisms.

Many of the ore deposits throughout the Lachlan Orogen formed during a significant mineral epoch at 440 Ma (Perkins et al. 1995). Vos et al. (2006) (in this issue) suggest that the 440-Ma porphyry Au–Cu systems of the eastern Lachlan and the 440-Ma orogenic gold deposits of the western Lachlan formed due to major asthenospheric upwelling in response to slab rollback on a single "mega-subduction" zone. Such upwelling can cause magmatism and regional scale evolution and migration of hydrothermal fluids responsible for mineralisation. Goldfarb et al. (1998) suggested that the melting of the lower thickened crust during arc formation, slab rollback and extensional tectonism or subduction of a slab window beneath the seaward part of the forearc could also provide the required heat for initiation of the ore-forming processes.

From west to east (Figs. 2 and 3), and in fitting with the Gray and Foster (1997) tectonic model of the Lachlan Orogen, the western Lachlan Orogen comprises an accretionary collisional zone characterised by major Silurian to Devonian orogenic and magmatic gold deposits (Figs. 2, 3). The central Lachlan Orogen (Figs. 2 and 3) comprises (1) a supra-subduction zone magmatic arc characterised by Silurian granite-related Sn–W deposits from melting of the lower crust; (2) an accretionary collisional zone characterised by minor orogenic gold deposits and (3) a Late Silurian–Early Devonian fore-arc and intra-arc rift basin characterised by sedimentary-hosted Cu–Au deposits, from rifting and bimodal volcanism during crustal thinning (Gray and Foster 1997). The eastern Lachlan Orogen (Figs. 2 and 3) comprises (1) an Ordovician oceanic island arc characterised by porphyry Au–Cu deposits; (2) Late Silurian–Early Devonian intra-arc rift and inverted forearc rift basins characterised by sediment-hosted Cu–Au deposits and VHMS deposits, respectively, from rifting and bimodal volcanism during crustal thinning and (3) an accretionary collisional zone characterised by minor Middle-Late Devonian orogenic gold deposits (Gray and Foster 1997).

Following is a review of the five main ore deposit types within the Lachlan Orogen in chronological order of formation: (1) orogenic gold, including metamorphic (lode) Au, magmatic (intrusion-related) Au and epizonal (disseminated-stockwork) Au–Sb; (2) intrusion-related (porphyry) Au–Cu and Au deposits; (3) VHMS deposits; (4) granite-related Sn–W deposits and (5) sediment-hosted Cu–Au and Pb–Zn deposits.

Orogenic Au deposits

Orogenic gold deposits of the Lachlan Orogen are found predominantly in the western Lachlan Orogen, specifically in western-central Victoria and north-eastern Tasmania (Fig. 2), and belong to the greater circum-Pacific orogenic gold zone (Goldfarb et al. 1998). The orogenic gold deposits of Victoria contributed 90% of all hard rock gold production in the state, and include historical mines such as Ballarat, Bendigo, Castlemaine, Stawell, Maldon and Walhalla (Phillips et al. 2003). Orogenic gold deposits in Tasmania are found in the north and north-east of the state (Green 1990) and include the Tasmania Reef in Beaconsfield and the historically important Mangana and Mathinna deposits. Notably, the western Lachlan Orogen is one of the world's most intensely mineralised regions in terms of ounces of gold produced per square kilometre (Phillips and Hughes 1996).

The concentration of gold mineralisation is thought to have formed due to structural thickening and metamorphism within an accretionary wedge of a west-dipping subduction zone along the Gondwana margin during the Palaeozoic (Goldfarb et al. 1998; Bierlein et al. 2002). Three phases of orogenic gold mineralisation are recognised in the western Lachlan Orogen. The first phase was closely associated with peak metamorphism at 440–455 Ma (Foster et al. 1998; Bierlein et al. 2001) and also produced most of the economically important gold deposits in the western Lachlan (Foster et al. 1998). Fault reactivation at 420–400 Ma (Foster et al. 1998), and a thermal event at ~400 Ma (Foster et al. 1998), and again at 390–360 Ma (Foster et al. 1998), produced mostly smaller deposits, with the notable exception of the rich Woods Point and Walhalla deposits in the easternmost portion of the western Lachlan (Bierlein et al. 2001; Gray and Foster 2004). In comparison, the metamorphic gold mineralisation in north-eastern Tasmania occurred between 395–365 Ma (Bierlein et al. 2005).

Orogenic gold mineralisation in the western Lachlan was long assumed to be confined to quartz veins associated with carbonate, sericite, chlorite and sulphide alteration. However, Bierlein and Maher (2001) recognised that end member mineralisation styles of orogenic gold are represented by (1) quartz veins (metamorphic and intrusion-related lode gold) and (2) disseminated gold, brittle fracturing and stockwork systems (epizonal Au–Sb) at shallower levels in the later stages of uplift and exhumation. Unlike intrusion-related deposits (see below), metamorphism-related orogenic gold mineralisation in the western Lachlan Orogen can generally be shown to be genetically and temporally unrelated to major felsic magmatism (Bierlein et al. 2001).

Magmatic (intrusion-related) Au deposits

Magmatic (intrusion-related) gold deposits are found throughout the Lachlan Orogen, predominantly in the western Lachlan [e.g. Maldon, Malmsbury, Mt Piper, Wonga and Blue Tier (Tasmania) deposits], in the central Lachlan (e.g. Mt Wills and Cassilis deposits) and in the eastern Lachlan (e.g. Cowarra and Major Creek deposits) (Bierlein et al. 2001).

Intrusion-related gold deposits differ from metamorphic (lode) gold deposits as they are characterised by polymetallic gold assemblages (elevated Sb, W, Mo and Cu) and form in brittle conditions at shallow crustal levels (Bierlein and McKnight 2005). Importantly, these deposits are spatially and temporally related to mafic and felsic magmatism during the Early Devonian and Mid to Late Devonian, and therefore postdate the emplacement of metamorphic (lode) gold. The style of mineralisation is disseminated to stockwork, and the alteration zones include sericitisation, sulphidation, silicification, carbonatisation and tourmalinisation.

Epizonal (disseminated-stockwork) Au–Sb deposits

Epizonal (disseminated-stockwork) Au–Sb deposits, such as Fosterville, Nagambie, Costerfield and Lefroy (Tasmania), are found almost exclusively in the western Lachlan and are temporally and spatially associated with the third and final phase of Late Devonian gold mineralisation. At least in Victoria, these deposits appear to be temporally and spatially related to the Late Devonian thermal event associated with felsic magmatism of the central Victorian magmatic province in the western Lachlan Orogen at 370 Ma (Hughes 2006, in this issue).

The Au–Sb deposits formed in brittle conditions at shallow depths (~1,500 m) and are characterised by stibnite, pyrite, arsenopyrite, antimony and gold. Despite their apparent spatial and temporal close association with Devonian granites in Victoria, Au–Sb mineralisation is generally not considered to be intrusion-related, as Pb, S and O isotope data suggest that the deposits formed due to circulating fluid of metamorphic origin, possibly driven by Late Devonian thermal activity in the upper crust (Hughes 2006, in this issue).

Porphyry (and porphyry-related) Au and Au–Cu deposits

The porphyry (and porphyry-related) Au–Cu deposits of the Lachlan Orogen are found in the eastern Lachlan province (Fig. 2) (e.g. Cadia, Parkes, Copper Hill, Cowal, Peak Hill, Goonumbla and Wyoming) and are predominantly gold-rich (Walshe et al. 1995a,b; Bierlein et al. 2001). The 35 known occurrences are concentrated in the Narromine-Junee Volcanic Belt, the Molong Volcanic Belt, the Rockley-Gulong Volcanic Belts and the West Wylong-Temora Volcanic Belt, often collectively referred to as the Macquarie Arc (Smith et al. 2004).

The four major types of Ordovician porphyry (and porphyry-related) Au–Cu deposits in the eastern Lachlan province include (1) porphyry, (2) skarn, (3) high-sulphidation epithermal deposits and (4) carbonate-based epithermal deposits (Smith et al. 2004).

The porphyry Au–Cu deposits of the eastern Lachlan Orogen can be divided into two groups (Nie et al. 2000), those with shoshinite features associated with monzonite (alkalic; e.g. Cadia and Goonumbla) and those associated with diorite and dacite (calc-alkalic; e.g. Copper Hill and Cargo). The most significant deposits are the alkalic porphyry Au–Cu deposits, and they are characterised by quartz-sulphide stockwork or quartz vein sheets and potassic alteration (Smith et al. 2004).

The epithermal gold skarn deposits, such as the Sheahan-Grants deposit, are associated with monzonitic intrusive complexes of Late Ordovician age (430–439 Ma; Nie et al. 2000). The epithermal gold deposits (e.g. Gidginbung and Peak Hill) are associated with andesites and volcanic rocks of Late Ordovician age also, and are associated with advanced argillic alteration (Walshe et al. 1995b). They are characterised by zonation of ore minerals (including pyrite, tennantite, luzonite, enargite and chalcocite) and high sulphidation.

The carbonate-based epithermal deposits (e.g. Endeavour 42 deposit at Lake Cowal) occur in quartz-carbonate veins related to calc-alkaline volcanic and intrusive rocks and are characterised by low sulphidation (Heithersay and Walshe 1995; Bywater et al. 2004). These deposits form at shallower levels to their related porphyry systems.

VHMS deposits

The VHMS deposits of the Lachlan Orogen developed in the central (e.g. the Benambran VHMS deposits: Wilga and Currawong) and eastern Lachlan provinces (e.g. Woodlawn and Captains Flat) (Fig. 2), in inverted rift basins during the Late Silurian to Early Devonian (Glen 1995; Gray and Foster 2004). The Wilga and Currawong deposits are analogous to Besshi/Kielsagar-type VHMS deposits, the Woodlawn deposit is analogous to Kuroko-type VHMS deposits and the Captains Flat is analogous to Cyprus-type VHMS deposits.

The massive sulphide deposits lie in discrete horizons, having formed in sub-aerial conditions concurrently with the deposition of volcanoclastic and volcano-sedimentary rock in close proximity to volcanic centres. Alteration is controlled by intersecting growth faults (Solomon and Groves 1994) and is characterised by phyllosilicate assemblages.

Granite-related Sn–W deposits

The granite-related Sn–W deposits of the central Lachlan Orogen (Fig. 2) formed in the Late Ordovician–Early Silurian Wagga-Omeo metamorphic complex (e.g. Ardlethan, Mammoth Lode, Mt Murphy, Beechworth), and also in north-eastern Tasmania (e.g. Anchor and Aberfoyle) (Walshe et al. 1995a,b; Bierlein et al. 2001). The Ardlethan deposit of the Wagga-Omeo metamorphic complex is hosted in the most fractionated granite within the Lachlan Orogen. The tin deposits of north-east Tasmania are related to Middle to Late Devonian alkali feldspar granites of the Blue Tier and Eddystone Batholiths of north-eastern Tasmania, which intruded the Ordovician-Devonian Mathinna turbidite unit (Sun and Higgins 1996).

Sn–W–Mo mineralisation characteristically is genetically related to I- and S-type granites, which is a function of the relative oxidation state and degree of fractionation within associated granites. Tin deposits can be divided into two types: greisen-associated tin deposits (e.g. Anchor) and tin–tungsten vein deposits (e.g. Aberfolye and Storeys Creek) (Green 1990). The greisen-associated tin deposits are characterised by small, low-grade disseminated cassiterite deposits, whereas the small tin–tungsten deposits are characterised by quartz–wolframite and cassiterite dilational veins (Collins and Williams 1986).

The high-temperature metamorphic complex in the central Lachlan is part of a more evolved, differentiated magmatic arc associated with the centrally located north-west-trending, east-dipping subduction zone (Blevin and Chappell 1995; Gray and Foster 2004) in the context of a Pacific-style multiple subduction system. The tin-hosting granites, in contrast to the other granites of north-eastern Tasmania, are thought to be derived from a different parent source with distinctive chemical–isotopic systematics, due to mixing of an alkali feldspar granite-derived magmatic fluid with meteoric fluid (Sun and Higgins 1996).

Sediment-hosted (epigenetic) Cu–Au and Pb–Zn deposits

The sediment-hosted basemetal deposits of the central (e.g. Elura, Cobar and Queen Bee) and eastern Lachlan (e.g. Clarkes Reef and Buchan) (Fig. 2) formed within high-strain zones of rift-related extensional sedimentary basins (Walshe et al. 1995b) during the Late Silurian to Early Devonian (Bierlein et al. 2002). Elura (Zn–Pb–Ag) is the only exclusively zinc–lead–silver deposit to be discovered in the Cobar province (dominantly Cu–Au plus minor Zn, Pb or Ag; de Roo 1989; Schmidt 1990). The deposits formed within a thinly bedded turbidite sequence at shallow depths, within the brittle–ductile transition zone. At least a portion of the mineralisation was structurally controlled, and therefore, syn-deformational, therefore differing from syn-depositional VHMS deposits. The deposits are commonly characterised by narrow irregular zones of sulphide (+quartz) veinlets or massive and disseminated sulphide lenses within faults or shear zones.

Outstanding issues and future directions

With a resurgence of research and exploration in the Lachlan Orogen, previously unsolved issues of the tectonic and metallogenic evolution of the orogen can now be addressed with a multidisciplinary approach aided by new technologies, tools and methods. As most of Australia's shallow mineral deposits have been discovered, it has been realised that technologies and methods for detecting buried deposits need to be developed, such as 3D modeling, geophysics, lithogeochemistry and technologies to drill to greater depths.

In the last decade, 3D mapping has gained recognition as a powerful tool (Mallet et al. 1989; Mallet 2000; Jessell 2001; Rawlings et al. 2004). 3D modelling has enabled users to integrate, reconcile and interrogate multiple data sets, such as geology, geochemistry, geophysics, drill hole data and even fluid flow, which can then be visualised and conceptualised into complex geological models. The 3D models range in scale from microscopic to lithospheric and can also be used to further test emerging theories such as modelling of thermodynamic properties or fluid chemistry along complex fault networks.

A long-term objective (e.g. Cooperative Research Centre for Predictive Mineral Discovery) is to develop 3D and 4D computational models of major Australian mineral systems to advance predictive capabilities of the gold mineralisation in western Victoria, the Tasmanides and other Australian metallogenic regions. Collaborative research in the Woods Point–Walhalla goldfield of central Victoria is currently aided by 3D models of various mineralising systems (Hough et al. 2005; Thorp et al. 2005) in an effort to constrain the relationship of gold mineralisation within the structural framework.

Chemical modeling by Mernagh and Bierlein (2004) has tested the chemical parameters of gold deposition from aqueous fluids flowing upwards through a fault within a sandstone-dominated sedimentary rock, analogous to the many orogenic gold deposits in the Lachlan Orogen. Fluid conditions were varied, such as temperature, CO_2 content, sulphur content, fugacity and pH, and it was discovered that gold could be precipitated over a wide range of temperatures from CO_2-bearing, low salinity, aqueous fluids, resulting in quartz vein compositions comparable to that found in the Lachlan Orogen (Mernagh and Bierlein 2004).

New satellite technology, such as the advanced space-borne thermal emission and reflection radiometer (ASTER), is currently being tested by the Commonwealth Scientific and Industrial Research Organization Mineral Mapping Technologies Group on several Australian sites. ASTER imagery is more detailed than Landsat, as it has wide spectral coverage, high spatial resolution, and can be viewed in stereo. ASTER imagery will be applied to mineral exploration, especially for mineral abundance modelling and for discerning zones of alteration and mineralisation, although its usage in heavily vegetated regions (e.g. the Lachlan Orogen) may be limited.

Such an example of the application of ASTER technology is the testing of lithogeochemistry (Wilde et al. 2004) as an exploration strategy for gold system indicators in mineralised areas buried by post-mineralisation cover rocks. ASTER short-wave infrared analysis of weathered or unweathered samples defines the ratio of kaolinite to white mica, thereby delineating the primary hydrothermal alteration zones related to ore mineralisation. Wilde et al. (2004) successfully tested the lithogeochemistry technique in Bendigo, Stawell and Fosterville.

Thought amongst industry and academia has now advanced to place mineral systems in the context of the evolving tectonics of the Lachlan Orogen (Bierlein et al. 2001; Gray et al. 2002a) and to develop predictive models and new mineral exploration strategies, with a strong focus on crustal architecture, the nature of the sub-continental lithosphere and timing of critical events. Such an example is the classification of the Late Devonian gold mineralisation in Victoria into mineralogical domains of continuous mineralogy, as opposed to lithology, ore structure and zones (Hughes 2006, in this issue). By viewing the deposits in terms of mineralogical domains and geological age, the regional fluid flow events and related deep-seated processes may be better understood.

Wilde et al. (2002) have recognised the unconventional occurrence of platinum group element deposits in geological environments not associated with mafic and ultra-mafic intrusive rocks, such as intracratonic rift environments (transported by oxidised brines), deformed massive margins (bisulphide coplexes in reduced hydrothermal fluids) and surface environments (hydroxyl complexes in oxidised low-salinity waters). This discovery introduces the potential for exploration of economic deposits of Pt and Pd (±Cu, U and base metals) in the Lachlan Orogen, with emphasis on orogenic sediment-hosted gold deposits and carbon- and sulphur-rich (reduced) hostrock lithologies (Wilde et al. 2002).

Structural relationships with regards to mineralisation, especially gold mineralisation, is also now better understood. The interplay of brittle vs ductile events and quartz vein emplacement (Schaubs and Wilson 2002) has established that quartz vein gold deposits are characteristically related to high-angle reverse faults. An example of this is the classic auriferous "saddle reefs" of the Bendigo goldfields. It is now recognised that saddle reefs with significant gold mineralisation were formed when bedding-parallel unauriferous quartz veins associated with fold hinges were later intersected by high-angle reverse faults and the ensuing auriferous quartz vein emplacement (Bierlein et al. 2004).

The recent recognition and definition, and in some cases re-classification, of various styles of deposits within the Lachlan Orogen has led to an increase in the potential exploration research space. This has led to renewed exploration and subsequent discovery of disseminated (primary) gold (e.g. at Fosterville) and intrusion-related gold (e.g. Wonga deposit, Stawell) in the western Lachlan Orogen, and orogenic gold (e.g. Wyoming) and epithermal gold (e.g. Peak Hill) in the porphyry Cu–Au dominated Macquarie Arc in the eastern Lachlan Orogen.

A database of the significant number of mineral occurrences associated with Phanerozoic granite and volcanic rocks in the Lachlan Orogen and elsewhere is currently under development. As a result, Wyborn (2003) and Champion et al. (2004) recognised that mineral systems associated with Phanerozoic granites within the Lachlan Orogen are largely controlled by characteristics of the wall rock, such as oxidation state, competency, porosity, structure and lithology. Interrogation of such a database will enable explorationists to define and rank targeting criteria.

Collaboration between industry and academia remains the key to future exploration. Geoscience Australia, along with collaborating state geoscience departments, are now developing Australia-wide geographic information system geoscientific databases to include previous and current geological data and research with the aim to understand the relationship between hostrock geology, metallogenesis and tectonics in the Lachlan Orogen.

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