The Lachlan Orogen: New boundaries, new data, new ideas, new deposits

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Introduction: the Lachlan Orogen in a Tasmanide Context

The Lachlan Orogen of NSW, Victoria and northeast Tasmania forms the keystone in our understanding the tectonic and metallogenic evolution of all of eastern Australia. In this paper, I first discuss the Lachlan Orogen within its eastern Australian context, before focusing on its boundaries and then on key tectonic, structural and metallogenic aspects of its formation. In this way I hope to construct plate tectonic and architectural frameworks within which we can place a discussion of mineral deposits.

Palaeozoic to Mesozoic rocks in eastern Australia constitute the Tasmanides, itself part of Gondwana. The Tasmanides record the break-up of the supercontinent Rodinia, from ~750 Ma until ~525 Ma, followed by ~300 million years of largely convergent margin interaction with the proto-Pacific plate until the Late Triassic.

How do we try and describe the geological chaos that eventuates from such plate interactions, especially since we are looking back over 480 million years and lessons from the SW Pacific tell us that arcs are born and die (ie are subducted) in only a few million years. There are two main ways.

The first is to divide the Tasmanides into areal packages. This is conventionally done by subdividing it into a collage of orogenic belts (or orogens, known as fold belts before the importance of linked fault systems was appreciated). This subdivision is a structural one, and is based on estimating the areal extents of deformations of different ages. In this way, the Tasmanides are subdivided into five orogenic belts. In the southern Tasmanides are the Delamerian (=Tyennan in western Tasmania), the Lachlan and the southern New England Orogen. In the north lie the Thomson Orogen, the northern New England Orogen and to the north the North Queensland Orogen. Just to complicate things, an internal Permian-Triassic rift-foreland basin system, the Bowen-Gunnedah-Sydney Basin System, separates both the Lachlan Orogen and Thomson Orogen from the New England Orogen. Using this system of subdivision, rocks of the Delamerian Orogeny were deformed by the Middle-Late Cambrian Delamerian Orogeny, the Lachlan Orogen was deformed at the end of the Ordovician (Benambran Orogeny), as well as in the Middle Devonian (Tabberabberan Orogeny) and also in the Early Carboniferous (Kanimblan Orogeny). Complications occur where orogenies consist of phases separated by sedimentation and/or igneous activity, and where post-orogenic stratigraphic units lie above rocks deformed in these defining orogenies, making it difficult to recognise and interpret boundaries between orogens.

Other problems also arise, from this classification system. For example, how do we classify Cambrian mafic and ultramafic rocks that characterise much of the Delamerian Orogen but which also lie east of the Delamerian Orogen? Outcrops occur in both the New England Orogen (along the Peel-Manning Fault System) and in the Lachlan Orogen, for example in the hangingwalls of the Heathcote, Mt Wellington and Governor fault zones. Because these rocks, as far as we know, were not deformed in the Delamerian Orogeny, we can’t put them into the Delamerian Orogen.

The solution lies in sub-dividing the Tasmanides into time packages. The concept of tectonic cycles or supercycles (Glen 2005) gets around this problem by erecting a series of tectonic cycles which are independent of geography. Then, by using the plate tectonic paradigm, we can categorise rock sequences and structures into plate tectonic elements in an individual time slice into (ie a convergent margin consisting of, perhaps, an arc, backarc basin, subduction complex), or extensional margin or strike-slip margin.

A complete tectonic cycle includes sedimentation and igneous activity (either one of, or a combination of, convergent, strike-slip or extensional or intraplate) followed by deformation that commonly appears to reflect the accretion of a terrane, such as an arc or subduction complex, to Gondwana. Each cycle is named after its terminal deformation. Temporally, the Tasmanides comprise three (super)cycles, each encompassing sedimentation and igneous activity, terminated by orogenies. The supercycles are the Delamerian (Neoproterozoic to latest Cambrian), terminated by forearc or arc collision with the craton in the Middle to Late Cambrian (with post collisional granites and molasse), the Lachlan (basal Ordovician to Early Carboniferous and divided into three cycles all terminated by orogenies - the Benambran, the Tabberabberan and the Kanimblan) and the Hunter Bowen (Late Devonian to Late Triassic) terminated by accretion of an intraoceanic arc.

Using tectonic cycles in this way shows that from the Middle Cambrian to the Late Triassic, the Tasmanides evolved by long periods of sedimentation, arc and back arc activity along the east Gondwana margin, coupled with formation of subduction complexes related to generally west-dipping subduction. These were punctuated by the short-lived, ?orthogonal as well as highly oblique accretion of craton-derived turbidite terranes, island arcs and subduction complexes that developed along the east Gondwana margin that also acted to close back arc basins. The proto-Pacific Ocean itself was never closed.

In the Tasmanides, rocks generally get younger from west to east, away from cratonic Australia, so that rocks in the Delamerian Orogen are generally older than those in the New England Orogen. This fits a model in which the Tasmanides grew by the accretion of rock masses at plate boundaries. However, there are two important caveats (Glen 2005): i) there is no sign of accretion in the North Queensland Orogen, where Neoproterozoic to Permian rocks are stacked on top of each other, and remain close to the cratonic margin. This in marked contrast to the southern Tasmanides, where the eastern margin of the Delamerian Orogen lies ~400 km east of cratonic Australia (the Gawler Craton). Rocks in the Lachlan Orogen may lie up to an extra ~700 km farther east and the New England Orogen up to ~300 km farther east again. And these are deformed widths! This important difference between the northern and southern Tasmanides may indicate that rollback of the proto-Pacific plate only occurred in the south, and must reflect segmentation or oblique spreading of that plate.
ii) rollback of the southern part of the proto-Pacific plate is reflected by some of the outboard orogens containing old rocks (eg rocks of the Delamerian supercycle in the Lachlan Orogen and New England Orogen and rocks of the Lachlan supercycle in the New England Orogen). These represent pieces of older cycles rifted off during rollback in the Ordovician and again in the Silurian-Devonian (Glen 2005) and now forming partial basement to the new cycle.

The Lachlan Orogen: boundaries The eastern boundary of the Lachlan Orogen with the New England Orogen is obscured by young rocks of the Sydney and Gunnedah basins. The western boundary with the Delamerian Orogen is controversial and is discussed by Hallett *et al*. (2005) and Hallett (this volume). ~500 Ma white mica cooling ages reported from parts of the Stawell Zone in western Victoria (Miller *et al.* 2005) suggest that the Lachlan-Delamerian Zone boundary lies east of the Coongee Break (east of the Stawell gold mine) and it is here taken to lie along the Avoca Fault, west of the Bendigo Zone. Extensions of the Stawell and Bendigo zones into southwestern NSW have considerable economic implications. The northern boundary with the Thomson Orogen occurs in the Tibooburra-Brewarrina area of far northwestern NSW and is a curvilinear east-west trending, north-dipping crustal scale thrust. Results of seismic reflection profiling across this contact are discussed by Glen *et al*. (this volume).

Before concentrating on the Lachlan Orogen, I must make brief comment on the Delamerian supercycle.

The Delamerian supercycle consists of two cycles. The first cycle records a prolonged rifting event from 750 Ma till ~580 Ma as Rodinia was broken up. The inboard part is largely amagmatic and is represented by the Adelaide Rift Complex. The outboard part is characterised by development of smaller rift basins and a major alkaline magmatic rift system from 600-580 Ma. The second cycle is marked by a switch to convergent margin magmatism in the outboard part of the Delamerian Orogen that began about 525 Ma. This was approximately synchronous with a new rifting event, leading to formation of the Kanmantoo Trough in the inboard part of the orogen. Cycle two is reflected by the formation of mafic to ultramafic boninitic forearc crust in western Tasmania and probable arc rocks as well as forearc crust on the mainland. Both east and west dipping subduction have been proposed and more than one arc may have been developed sequentially. Accretion of arc and forearc rocks occurred around 510-505 Ma and was followed by extension, post-collisional volcanism and then later deformation at the end of the Cambrian.

The Lachlan Orogen: cycles and metallogeny

The Lachlan Supercycle is divided into three cycles – the Benambran, the Tabberabberan and the Kanimblan

The Benambran cycle began with molassic sedimentation on the old Delamerian Orogen, but was mainly characterised by rollback of the southern part of the proto-Pacific plate after the Delamerian Orogeny. A new plate boundary was established about 1000 km east of the old Delamerian margin, and led to the formation of the intraoceanic mafic to intermediate Macquarie Arc opposite a 1000 km long, west-dipping, highly convergent part of the plate boundary. Blueschists associated with this subduction zone now occur as knockers in fault slices in the southern New England Orogen and were probably displaced ~200 km to the north in the end-Ordovician Benambran Orogeny. Ordovician quartz-rich turbidites and shales formed in separate terranes that show differences in lithology, thickness and fauna: one was probably in situ, deposited in a back arc basin, but the others are allochthonous and formed off present-day west Antarctica. One of these, the Bega Terrane, lies east of the Macquarie Arc and was transported northwards along a largely transform plate boundary in the Late Ordovician. It and the Macquarie Arc were accreted by a combination of thick and thin-skinned thrusting and multiple deformation around the Ordovician-Silurian boundary in the Benambran Orogeny. The largely Ordovician oceanic Narooma Terrane was accreted to the Bega Terrane in the Benambran Orogeny as well. MORB-like mafic volcanic + chert terranes represent ocean crust formed during mid-Ordovician seafloor spreading and were imbricated with other terranes during closure of ocean basins in the Benambran Orogeny. The allochthonous Bendigo Terrane also underwent a simple thin-skinned deformation in the Benambran Orogeny (well south of its present position), but only in the western part. In its eastern part, deposition continued into the Early Devonian during northwards strike-slip transport, and was only terminated by accretion at the end of the Early Devonian in the Tabberabberan Orogeny.

Metallogeny

Rocks of the Benambran Cycle contain the two world-class groups of deposits in the Lachlan Orogen: structurally-controlled gold deposits in the Bendigo Zone and porphyry gold-copper deposits (and other styles) in the Macquarie Arc. Although both underwent major mineralising events at ~440 Ma, the terrane model for the Benambran cycle suggests that they formed thousands of kilometres apart. Bendigo zone gold is syndeformational. Porphyry gold copper deposits in the Macquarie Arc formed during critical events in the evolution of the arc, related to interruptions, cessation or restarts of magmatism, not to steady-state subduction. Critically the ~440 Ma porphyries were emplaced during accretion of the arc in the Benambran Orogeny, with control apparently exercised by cross structures (see below).

Tabberabberan cycle

With the exception of the Bendigo Terrane, the enlarged eastern part of Gondwana was in tension from the Early Silurian to the Middle Devonian in the Tabberabberan Cycle. In the southern Tasmanides, crustal extension occurred in a wide developing back arc region that formed as a result of rollback of the southern part of the proto-Pacific Plate. This led to the relocation of a new west-dipping subduction zone and development of an intraoceanic arc and subduction complex, both now preserved in the southern New England Orogen. This Silurian-Devonian extension led to dismembering of the Ordovician Macquarie Arc into several structural belts, formation of sedimentary rift and transtensional basins and emplacement of both I and S-type granitic batholiths. The well known basins like Cobar Basin, Mt Hope Trough, Rast Trough, Cowra Trough, Hill End Trough, Canberra-Yass Shelf etc all formed during this event. Several rift events can be recognised, separated by sag-phase deposition of shales or limestone. Rifting occurred around 430 Ma, at the base of the Wenlock (Early-Late Silurian boundary), and again at around 413 Ma in the middle Lochkovian in the Early Devonian. Rift packages may be separated by provenance changes and/or extensional unconformities. Contractional deformation around the Silurian-Devonian boundary only occurred in basins near the NNW-trending Gilmore Fault Zone and its linked systems.

The Middle Devonian Tabberabberan Orogeny was marked by inversion of sedimentary and volcanic rich rifts, deformation of granitoids and re-deformation and renewed imbrication of older rocks. It was in part driven by changes along there plate margin and in part by the accretion of the Bendigo Terrane.

<u>Metallogeny</u>

The classical structurally controlled deposits in the Cobar Basin and Hill End Trough are hosted by Early Devonian sedimentary rocks, although their formation occurred during basin inversion, either Devonian or Carboniferous. Base metal-rich deposits in Silurian rifts in the eastern Lachlan Orogen seem to be largely structurally controlled and thus inversion related but whether this is Middle Devonian or Early Carboniferous is uncertain. Some mineralisation is syngenetic.

Granite-related mineralisation is often seen as high-risk in the Lachlan Orogen.. Fractionated I-type granites like the Braidwood (containing Dargues Reef) and those of the Boggy Plain Supersuite (eg Yeoval Complex with its large number of small showings) seem to have the most potential. In this context, interpretation of large areas of low-strain high level Early-mid-Devonian igneous complexes under cover north of the Narromine and Dubbo 1:250 000 sheets (Dawson & Glen 2006) increases the potential to find granite-related deposits, especially given their interpretation belonging to the Boggy Pain Supersuite (P. Blevin pers. comm. 2006).

Disseminated fine-gold deposits (‘Carlin-style’) also form exploration targets in carbonate rich basins, especially those that experienced multiple rifting events with associated magmatism and structures perhaps inherited from the Benambran cycle. Fine-grained gold may also occur in clastic sedimentary rocks too.

The Kanimblan Cycle (which overlaps in time with the Hunter-Bowen Supercycle of the New England Orogen) began with limited rifting, with formation of granites and volcanics in small, narrow rifts (A-type in NSW, S- and I-type in Victoria). Extension was rapidly aborted and replaced by deposition of a 3-4 km blanket of continental sedimentary rocks. These rocks extend from the Delamerian Orogen right across the Lachlan Orogen. Deformation occurred in the Early Carboniferous, with emplacement of post-tectonic Early Carboniferous granites.

<u>Metallogeny</u>

I-type Carboniferous granites and adjacent skarns host small deposits. Structurally controlled gold in Ordovician Sofala and Burranah Volcanics, in the eastern, Rockley-Gulgong Volcanic Belt of subduction-related volcanics and in the Silurian Chesleigh Formation at Hill End formed during Carboniferous deformation.

Hunter-Bowen Supercycle and Metallogeny

The Hunter-Bowen supercycle covers the Late Devonian to Late Triassic development of the Tasmanides and is best seen in the New England Orogen. Here two cycles of convergent margin development that led to formation of continental margin arcs are separated by Early Permian extension. In the Late Devonian and the Carboniferous, the outboard part of the Tasmanides developed into a classical convergent margin related to west-dipping subduction. From west to east, this margin consisted of a continental margin arc, a forearc basin and subduction complexes. A feature of the northern New England Orogen was the development of a Late Devonian to mid-Carboniferous back arc basin (Drummond Basin) on continental crust west of the arc. The Drummond Basin was filled by a lower volcanic-rich package, a middle quartz-rich package derived from the craton and an upper volcaniclastic package that is arc-derived. There are Late Carboniferous intrusives. The presence of epithermal deposits like those at Pajingo indicates the prospective nature of this basin, and forces the question whether a similar backarc basin lies in NSW opposite the southern New England Orogen. If so, it lies beneath the Gunnedah Basin, in an area recently interpreted as containing Carboniferous granites (Dawson & Glen 2006).

The Lachlan Orogen: architecture and metallogeny

Much of the architecture of the Lachlan Orogen was set up during the Benambran Orogeny, when Ordovician arc and turbidite terranes were accreted to Gondwana. This accretion was oblique, and resulted in the formation of both thin and thick (ie all of crust) skinned structures. The north-south component of this accretion was accommodated by the formation of cross structures with WNW to east-west trends and by strike-slip movement on the NNW to N-trending thrust faults. (The term 'thrust fault' is used here to describe those contractional faults that lie at low angles to the rock envelope. The angle to the present day horizontal, the text book definition of a thrust, is irrelevant in a situation where these faults were passively rotated, along with their enclosing rock packages, during subsequent deformation). Extension in the Silurian to Middle Devonian Tabberabberan cycle was accommodated in the upper crust by formation of major normal and oblique-slip faults that created space for the formation of sedimentary basins. Basin margins provided suitable pathways for fluids during both deposition and inversion, as well as localising deformation during inversion events. It is thus no surprise that hinge areas and margins are the sites of major mineral deposits. It is debateable how many of these basin-bounding structures were inherited from the Benambran Orogeny and how many formed as new structures that cut across the regional fabric.

The recognition that faults and folds form parts of linked systems not only helps explain how deformation (extensional and contractional) was partitioned through the upper crust, but also provides pathways for the migration of fluids up into the upper crust or down into the middle crust. In a structural environment characterised by oblique and strike-slip faults, the presence of jogs, with their potential for dense fracturing and thus greater permeability, provides suitable targets for both magmas as well as ore-bearing fluids.

The Lachlan Orogen: Cross structures

In such an environment of oblique accretion, the presence of cross structures becomes a significant feature of the Lachlan Orogen. On a regional scale are features like the Lachlan Transverse Zone. Restoring the Silurian-Devonian disruption of the Macquarie Arc suggests that this zone developed from a Late Ordovician transform fault lying at high angles to the plate boundary. In the Late Ordovician-Early Silurian, the Lachlan Transverse Zone localised the intrusion and shapes of porphyries such as at Cadia. Smaller WNW-tending structures that seem to localise intrusions and plumbing systems include those at Wyoming (Alkane Exploration Ltd website) and Copper Hill (Golden Cross Resources Ltd website) and Dargues Reef (Moly Mines Limited website). The Lachlan Transverse Zone was then reactivated through to the Carboniferous, controlling and partitioning upper crustal extension and contraction in a subtle way, and extending father west into the Cobar region.

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