Modelling the Palaeozoic tectonic evolution of the Lachlan Orogen

Thomas Schaan
ACR Centre of Excellence
In Ore Deposits
Private Bag 79, University of Tasmania
Thomas.schaap@utas.edu.au

Sebastien Meffre
ARC Centre of Excellence
in Ore Deposits
Private Bag 79, University of Tasmania
sebastien.meffre@utas.edu.au

Joanne Whitakker
Institute for Marine and Antarctic Studies &
University of Tasmania
Private Bag 129, Hobart, Tasmania
Chris.lewis@ga.gov.au

Matthew Cracknell
ARC Centre of Excellence
In Ore Deposits
Private Bag 79, University of Tasmania
m.j.cracknell@utas.edu.au

Michael Roach
ARC Centre of Excellence
In Ore Deposits
Private Bag 79, University of Tasmania
Michael.roach@utas.edu.au

SUMMARY

The Lachlan Orogen's mineral wealth is a direct result of tectonic processes that took place in the early Palaeozoic, but the exact nature and timing of events is widely contested. Here, we apply new methods of deforming tectonic reconstruction modelling to the area. The resulting reconstructions enable us to consistently compare alternative, previously-proposed models and test them against new and old data. This approach highlights model self-inconsistencies and incompatibilities with available data. We adopted an approach where the most valid components of individual tectonic reconstructions were combined to produce a new reconstruction model constrained by the most recent data. The new model invokes two concurrent subduction zones from the Early Cambrian to the Late Ordovician. It includes a consistent continent-dipping subduction at the Eastern Gondwanan margin, and an outboard subduction complex, which experiences multiple reversals. These are responsible for an unnamed Cambrian Arc and its obduction in Tasmania, which is part of the microcontinent VanDieland before accretion to Gondwana in the late Cambrian. The Macquarie Arc later develops in the Ordovician over the Cambrian Arc. A single continent-dipping system then resumes following the Benambran Orogeny, when oroclinal folding occurs across south-eastern Australia followed by east-west shortening of the Tabberabberan Orogeny.

Key words: Lachlan Orogen, Orocline, Tectonic Reconstructions, Macquarie Arc, GPlates

INTRODUCTION

The Palaeozoic Lachlan Orogen encompasses much of south-eastern Australia, including much of New South Wales, Victoria, and Tasmania, as well as Northern Victoria Land in Antarctica, parts of South Island New Zealand and the Lord Howe Rise (Figure 1). It is host to numerous economically-important world-class ore deposits (Hough, et al. 2006), however much of the basement rock lies under thick cover sequences, hence vast, potentially mineralised areas remain unexplored. Tectonic modelling aims to provide a means of determining the history of the Lachlan Orogen, and subsequently the characteristics of covered bedrock, which may aid in the increasingly-important endeavour of deep-cover mineral exploration.

Many attempts have been made to reconstruct the tectonic history of the Lachlan Orogen. Many of these published models implement the accretion of the microcontinent "VanDieland". Thought to comprise Proterozoic basement rock, it lies beneath the Melbourne Zone and is connected to the Western Tasmania Terrane (WTT) (Cayley 2011, Pilia, et al. 2015, VandenBerg, et al. 2000).

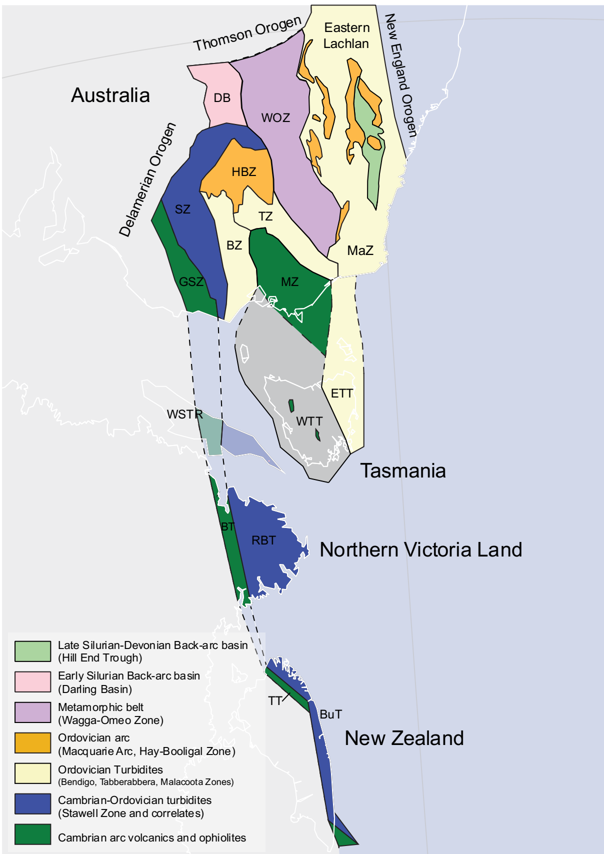

Figure 1. Modern distribution of Lachlan Orogen terranes superimposed on a Middle Palaeozoic tectonic reconstruction. Abbreviations: BT – Bowers Terrane; BuT – Buller Terrane; DB – Darling Basin; ETT – East Tasmania Terrane; GSZ – Grampians-Stavely Zone; MaZ – Mallacoota Zone; MZ – Melbourne Zone; RBT –

Robertson Bay Terrane; SZ – Stawell Zone; TT – Takaka Terrane; TZ – Tabberabbera Zone; WOZ – Wagga-Omeo Zone; WSTR – West South Tasman Rise; WTT – West Tasmania Terrane. Modified from Glen (2013).

The concept of Silurian-Devonian oroclinal folding is gaining increasing traction in modern models, based on structural vergence (Musgrave 2015) and geodynamic modelling (Moresi, et al. 2014). In this paradigm, originally parallel, north-striking accretionary terranes exist on the forearc of a continent-dipping subduction zone at the Gondwanan margin. The accretion of VanDieland causes the subduction zone to become “pinned” in the south, subsequently retreating asymmetrically and wrapping around VanDieland, dragging the forearc crust with it and causing it to fold as an orocline, resulting in the convoluted distribution of structural zones seen today.

One of the outstanding enigmas these models grapple with is the quantity, timing, polarity, and placement of subduction zones throughout the Palaeozoic. Some models opt for singular subduction (e.g. Cayley, et al. 2018), while others invoke multiple concurrent subduction zones that experience polarity reversals and retreats (e.g. Fergusson and Colquhoun 2018).

Further complicating the issue is that many published models do not consider the Lachlan Orogen in its entirety, often focussing on narrow areas in time and space. Moreover, research that has taken a broader perspective often omits the roles of Northern Victoria Land and New Zealand.

This research aims to utilise modern plate reconstruction software (*GPlates*) as a medium to produce intuitive, quantitative models that test current tectonic concepts against empirical data. This approach will facilitate the development of new models that consider the most robust aspects of the literature as well as identify areas of uncertainty.

METHOD

Tectonic reconstructions are commonly presented as two-dimensional paleogeographic maps depicting important geodynamic events at specific points in geological time. To construct a time-continuous animated tectonic reconstruction in GPlates, static tectonic models were selected from the literature that were: (a) easily testable against data and knowledge; (b) exemplars of a particular geodynamic concept; and (c) considered geologically robust. Based on these criteria, a series of published models collectively covering the entire Lachlan Orogen over a period from the Neoproterozoic to the Devonian were considered.

Static time slices from the selected tectonic models were georeferenced and imported into *GPlates* as raster images and digitised into vector features suitable for manipulation. Terranes were digitised as topological network features which, unlike normal polygons, are able to be distorted. This is useful as these features can then be used to calculate strain rates and crustal thickness changes, as well as the original geometries of enclosed structures (Gurnis, et al. 2018). The Lachlan Orogen models produced here were superimposed on a global Phanerozoic *GPlates* model (Wright, et al. 2013) combined with a model of Australian cratonic subdivisions (Collins and Pisarevsky 2005).

Published models were compared where they described similar events, and/or where they overlapped in time and space. Individual models were also assessed against more regional spatio-temporal events and constraints. For example, a given model may describe events which occur during the Cambrian in Tasmania with greater accuracy than others, but these may not be tectonically possible in the context of events occurring in Antarctica and Australia. Modifications were either made to the model in question and/or the spatio-temporal context, or it was rejected.

The models considered in this project were compared and tested against empirical data to assess their feasibility. Datasets directly used and experimented with include regional Australian magnetics and gravity grids, geochronology, structural geology (e.g. shortening estimates) and palaeobiology. These data are readily integrated into *GPlates* where they can be reconstructed according to the motion and deformation of the geology. Once the relative strengths and weaknesses of each model were determined, the most robust components of each model were extracted and iteratively modified into a new workspace to provide a comprehensive model incorporating the entire Paleozoic evolution of the Lachlan Orogen.

RESULTS AND DISCUSSION

Models were digitised and assessed, and a new comprehensive model is herein discussed, summarised by Table 1 and Figures 2a-d and 3. As work progresses and new data become available, this new model will be adjusted accordingly.

In the Neoproterozoic-Early Cambrian, most models consider VanDieland as a rifted microcontinent lying in the Palaeo-Pacific outboard of the Gondwanan margin following the breakup of Gondwana and Laurentia. Subduction to the east developed an unnamed intra-oceanic island arc which was drawn towards Tasmania and Australia, eventually obducting to form ophiolite sequences (Cayley 2011, Glen 2013, Münker and Crawford 2000). An alternative model (e.g. Cayley, et al. 2018) invokes a single continent-dipping subduction zone between VanDieland and Gondwana in the Cambrian, or alternatively at the New Zealand and Antarctica boundaries, synchronous to ocean-dipping subduction at Australia and Tasmania (Münker and Crawford 2000). These models invoke a genetic link between the Mount Read Volcanics and the Stavely Arc. However, while these formations are similar in age and chemistry, they have disparate Pb-isotope signatures indicating that the Stavely Arc formed on the forearc of the Gondwanan margin, whilst the Mount Read Volcanics formed within the outboard VanDieland block (Duncan and Bastrakov 2018). The Cambrian Mount Wright Volcanics at Broken Hill and the Mount Windsor Volcanics in Queensland’s Charters Towers Province are here considered as northern extensions of the Stavely Arc (Cayley, et al. 2018). Subduction of the Palaeo-Pacific plate eventually draws VanDieland into a collision with the Gondwanan margin, representing the Ross-Delamerian-Tyennan orogenies (Cayley 2011) (Figure 2a-b).

Potential correlates of the Stavely Arc are inferred south of Victoria in the Western South Tasman Rise (WSTR; Gibson, et al. 2011), in Northern Victoria Land’s Bowers Terrane (Finn, et al. 1999), and in New Zealand’s Takaka Terrane (Bradshaw 2007, Wombacher and Münker 2000), indicating a belt of forearc volcanics extending across the Gondwanan margin above continent-dipping subduction. Flanking this arc are the Cambrian-Ordovician clastic sedimentary sequences of the Stawell Zone in Australia, the Robertson Bay Terrane in Antarctica (and its alleged correlate in the WSTR), and the

Buller Terrane in New Zealand (Figure 2b). The position occupied by New Zealand during the Palaeozoic is scarcely mentioned. Presuming the aforementioned correlations with the Takaka and Buller Terranes are accurate, our model places Palaeozoic New Zealand on the Gondwanan forearc south of Northern Victoria Land, situated such that the modern west coast is on the outboard side of Gondwana (Münker and Crawford 2000).

In the Ordovician, Cayley (2011) invokes sinistral strike-slip motion on the Gondwanan boundary which carried Northern Vitoria Land and the accreted VanDieland north towards mainland Australia. Synchronous to this was the early development of the Macquarie Arc overlying the former Cambrian Arc basement in the Palaeo-Pacific. While this arc was likely initially striking parallel to the Gondwanan margin, a change in subduction polarity is invoked by Fergusson and Colquhoun (2018) with ensuing rollback and clockwise rotation of the arc, allowing for Gondwana-derived turbidite sequences to surround the Macquarie Arc. A second subduction reversal brought the Plaeo-Pacific crust back towards Gondwana, culminating in the Benambran Orogeny (Figure 2c-d; Glen, et al. 2007). Palaeomagnetic data from the Macquarie Arc may further develop this aspect of the model.

Following the Benambran Orogeny, the hypothesised orocline described and modelled by Moresi et al. (2014) begins to form. Results of testing for the presence of a Lachlan Orocline are yet to be finalised, but the concept is carried forward here as a means of creating a digital workspace into which new data, such as palaeomagnetism, can be integrated. Orocline development concludes with the Devonian Tabberabberan Orogeny, bringing much of the Lachlan Orogen into its modern configuration (Figure 3). Later work aims to implement palaeomagnetic data currently being collected to test for this orocline (Musgrave 2015). An important question raised in this portion of the models is the role and composition of the Hay-Booligal Zone, which is depicted by Moresi et al. (2014) as a southern extension of the Macquarie Arc transported west by dextral strike-slip motion.

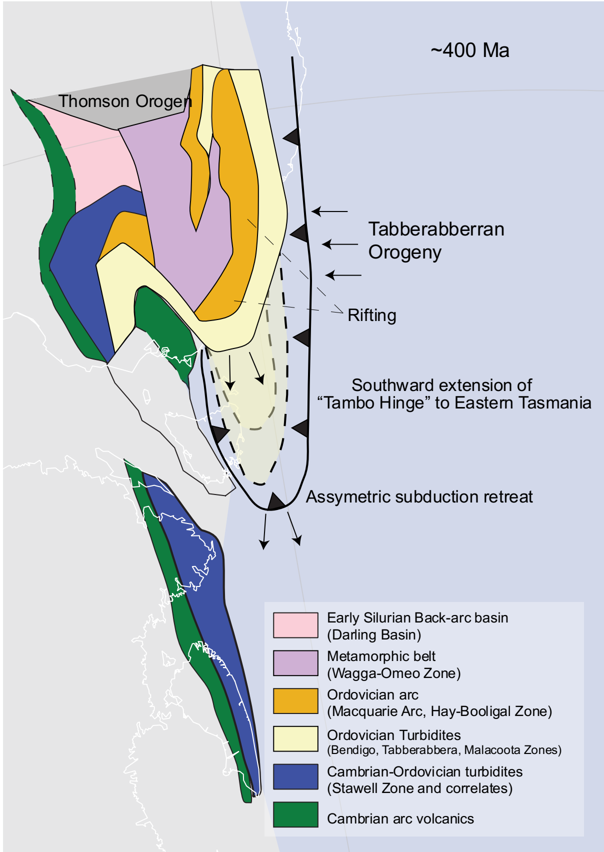

Figure 3. Oroclinal folding of the Lachlan Orogen following the Benambran Orogeny. Final configuration shown in Figure 1.

Table 1. Summarised sequence of geodynamic events and palaeogeography described in the new tectonic model for the Lachlan Orogen

Time	Palaeogeography/event	Relevant literature
Early-Mid Cambrian	Continent-dipping subduction at Gondwanan Margin	Duncan and Bastrakov (2018)
	East-dipping subduction in Palaeo-Pacific, ophiolite obduction	Cayley (2011) Münker and Crawford (2000) Mortensen, et al. (2015)
	VanDieland microcontinent on Palaeo-Pacific plate	Cayley (2011) Fergusson and Colquhoun (2018)
Late Cambrian	Ross-Delamerian-Tyennan Orogeny: accretion of VanDieland	Cayley (2011) Pilia, et al. (2015) Bradshaw (2007)
Early Ordovician	Sinistral strike-slip of Tasmania and NVL	Cayley (2011)
	Formation of Macquarie Arc over Cambrian Arc	Glen, et al. (2012) Crawford, et al. (2007)
Middle Ordovician	Subduction reversal in Palaeopacific, drawing Macquarie Arc towards Gondwana	Fergusson and Colquhoun (2018)
Early Silurian	Benambran Orogeny	Glen, et al. (2007)
Silurian	Lachlan Orocline	Moresi, et al. (2014) Musgrave (2015)
Devonian	Tabberabberan Orogeny	Fergusson (2017)

CONCLUSIONS

The many sources of literature that consider the tectonic evolution of the Lachlan Orogen have resulted in an array of contesting models. With the aid of digital plate reconstruction software, these models were systematically analysed and compared. Components of models that do not adequately reflect geological observations have been identified and rejected, and robust components integrated into a new model. This model will be continually adjusted as new data become available. Our model suggests that Cambrian accretion of the microcontinent VanDieland, lying between two opposing subduction zones in the Palaeo-Pacific outboard of Gondwana and their respective volcanic arcs, is accountable for the Ross-Delamerian-Tyennan orogenies. Development of the Macquarie Arc in the Ordovician overlaps the pre-existing Palaeo-Pacific island arc as two episodes of subduction reversal cause it to alternately rotate about its southern point before accretion in the Benambran Orogeny. Later suturing of VanDieland with mainland Australia in the Early Silurian affords the conditions for oroclinal bending of the originally north-striking terranes of the modern southern Lachlan Orogen such that it assumes its modern configuration following compression in the Tabberabberan Orogeny.

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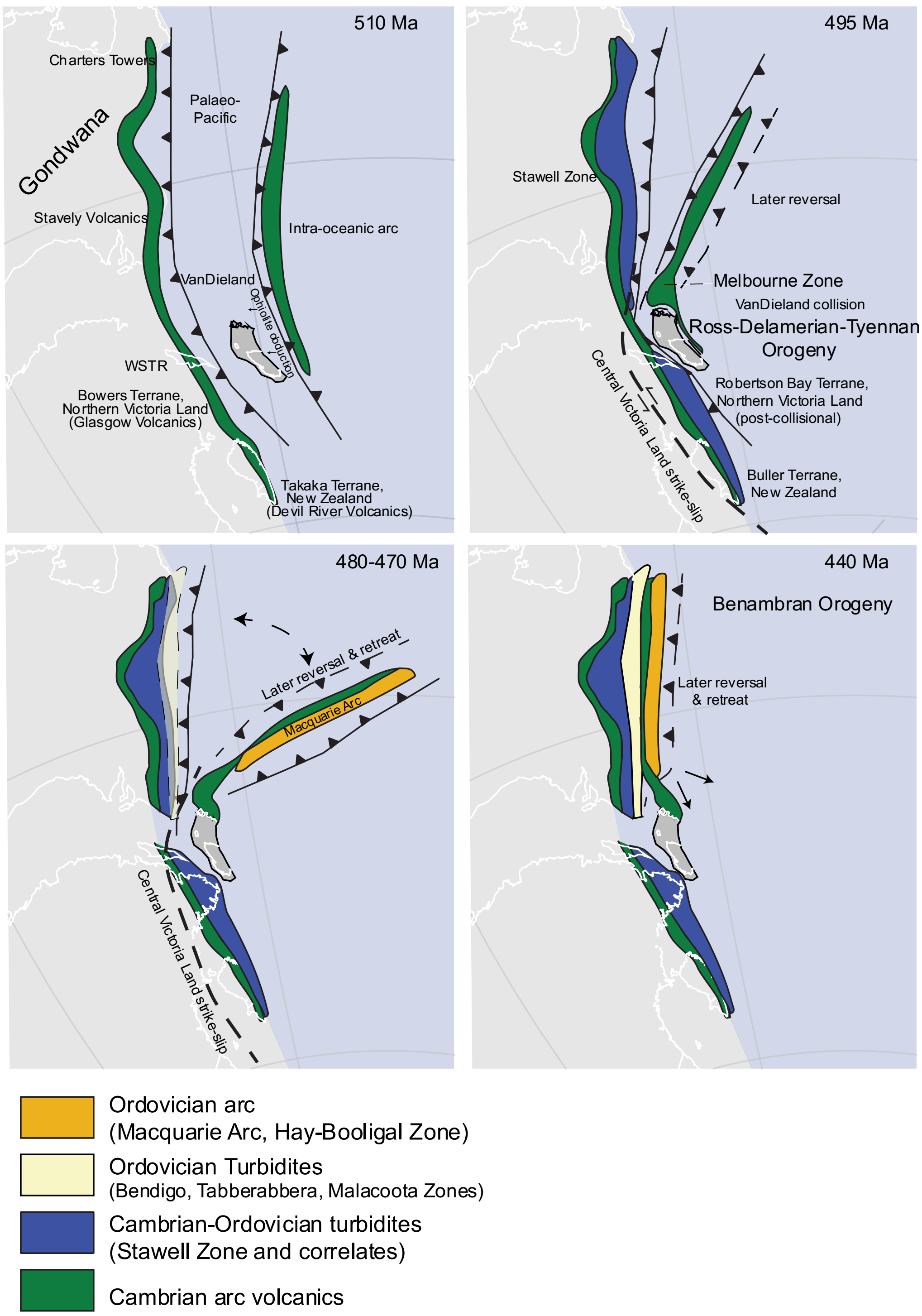

Figure 2. New tectonic model proposed for the Lachlan Orogen in the Early Palaeozoic.