# Understanding the 3D structure of the Gilmore Fault Zone through geophysical modelling: implications for Lachlan tectonic reconstructions

**Deepika Venkataramani ***
University of Newcastle
University Drive Callaghan, 2308
c3157359@uon.edu.au

**Robert Musgrave**
Geological Survey of NSW
NSW Department of Industry
516 High Street, Maitland
robert.musgrave@industry.nsw.gov.au

**David Boutelier**
University of Newcastle
University Drive Callaghan, 2308
david.boutelier@newcastle.edu.au

## SUMMARY

This study aims to clarify the tectonic evolution of the Lachlan Orogen by modelling the subsurface morphology of the Gilmore Fault Zone (GFZ). The GFZ marks a distinct geophysical contrast between (high gravity, low magnetic intensity) high-grade metamorphic rocks found in the Wagga metamorphic belt (WMB), to the west, and the (low gravity, uniformly high magnetic intensity) low-grade volcanic rocks found in the Macquarie Arc and Silurian rift basins to the east. Understanding the structure of this fault at depth should provide constraints on existing models for the tectonic evolution of the Lachlan Orogen.

Subsurface structure around the GFZ in the vicinity of Barmedman has been inverted by iterative 2.5D potential-field modelling of gravity and magnetics, constrained by pre-existing reflection seismic profiles, potential-field interpretations by previous workers, and physical properties data collected on representative lithologies.

Preliminary findings show that the surface structure mapped as the Gilmore Fault is an east-dipping, shallow thrust fault, and doesn't correspond to the major crustal 'suture' envisaged in regional tectonic studies. It is a secondary antithetic structure off the main west-dipping, crustal penetrating fault that separates the Macquarie arc and the WMB. Another, steeper west-dipping fault cuts these structures and separates the WMB from the Silurian Tumut Trough. This larger structure defines the regionally extensive tectonic feature of the GFZ. The trace of the mappable Gilmore Fault (as opposed to the GFZ) is curved, and terminates abruptly to the north, indicating the Gilmore Fault is the base of a series of thrust flakes imposed on the pre-existing main fault in the GFZ.

West-dipping crustal-penetrating thrust faults east of the GFZ are indicative of successive collision, accretion and extension events. Thus far the modelled structure of the GFZ is not consistent with the terrane accretion model but is consistent with the accretionary orogen and orocline model.

**Key words:** Gilmore Fault Zone, Gilmore fault, potential field modelling, Lachlan orocline

## INTRODUCTION

This study aims to elucidate some key aspects of the tectonic evolution of the Lachlan Orogen within the Tasmanides of Eastern Australia. The Tasmanides are a series of Neoproterozoic to Palaeozoic accretionary orogenic belts that form the eastern third of Australia, and which once marked the Paleo-pacific edge of the greater Terra Australis Orogen (Cawood, 2005), along the Gondwanan margin. There are three major orogens in the southern Tasmanides: the Delamerian, the Lachlan (LO) and the New England orogen (NEO).

The LO constitutes a majority of the landmass of New South Wales, Victoria and Tasmania and is positioned between the older early Cambrian to early Ordovician Delamerian orogen in the west and the Silurian to Carboniferous NEO to the east. It is further subdivided into three "provinces": Western, Central and Eastern. The Gilmore Fault Zone (GFZ) is a prominent feature that forms the boundary between the Central and Eastern provinces.

The GFZ extends for many hundreds of kilometres through NSW and VIC. It marks a very distinct lithological contrast between high-grade metamorphic rocks found in the Wagga Metamorphic Belt (WMB) and the low-grade volcanic rocks of the Macquarie arc and underthrusting Silurian rift basins to the east (Scheibner,1985; Wormald &Price,1990). Understanding the structure of this fault at depth should provide severe constraints on the models for the tectonic evolution of the LO.

The approach we have taken is inversion by iterative 2.5D forward potential-field modelling of gravity and magnetics, constrained by pre-existing reflection seismic profiles, and by physical properties data collected on local lithologies in outcrop and drill core. This approach has allowed us to image the deep crustal structure of the GFZ and so draw inferences for the kinematic history of the fault zone, and the relationship between the central and eastern LO. In turn, this has allowed us to test the validity of the three major models for the tectonic history of the LO.

**BACKGROUND GEOLOGY:**

The oldest widespread rocks in the Lachlan orogen are near-ubiquitous turbidite-dominated Cambro-Ordovician sediments and the Ordovician to Late Silurian Macquarie Arc (Scheibner, 1978, 1985; Coney et al., 1990). Sedimentary and igneous rocks, and the locus of orogenesis, generally young from west to east. The WMB dominates the central zone and the eastern zone is characterised by a series of Silurian-to Devonian rift basins (e.g., the Tumut Trough, which is adjacent to the GFZ) and granite batholiths developed on a Cambro-Ordovician basement. The GFZ separates the high-grade metamorphics and S-type granitoids of the WMB from the Ordovician to Devonian turbidites, volcanics and intrusive I and A type granites of the Silurian troughs in the eastern zone (Wormald & Price, 1990).

The Lachlan Orogen contains evidence of at least three contractional deformation events: the Benambran (Ordovician, about 440 Ma), Tabberabberan (mid Devonian) and Kanimblan (early Carboniferous) separated by longer-term extensional episodes (Collins, 2002), with an additional, Bindian Orogeny (late Silurian to early Devonian) considered to be regionally significant by some authors. The Benambran Orogeny (about 440 Ma) terminated subduction on the Macquarie Arc (Glen, 2005).

Morand & Gray(1991) suggest that the GFZ formed during the Bindian orogeny in response to NNE-SSW compression event in which Ordovician volcanics that form the Macquarie arc were thrust under the WMB. It is also suggested that south-east directed slab rollback during the Bindian initiated oroclinal folding of the Macquarie arc system (Cayley & Musgrave,2016).

During the Tabberabberan orogeny crustal extension in a wide backarc region formed from earlier rollback of the proto-Pacific plate led to the re-establishment of a new west dipping subduction complex and intra-oceanic arc now preserved in the New England fold belt. The Tabberabberan also saw the formation of multiple sedimentary rifts, transtensional basins and the emplacement of I and S-type granites from dismemberment of the Macquarie arc. Only the basins near the GFZ preserve contractional deformation.

**BACKGROUND GEOPHYSICS:**

The disparity between the high- moderate magnetic intensity signature of the Tumut trough and the consistently low magnetic intensity and relief of the WMB clearly define the GFZ over its length in the 1:250 000 Cootamundra map sheet (Warren et al,1995; Stuart-Smith,1991; Suppel et al, 1986; Wyatt et al, 1980). A fault-flake (around the latitude of Barmedman) west of the GFZ also has this high magnetic intensity. The GFZ is marked by a high gravity anomaly on its west side. The steepest gravity gradient appears just east of the GFZ. The source of this anomaly thus appears to dip west presumably corresponding to Macquarie arc rocks.

## WHAT IS THE POSSIBLE SUBSURFACE CHARACTER OF THE GFZ FOR EACH OF THE PREVAILING TECTONIC MODELS?

1.    The Lachlan formed by suspect terrane accretion

The GFZ is considered by Scheibner (1985) to be a terrane boundary between a Victorian microcontinent that collided with and overthrust a volcanic island arc (Aitchison & Buckman, 2012). Episodic terrane accretion and dispersion coupled with subduction zone tectonics were responsible for many of the extensional features observed such as volcanic arcs, rifts and basins as well as the resulting position of the Tasmanides. If the GFZ is a terrane boundary it should juxtapose crustal segments of fundamentally different geological and geophysical character-contrasting density and magnetic susceptibility of the mid-lower crust on either side of the GFZ should indicate this boundary furthermore if the GFZ is a convergent suture it should be indicated by a crustal-penetrating thrust fault.

2.    The Lachlan formed as an extensional accretionary orogen

It is also suggested that the Lachlan was an extensional accretionary orogen that evolved from growth and destruction of volcanic arc and back arc systems by slab rollback coupled with rapid orogenic growth cycles from the mid Cambrian to the Silurian (Collins,2002a,b).
This alternating pattern of long-term slab retreat and short-term subduction advance has been linked with the formation of HTLP zones and S-type granites with a tripartite association (Collins & Richards, 2008). The WMB and the tripartite association is considered indicative of tectonic switching. In this model the generation of the S-type granites is part of Silurian (435-430Ma) extension, during which time rift basins such as the Tumut trough should have formed. The southern extent of the GFZ is the western flank of the Tumut trough. If it is an extensional fault, the eastern side of the GFZ should create a deep Silurian sedimentary pile(part of the Tumut trough) but if there is evidence of earlier compression pre-dating the Silurian extension then the fault should have a dipping thrust geometry. However the fault may have been reactivated at a later stage.

3.    The Lachlan achieved its current form by oroclinal bending

The idea of tectonic escape from subduction rollback through curvature of orogens (Moresi et al.2014) and the subsequent idea of oroclines (Cayley,2012;Musgrave,2015;Cayley & Musgrave,2016) provides a much more simple view of Tasmanide evolution and accounts for  many of the aeromagnetic and petrographic trends visible. The model suggests that the Macquarie arc was the only arc and associated subduction zone active during LO formation during the Ordovician. The terminal 'Lachlan orocline' forms a giant z-shaped megafold brought about by clockwise oroclinal folding and Southeast directed slab rollback during the Bindian (400Ma) orogeny. According to the orocline model the WMB is in the south-moving core of the orocline. If so, deformation in the WMB should be extensional or transtensional and the high-grade metamorphism should be synchronous with development of the GFZ.

Therefore the GFZ should also have a major component of syn-kinematic high grade metamorphic rocks on its western margin. Increased metamorphic grade should be reflected in increased density, and should therefore be revealed during gravity modelling. Transtensional motion should also be recorded in steeply dipping, crustal penetrating faults.

**METHODS**

The models proposed by Direen et al.(2001) and Glen et al.(2002) are used as a reference model to which all further models are compared.

The geology and crust surrounding the GFZ are modelled using forward potential field modelling. Parametric inversions (using simple geometric shapes) are used instead of voxel inversions (Pratt et al., 2006) to create a 3D model based on 2.5D cross section slices. The ModelVision software is used for this purpose.  Cross sections are modelled across three separate areas of interest along the fault zone. Direct inversion methods are not used as the GFZ is a geologically complex area.

Data from the seismic reflection surveys conducted by the Australian Geodynamics Cooperative Research Centre (AGCRC) and the NSW Department of Mineral Resources in 1999(lines 99AGS-L1, 99AGS-L2, 99AGS-L3) are used in the deep crustal interpretation. The models proposed by Direen et al.(2001) and Glen et al.(2002) are modelled directly from these lines however our models are based on longer cross section profiles that are slightly offset from the original position in order to best target observed anomalies. No depth-time conversions were done on seismic data.

Total magnetic intensity and gravity are the potential fields being modelled. Preliminary modelling is based on joint inversion of gravity and magnetics extracted from gridded base maps (Table 1). In an attempt to validate the base maps, gravity and magnetic data were collected during field excursions and are being processed using Oasis Montaj software.

Magnetic susceptibility, saturated density and Konigsberger ratios (1938) were the physical properties collected and analysed in the lab (Table 2). As outcrop was limited, samples were taken from drill core of representative lithologies. Drill samples were cut into cylindrical pieces sized to fit the Spinner magnetometer. Magnetic susceptibility of samples was obtained before saturated density was calculated using the Archimedes principle. Lastly, samples were analysed in the Molspin minispin spinner magnetometer for NRM. Konigsberger ratios were then calculated.  These additional parameters allowed the refinement of both the long and short wavelength features in the model.

| GRIDDED DATA | SPECIFICATIONS | MODELLING PARAMETERS USED | PROJECT PARAMETERS |
|---|---|---|---|
| Magnetics | 50m interval, 250m line spacing, 200m flight height TMI_RTP | regional field:54028 SI | Datum:GDA94 Projection type: UTM Zone: MGA55 IGRF- Total intensity:57656 SI, Inclination:-64.9, Declination:11.3 |
| Gravity | 500m spacing, Bouguer corrected | regional field: - 300 gu | |
| Seismics | 6000m.s$^{-1}$ assumed ave crustal velocity | not depth/time converted | |

**Table 1: Table shows parameters used in our model as well as information pertaining to the previously existing gridded data.**

| COLLECTED SAMPLES/DATA | TECHNIQUE | INSTRUMENT | SPECIFICATION |
|---|---|---|---|
| Physical properties data | Vacuum saturation | vacuum pump desiccator | |
| | Saturated density | using Archimedes principle | |
| | NRM | Molspin minispin spinner magnetometer | calibration standard used: 694 MA.m$^{-1}$ |
| | Magnetic susceptibility | Bartington(MS2) Magnetic susceptibility meter | MS2b(well-type)sensor run at 1.0 x 10$^{-5}$ sensitivity level using LF setting(460Hz) |
| potential fields data | Magnetics | rover magnetometer | 25m spacing |
| | Gravity | Scintrex CG-5 Autograv gravimeter | 100m spacing |
| | Differential GPS | Leica GNSS | 20cm sensor height |

**Table 2: Table shows the Laboratory techniques and instruments used to extract physical properties obtained from collected samples. Table also shows instruments and parameters used in potential field data collection.**

## RESULTS

We produced a 2.5D model using the same magnetic, gravity and seismic data (line 99AGS-L3) as modelled by Direen et al.(2001) and Glen et al.(2002). Attempts were made to validate the model but we found that modelling the same geometries would not yield an ideal fit to the observed magnetics. There are some major differences particularly in the number of separately modelled bodies and in the resolution of the observed signals (Figure 1). There is also a strong mismatch between the gradients of the peaks at the flanks of modelled bodies and the naturally observed magnetics and gravity.
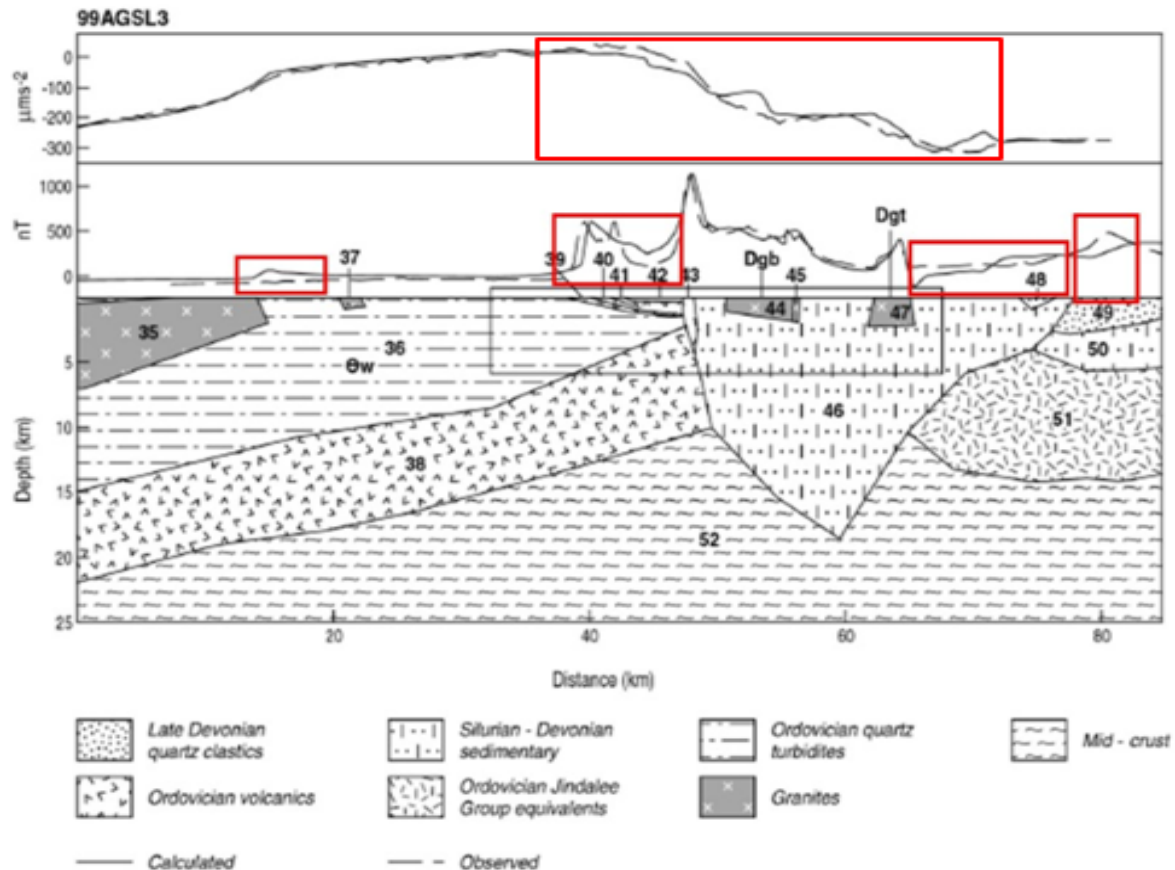


**Figure 1: Reference model based on seismic line (99AGSL3). Note the red squares that highlight the disparity between modelled and observed magnetics. Adapted from Direen et al. (2001).**

The initial model shows the Gilmore as a shallow east-dipping feature. Most literature places the Gilmore as a west-dipping fault. We conducted a sensitivity test to ratify this hypothesis and we agree with the east dipping fault as modelled by Direen et al.(2001) however our model (Figure 2) suggests a far steeper dip and lacks the 'flower symmetry' found in the previous model.

Unlike previous models, remanence was taken into account. From the analysed samples we can deduce that Q >0, implying that the resultant magnetisation of the sources of anomalies is close to being purely induction, and hence parallel to the present field thus remanence is not a major factor in the measured magnetics.

Multiple deep west-dipping faults are seen in our model. A distinction needs to be made between the GFZ and the Gilmore fault(GF). The GF is a mappable shallow structure that corresponds to the east-dipping fault around the latitude of Barmedman. This represents the boundary between the WMB and the Silurian Tumut trough (east). The GF appears to be an antithetic fault off a deep west-dipping fault interpreted to be the Benambran boundary between the WMB and the underthrusting Macquarie arc. These structures are cut by a steeper west dipping fault interpreted to be the GFZ. This previously absent distinction appears to be the source of confusion surrounding the dip direction of the GF and GFZ (Glen et al., 2002).
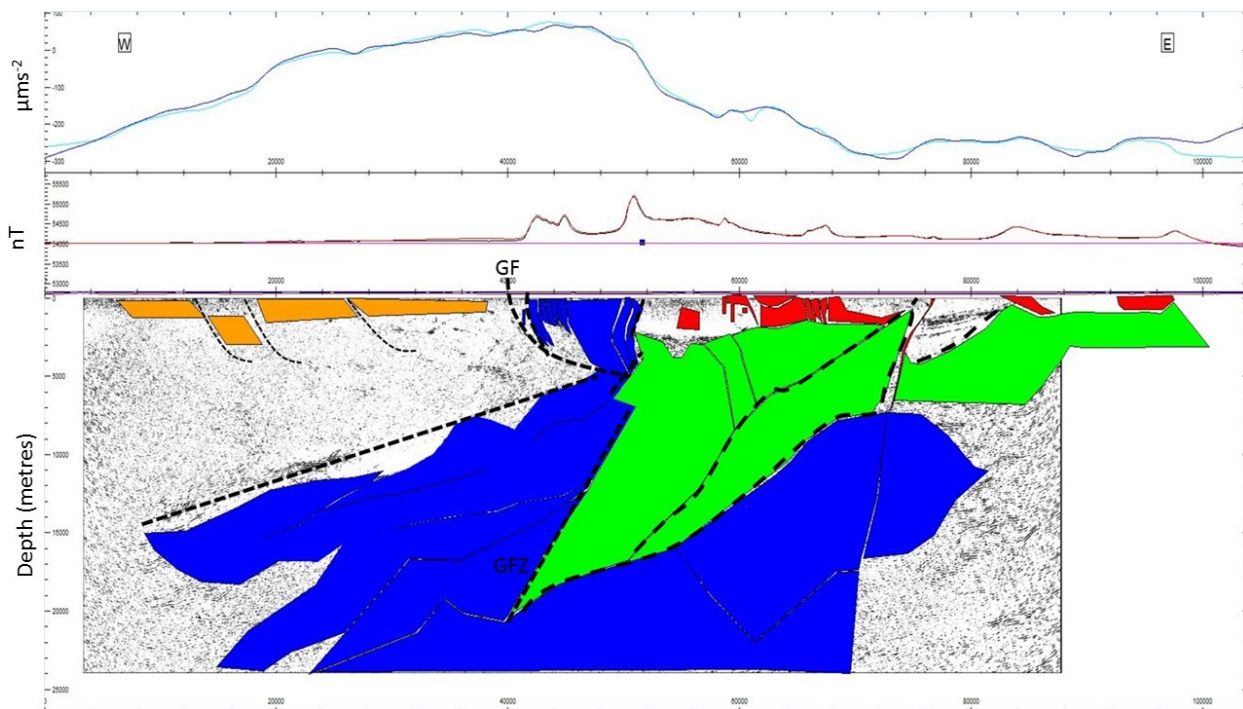
**Figure 2: Model produced by the authors of the study. Gravity modelling units are μms$^{-2}$, magnetic modelling units are nT and depth is in metres. Note the closeness of fit between observed (blue, red lines) and calculated (navy, black lines) potential fields. Seismic line AGS-L3 is placed in the background. Black dashed lines represent faults.**
**The modelled bodies are distinguished by colour:**

- **The (green) west dipping bodies show very poorly in the seismics and had a uniformly low gravity signature. This rock package is assumed to represent the Silurian Tumut trough.**
- **The Macquarie Arc (blue) bodies were distinctly visible in the seismics. The deeper Ordovician volcanics were not resolvable in the magnetics but had strongly expressed density.**
- **The Wagga metamorphic belt (orange) was magnetically and seismically quiet but like the underlying Macquarie arc, had a strong gravity signature.**
- **The Silurian-Devonian aged intrusions (red) are modelled using gravity and magnetics alone as the seismics were a very poor constraint on geometry.**

## CONCLUSIONS

A distinction needs to be made between the GF and the GFZ.  The GF is a mappable, shallow east-dipping antithetic fault off a deeper fault that represents the Benambran boundary between the WMB and the Macquarie arc. The main GFZ, which is a west-dipping crustal penetrating fault, is a Silurian Bindian structure that intersects these faults and effectively separates the WMB from the Tumut trough (adjacent Silurian rift basin). This fault is truncated by younger west dipping faults possibly associated with basin inversion and fault reactivation.

According to the model published by Direen et al. (2001) and Glen et al.(2002), the GF is east dipping and what appears to correspond to the GFZ is also east dipping. Although this model is a good first-pass model we believe that we have produced a different model that better fits the observed magnetic and gravity signals.

Preliminary findings show that the structure mapped at the surface as the Gilmore Fault is an east-dipping, shallow thrust fault, and doesn't correspond to the major crustal 'suture' envisaged in regional tectonic studies. West-dipping crustal-penetrating thrust faults east of the GFZ are indicative of successive collision, accretion and extension events. Thus far the modelled structure of the GFZ is not consistent with the terrane accretion model but is consistent with the accretionary orogen and orocline model.

We believe that at least one of these two tectonic models most closely represents the construction of the Lachlan orogen, but further modelling along-strike is required to determine their true geodynamic significance.

## ACKNOWLEDGMENTS

## REFERENCES

Aitchison, J.C. & Buckman, S., 2012. Accordion vs. quantum tectonics: Insights into continental growth processes from the Paleozoic of eastern Gondwana. *Gondwana Research*, 22(2), pp.674–680. Available at: http://linkinghub.elsevier.com/retrieve/pii/S1342937X1200192X [Accessed August 7, 2014].

Cawood, P.A., 2005. Terra Australis Orogen: Rodinia breakup and development of the Pacific and Iapetus margins of Gondwana during the Neoproterozoic and Paleozoic. Earth-Science Reviews 69, 249-279,doi:10.1016/j.earscirev.2004.09.001.

Cayley, R.A., 2012.Oroclinal folding in the Lachlan Fold Belt: consequence of Southeast-directed Siluro-Devonian subduction rollback superimposed on an accreted Ordovician arc assemblage in Eastern Australia, 2012.Abstract, Selwyn Symposium, GSA Victoria division Geological society of Australia

Cayley, R.A., Musgrave,R.J.,2016.The giant Lachlan orocline-a new geodynamic model for the Ordovician-Devonian evolution of Australia.,*Earth science Reviews*, in review

Collins, W.J., 2002a. Nature of extensional accretionary orogens. *Tectonics*, 21(4).

Collins, W.J., 2002b. Hot orogens, tectonic switching, and creation of continental crust. *Geology*, 30(6), p.535. Available at: http://geology.geoscienceworld.org/content/30/6/535.full [Accessed July 2, 2015].

Collins, W.J. & Richards, S.W., 2008. Geodynamic significance of S-type granites in circum-Pacific orogens. *Geology*, 36(7), pp.559–562.

Coney,P.J.,Edwards,A., Hine,R.,Morrison,F.,Windram,D.,1990.The regional tectonics of the Tasman orogenic system,eastern Australia.Journal of structural geology 12,519-543

Direen, N.G., Lyons, P., Korsch, R.J., and Glen, R.A., 2001. Integrated geophysical appraisal of the crustal architecture in the eastern Lachlan orogen, Exploration Geophysics, 32(3), p.252-262.

Glen, R.A., Korsch, R.J., Direen, N.G., Jones, L.E.A., Johnstone, D.W., Lawrie, K.C., Finlayson, D.M., and Shaw, R.R., 2002. Crustal structure of the Ordovician Macquarie arc, Eastern Lachlan Orogen, based on seismic reflection profiling,Australian Journal of Earth sciences, 49(778810998), 323-348.

Glen, R.A., 2005. The Tasmanides of eastern Australia. In: Vaughan, A.P.M., Leat, PT., Pankhurst, R.J. (Eds.), Terrane Processes at the margins of Gondwana: Geological Society, London, Special Publications, 246,pp. 23-96

Konigsberger,J.G.,1938,Natural residual magnetism of eruptive rocks, Terr. Mag. Atmos. Elec., vol43, pp.119-130,299-320.

Morand,V.J.& Gray,D.R.1991.Major fault zones related to the Omeo Metamorphic Complex, Northeastern Victoria. *Australian Journal of Earth sciences*,**38**, 203-221

Moresi,L.,Betts,P.G.,Miller,M.S.,Cayley,R.A.,2014.Dynamics of continental accretion. Nature, 508, 248

Musgrave, R.J., 2015, Oroclines in the Tasmanides. Journal of Structural Geology, 80, 72-98.

Pratt, D.A., Foss, C.A. & Roberts, S., 2006. User Guided Inversion & Visualisation of Interpretation Confidence.

Scheibner,E.,1978.Tasman fold belt system or orogenic system. Tectonophysics 48,153-157

Scheibner, E., 1985. Suspect terranes in the Tasman Fold Belt System, eastern Australia. In Tectonostratigraphic terranes in the Circum-Pacific region. Circum-Pacific Council for Energy and Mineral Resources - Earth Science Series I, 493-514.

Stuart-smith, P.G., 1991- Gilmore fault zone eastern Australia in tectonostratigraphic terranes in the circum-pacific region. Circum-pacific council for energy and mineral resources- Earth science series

Suppel,D.W.,Warren,A.Y.E.,Watkins,J.J.,Chapman,J.,Tenison Woods,K.& Barron,L.,1986.A reconnaissance study of the geology and gold deposits of the west Wyalong-Temora-Adelong District. New South Wales Geological Survey, Quaterly Notes,64,1-23

Warren A.Y.E., Gilligan L.B. and Raphael N.M. 1995. Geology of the Cootamundra 1:250 000 map Sheet. viii + 160 pp. Geological Survey of New South Wales, Sydney

Wormald,R.J.,& Price,R.C.,1990 The gabbro-qtz monzodiorite-alkai granite association in southern New South Wales: implications for intrusive related gold mineralisation. Geological society of Australia, Abstracts 25,265.

Wyatt,B.W.,Yeates,A.N.,&Tucker,D.H.,1980.Aregional review of the geological sources of magnetic and gravity fields in the Lachlan Fold belt of NSW.BMR Journal of Australian Geology and Geophysics,5,289-300.