Structure and kinematics of the Louth-Eumarra Shear Zone (north-central New South Wales, Australia) and implications for the Paleozoic plate tectonic evolution of eastern Australia

S. Dunstan, G. Rosenbaum and A. Babaahmadi

School of Earth Sciences, The University of Queensland, Brisbane 4072, Australia

ABSTRACT

The ∼E–W-trending Olepoloko Fault and ∼ENE-trending Louth-Eumarra Shear Zone in north-central New South Wales are approximately orthogonal to the dominant ∼N–S-trending structural grain of Paleozoic eastern Australia. These structures have been interpreted to represent the boundary between the Thomson and Lachlan orogens, but their exact geometry and kinematics remain unclear owing to the scarcity of surface exposure. Using gridded aeromagnetic data and limited field mapping, we obtained new data on the tectonic history of the Louth-Eumarra Shear Zone, which seems to represent a broad zone of dextral shearing with a component of crustal thickening indicated by the recognition of kyanite growth in a mica-schist. The timing of deformation is relatively poorly constrained, but at least a component of the dextral shearing appears to be coeval or younger than the age of displaced late Silurian and Early Devonian granitoids. Additional indicators for dextral kinematics farther north, along the ∼ENE-trending Culgoa Fault, suggest that the width of the zone that was subjected to dextral deformation is possibly >100 km. This raises the possibility that a large component of dextral displacement was accommodated in this region. In a broader geodynamic context, we discuss the possibility that the precursor of the Louth-Eumarra Shear Zone and Olepoloko Fault originated from segmentation between the northern and southern Tasmanides, perhaps during the Cambrian. The existence of such a discontinuity may have buttressed the process of oroclinal bending in the Silurian. The observed dextral kinematics has possibly resulted from reactivated deformation during the Tabberabberan and Alice Springs orogenies.

KEYWORDS

Louth-Eumarra Shear Zone; Olepoloko Fault; Lachlan Orogen; southern Thomson Orogen; dextral kinematics; Girilambone Group

Introduction

The Tasmanides of eastern Australia are a series of orogenic belts that have developed along the Australian margin from the Cambrian to the Triassic (Figure 1) (Glen, 2005, 2013). The dominant structural trend in the Tasmanides is ∼N–S (Figure 1b), and therefore, it has commonly been assumed that orogenesis was controlled by a N–S-oriented (in present coordinates) proto-Pacific subduction zone (Collins, 2002; Foster & Gray, 2000; Glen, 2005; Wellman, 1995). However, some major structures are discordant, such as the ∼E–W-trending Olepoloko Fault and Louth-Eumarra Shear Zone (Glen, Clare, & Spencer, 1996; Stevens, 1991), as well as the interpreted oroclinical structures in the Lachlan (Cayley & Musgrave, 2013; Musgrave, 2015) and New England orogens (Rosenbaum, 2012) (Figure 1). The presence of oroclines and ∼E–W-trending orogenic-scale structures cannot easily be explained by a N–S-oriented subduction model and likely requires more complex geodynamic interactions (e.g. Moresi, Betts, Miller, & Cayley, 2014). Understanding the origin, nature and kinematics of the ∼E–W-trending Olepoloko Fault and Louth-Eumarra Shear Zone may provide key information on such geodynamic processes.

This paper deals with an ∼ENE-trending structure in northern New South Wales, the Louth-Eumarra Shear Zone, which has been interpreted by some authors (e.g. Glen et al., 1996, 2013) as the boundary between the Thomson and Lachlan orogens (Figure 1a). Whether this structure represents the boundary between the Thomson and Lachlan orogens has been a matter of debate (Burton, 2010; Burton & Trigg, 2014; Glen et al., 2014), partly because of the poor exposure and scarcity of geological data north of the Olepoloko Fault and Louth-Eumarra Shear Zone, but mainly because the actual definition of the orogens is somewhat vague. The distinction between ‘Thomson’ and ‘Lachlan’ was made based on structural discordance recognised in gravity and aeromagnetic surveys (Figure 1) (Glen, 2005; Wellman, 1976, 1995), with the Thomson Orogen largely consisting of Neoproterozoic to Ordovician metasedimentary basin rocks (Brown, Purdy, Carr, Cross, & Kositcin, 2014; Carr et al., 2014; Draper, 2006; Murray, 1994; Murray & Kirkegaard, 1978) that are covered by non-metamorphosed Devonian to Early Cretaceous sedimentary...
basins (Finlayson, Collins, & Lock, 1984, 1988; Moss & Wake-Dyster, 1983; Murray & Kirkegaard, 1978). The orogenic history for the two orogens is not unique, with both recording evidence for Late Ordovician to Silurian (ca 455–424 Ma) deformation (Benambran Orogeny) (Cas, 1983; Gray & Foster, 1997; Thalhammer, Stevens, Gibson, & Grum, 1998). In this paper, therefore, we do not attempt to resolve the question whether the Thomson–Lachlan boundary is represented by the Louth-Eumarra Shear Zone, but rather, we focus on the possible implications of this ~E–W-trending structure in the context of the Paleozoic plate tectonic history of eastern Australia.

The aim of this paper is to provide constraints on the kinematics of the Louth-Eumarra Shear Zone. We present observations from deformed rocks in the Louth-Eumarra Shear Zone, complemented by geophysical data that inform us on the structure and kinematics of the shear zone. Results were obtained through field mapping, remote sensing of gridded aeromagnetic data, and microstructural analysis of rock samples collected from selected field sites and drill cores. Ultimately, the results provide new insights into the development of crustal scale ~E–W-trending structures separating the northern and southern Tasmanides.

Figure 1. (a) Subdivision of orogenic belts in eastern Australia showing the Tasman Line as the western margin of the Tasmanides (after Glen, 2005). LESZ, Louth-Eumarra Shear Zone; OF, Olepoloko Fault. Modified after Glen (2005), Glen et al. (2013). (b) Total Magnetic Intensity map of the Tasmanides with black box showing the location of Figure 3 (Milligan, Franklin, Minty, Richardson, & Percival, 2010).

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Geological setting

The Thomson Orogen is the largest and least understood component of the Tasmanides of eastern Australia, constituting the largest portion of subsurface basement of western and central Queensland (Figure 1a). However, surface exposure of the Thomson Orogen is extremely limited owing to widespread cover by sedimentary basin rocks (Glen, 2005; Johnson & Henderson, 1991; Kirkegaard, 1974; Murray & Kirkegaard, 1978). Phyllitic, schistose and quartzose rocks intersected in drill cores were interpreted to represent basement rocks of the Thomson Orogen and were suggested to have deposited largely in deep water environments during the Neoproterozoic and early Cambrian (Brown et al., 2014; Carr et al., 2014; Draper, 2006; Murray, 1994; Murray & Kirkegaard, 1978; Withnall, 1995). The Thomson Orogen comprises regional NE- and NW-oriented structural grain, associated with long-wavelength and low-amplitude geophysical anomalies, and deformation intensity that appear to increase towards the east (Spampinato, Betts, Ailleres, & Armit, 2015a; Spampinato, Ailleres, Betts, & Armit, 2015b). The basement crust of the Thomson Orogen was suggested to contain a non-magnetic upper crust and a magnetic lower crust, which is interpreted to reflect non-magnetic metasedimentary rocks in the upper crust and more mafic magnetic rocks in the lower crust (Spampinato, et al., 2015b).

The largest and most coherent exposure of the Thomson Orogen is the Anakie Inlier in east-central Queensland (Figure 1a), which comprises marine metasedimentary rocks that record contractional deformation and metamorphism to greenschist–amphibolite facies during the late Neoproterozoic and early Cambrian (Fergusson, Carr, Fanning, & Green, 2001; Withnall, 1995; Withnall, Golding, Rees, & Dobos, 1996). These rocks exhibit similarities to basement rocks of the Thomson Orogen penetrated in drill cores (Murray, 1994). However, the Anakie Inlier is located within a relatively high magnetic domain, which is different from the dominantly low magnetic zone that characterises the Thomson Orogen and the Louth-Eumarra Shear Zone (Burton, 2010). Evidence for younger contractional deformation, recognised both in the Anakie Inlier (Fergusson, Henderson, Lewthwaite, Phillips, & Withnall, 2005b) and in the southern Thomson Orogen, was interpreted to be associated with the Late Ordovician to Silurian Benambran Orogeny (ca 455–424 Ma) (Greenfield, Gilmore, & Mills, 2010; Thalhammer et al., 1998).

South of the Thomson Orogen, the Lachlan Orogen consists of three distinct tectono-stratigraphic units (Cas, 1983; Coney, Edwards, Hine, Morrison, & Windrim, 1990). These units, from bottom to top, include (1) lower–mid-Cambrian greenstone belts; (2) thick quartz-rich Ordovician–Silurian turbidite packages; and (3) widespread Silurian–Upper Devonian sedimentary, igneous and volcanic rocks (Cas, 1983; Coney et al., 1990; Foster & Gray, 2000; Vandenberg & Stewart, 1992). The Macquarie Arc occurs in the east-central Lachlan Orogen, and comprises a ~N–S-trending belt of mafic to intermediate volcanic rocks, volcanioclastic rocks, and interbedded limestone and chert (Fergusson, 2009; Glen et al., 2002). In addition to the Benambran deformation that is recorded in both the Lachlan and Thomson orogens, rocks in the Lachlan Orogen were also subjected to deformation during the Tabberabberan Orogeny (ca 390–380 Ma) and the Kanimbla Orogeny (ca 360–340 Ma) (Cas, 1983; Coney et al., 1990; Glen, 1992; Veever & Morgan, 2000). In the Thomson Orogen, in contrast, there is no clear evidence for Tabberabberan and Kanimbla deformation (Purdy, Carr, & Brown, 2013).

Owing to the paucity of outcrop, the boundary between the Thomson and Lachlan orogens has mainly been interpreted through analysis of potential field geophysical datasets (aeromagnetic and Bouguer gravity) (Glen et al., 2013; Kirkegaard, 1974; Scheibner & Basden, 1996; Wellman, 1990, 1995). The exact position of the boundary is contentious, but was originally suggested to occur where curvilinear NWN- and NE-trending aeromagnetic and gravity anomalies truncate N- and NW-trending lineaments of the Lachlan Orogen (Figure 1b) (Burton, 2010; Glen, 2005, 2013; Murray & Kirkegaard, 1978; Wellman, 1995). Some authors have argued that the actual boundary is represented by the north-dipping Opoloko Fault (Glen, 2005; Glen et al., 2013; Stevens, 1991) and the northern segment of the Louth-Eumarra Shear Zone (Figure 1a) (Glen et al., 1996). In contrast, Burton (2010) suggested that these structures in northern New South Wales reside entirely within the Lachlan Orogen, which, according to this author, continues at least ~500 km north into Queensland.

The Louth-Eumarra Shear Zone is located in the northern Lachlan Orogen (Glen et al., 1996). Rocks in the vicinity of the Louth-Eumarra Shear Zone are typically I-type granitoids of the Tarcoon Plutonic Complex (417.3 ± 2.0 Ma, Bobelah; 417.3 ± 2.6 Ma, Sainsbury Park; and 416.4 ± 2.5 Ma, Compton Downs granitoids), with an S-type granite (420.9 ± 2.3 Ma, Brewarrina Granite) found north of the Louth-Eumarra Shear Zone (Figure 3) (Black, 2006; Blevin, 2011; Fraser et al., 2014; Hegarty, 2011).

The Girilambone Group consists of interbedded sandstone, siltstone and claystone, as well as some chert horizons and a minor occurrence of mafic volcanic rocks (MacRae, 1987; Russell & Lewis, 1965; Fergusson et al., 2005a; Burton et al., 2012).
Metamorphic grade ranges from subgreenschist facies to localised amphibolite facies (Burton, 2010; Burton et al., 2012). Owing to its monotonous nature, the subdivision of the Girilambone Group into the Narrama, Lang and Ballast formations (Figures 2, 3) was mainly based on lithological considerations (chert and sandstone content) and micropaleontological evidence (Burton et al., 2012; Percival, 2006, 2007). The Narrama Formation contains rare thick packages of medium-grained metasandstone/C0 quartzite termed the Budgery Sandstone Member (Figure 2) (Rayner, 1969). Detrital zircon ages (496 ± 2.5 Ma) (Fergusson et al., 2005a; Fraser et al., 2014) and the identification of conodonts (Percival, 2006, 2007) constrain the maximum depositional age of the Girilambone Group to the Lower Ordovician.

Potential correlatives of the Girilambone Group exist north of the Louth-Eumarra Shear Zone (Byrnes et al., 1993; Glen et al., 2013). In particular, the Booda Formation (Figure 2), previously mapped as the Girilambone Group (Burton, Dadd, & Vickery, 2008; Byrnes, 1993), has a reported late Cambrian (495 ± 9 Ma) maximum depositional age (Fraser et al., 2014), consistent with the age of the Girilambone Group. The Booda Formation comprises interbeds of metasiltstone and fine- to medium-grained metasandstone with a potential turbiditic origin, and is unconformably overlain by medium- to coarse-grained fluvial sedimentary rocks (Moira and Mount Oxley formations) that are interpreted to belong to the Lower–Middle Devonian Mulga Downs Group (Figures 2, 3) (Byrnes et al., 1993; Glen, 1979; Hegarty, 2011).

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**Figure 2.** Time–space plot of rocks in the Louth-Eumarra Shear Zone and the southern Thomson Orogen in northern New South Wales. (1) Byrock Granite (414.7 ± 2.4 Ma; Black, 2006); (2) Tarcoola Suite Granitoids: Bobelah 417.1 ± 2.0 Ma; Sanisbury Park, 417.3 ± 2.6 Ma (Fraser et al., 2014); Compton Downs (416.4 ± 2.5 Ma; Black, 2006); (3) Gongolgon Granite (410.9 ± 2.5 Ma; Black, 2006); (4) Brewarrina Granite (420.9 ± 2.3 Ma; Bodorkos, Blevin, Simpson, Gilmore, & Glen, 2013). Compiled after Burton et al., 2012; Byrnes, 1993; and Fraser et al., 2014.
Figure 3. Geophysical—geological interpretation map of the bedrock geology of the Bourke 1:250 000 map sheet overlying the tilt map of gridded 50 m × 50 m total magnetic intensity (TMI-RTP) aeromagnetic data (modified after Hegarty, 2011). Location of field samples are shown in blue dots, and locations of samples received from the Geological Survey of New South Wales are shown in yellow dots.
**Methods**

The Louth-Eumarra Shear Zone covers a significant portion of the Bourke 1:250,000 geological map sheet, but rock exposures are scarce. Structural mapping was conducted in the area of the Brevelon Tank Quartzite (Figure 3), which is a thick sand package within the Girilambone Group at the southern extremity of the Louth-Eumarra Shear Zone. Mapping was done at 1:5000 scale using Google Earth images as a base map. Direct observations and measurements, in conjunction with Landsat 7+ ETM images (from USGS) and Google Earth imagery, were used to determine the extent of outcrop in the field site.

Polished thin-sections were made from samples collected in the field and from drill cores (see Figure 3 for sample locations). Each sample was cut into 25 × 50 mm billets that were oriented perpendicular to the dominant foliation. Petrographic analysis of microstructures was conducted on a Nikon eclipse ME600 microscope with QCapture Pro software used for taking photomicrographs. Foliations and shear sense indicators were investigated in thin-sections cut both perpendicular to the foliation and parallel to the dominant stretching lineation.

Gridded aeromagnetic data, provided by the Geological Survey of New South Wales, were used to identify and interpret major faults. The grid spacing of the aeromagnetic data is 50 and 80 m. Using the Intrepid software, a series of filters were operated on the gridded aeromagnetic data in the Fourier domain. These filtered gridded data are powerful tools for interpreting structures in both shallow and deep bodies. We used reduced-to-pole (RTP) gridded data, which locate anomalies directly above their sources (Cooper & Cowan, 2005; Swain, 2000). The first vertical derivative was operated to sharpen short wavelength sources and especially fault lineaments in shallower sources (Blakely, 1995; Nabighian et al., 2005). In particular, tilt derivative (the arc tangent of the ratio of the first vertical derivative to the absolute value of total horizontal derivatives) is a powerful filter for enhancing geological edges and fault lineaments from both shallow and deeper sources equally (Miller & Singh, 1994). The filtered gridded data include the positive values over magnetic sources, zero values over the edges, and negative values elsewhere (Miller & Singh, 1994). Another process that has been conducted on the gridded aeromagnetic data is upward continuation, which is the process whereby potential field is measured on a plane farther from all sources to highlight deeper sources and reduce the effects of shallower sources (Blakely, 1995). The resultant image is therefore useful for observing deep-seated geological structures. The gridded aeromagnetic data allowed us to recognise (1) offset and dragging of magnetic anomalies along faults; (2) pronounced structural lineaments; and (3) lensoid and en-echelon structures.

**Results**

**Petrographic analysis of samples from the Louth-Eumarra Shear Zone**

Rocks of the Girilambone Group, which have been collected from drill cores and field sites (Figure 3; supplementary file A1) within the Louth-Eumarra Shear Zone, show evidence for multiple phases of deformation and metamorphism. Three foliations are recognised within the samples. The dominant foliation (S2) occurs as a strongly developed crenulation cleavage, which has formed quartz–mica domains with growth of aligned euhedral—subhedral biotite and muscovite grains (Figure 4a—c). Earlier disjunctive foliations (S1) are recognised in the microclasts of the dominant foliation (S2) (Figure 4a). The latest generation of foliation (S3) is a weakly developed incipient kinked crenulation cleavage (Figure 4b). Undulose extinction is commonly observed in detrital quartz grains.

The growth of biotite and muscovite along the dominant foliation plane (Figure 4c) suggests that deformation was accompanied by greenschist facies metamorphism. This is supported by the growth of actinolite and chlorite parallel to the S2 foliation plane (syn-tectonic growth) and as euhedral crystals at an oblique angle to the dominant foliation (S2) (post-tectonic growth) within the Boomi BO-1 drill core sample (14-SD-08) at 133.4 m depth (Figure 4d). These observations suggest that rocks in the Louth-Eumarra Shear Zone were subjected to greenschist facies metamorphic conditions during and after deformation. Kyanite was observed in sample 14-SD-03 commonly as subhedral grains with no strain caps and an oblique orientation relative to the dominant foliation (Figure 4e; see also SEM data in supplementary file A2). These relationships may indicate post-tectonic growth, thus implying that peak temperature metamorphism at lower amphibolite facies condition may have continued after the development of the S2 fabric.

**Brevelon Tank Quartzite**

The Brevelon Tank Quartzite, which is located along the southern extremity of the Louth-Eumarra Shear Zone (Figure 3), is interpreted to be a metamorphosed thick-sand package within the surrounding metasedimentary rocks of the Girilambone Group (Figure 5). Rocks in the area display similar lithological characteristics to the Budgery Sandstone Member of the Girilambone Group (Rayner, 1969). Petrographic analysis of the Brevelon Tank Quartzite shows poorly sorted subrounded to angular quartz clasts that show undulose extinction, in a matrix of finer aligned quartz grains and minor muscovite grains that define a foliation (Figure 6a). Owing to the high levels of silicification, primary sedimentary features, such as bedding and grain-size, are ambiguous and were not easily recognised in the field. Rare subcrop exposures of interlaminated meta-siltstone and metasandstone from the Girilambone Group were found adjacent to the Brevelon Tank Quartzite (Figure 6d).

The outcrop pattern of the Brevelon Tank Quartzite (Figure 5) is assumed to represent bedding (S0). In addition, evidence for two sets of structural fabrics is recognised. The earliest structural fabric (S1), found elsewhere within microlithons (e.g. Figure 4a; Burton, 2010), has not been recognised in the study area. However, the choice of the S2 and S3 terminology is preferable because it allows us to correlate structural observations regionally (Burton, 2010; Fergusson et al.,...
The dominant S2 foliation in the quartzite appears as a steeply dipping planar cleavage. It is weakly to moderately developed in massive quartzite horizons (Figure 6b) and is strongly developed and closely spaced (<1 mm) in more phyllitic horizons (Figure 6c). In the southern part of the map, S2 strikes dominantly N−S, whereas in the north the strike is more variable and generally oriented NW and WNW. Based on these variations in S2 orientation, the mapping area can be subdivided into structural domains (Figure 5).

S3 is a NE−SW-oriented, moderately to steeply dipping kinked crenulation cleavage that is weakly developed throughout the field area. In outcrop, spaced S3 fabric is recognised parallel to the axial plane of mesoscopic (F3) folds (Figure 6c).

The overall structure of the Brevelon Tank Quartzite is interpreted as representing superposition of two fold generations (F2 and F3). F2 folds are isoclinal with axial planes parallel to the S2 foliation. Mesoscale F2 folds were locally observed as isoclinal folded quartz veins (Figure 6e), whereas larger asymmetric F2 folds are recognised in the map-scale pattern of the quartzite outcrops (Figure 5). The sense of asymmetry of these folds shows opposite vergence directions (black arrows in Figure 5), indicating the presence of a larger-scale F2 fold (Figure 5, I−IV).

F3 folds have an open-upright kink geometry, with a near vertical fold axes. Mesoscopic F3 folds were observed in outcrops (Figure 6d), and macroscopic folds are recognised as map-scale variations in the orientation of S2 (Figure 5). The map-scale F3 fold appears to create a kink in the S2 foliation (Figure 5) and is similar in style to the kinked S3 crenulations found in outcrop (Figure 6c). Stereographic projections of S2 foliations show subvertical beta axis (i.e. F3 hinge) in each structural domain, with a mean fold axis orientation (plunge angle and plunge direction) of 73−197°. This orientation is similar to the measured orientations of L23 intersection lineations (Figure 5).

**Structural correlations**

Figure 7 shows the location of the Brevelon Tank Quartzite in relation to two structural maps of the Girilambone Group metasedimentary rocks that were created in the Girilambone (Fergusson et al., 2005a) and Kenilworth (Burton, 2010) regions. In both regions bedding and multiple structural fabrics were recognised, with the earliest foliation (S1) attributed to Ordovician deformation and only identified through...
Figure 5. Basement geology interpretation map of the Brevelon Tank Quartzite. Equal area lower hemisphere stereographic projections show (1) poles to the dominant S2 fabric for four separate domains, (2) planes of S3 fabric for the entire field area (β axis for all S2 data points plotted), and (3) L23 lineations. Schematic illustration (I)–(IV) shows interpretation of F2 isoclinal fold, S2 fabric, F3 open fold, and S3 fabric development.
petrographic analysis, and the latest foliation (S₄) attributed to an Early Devonian deformation event potentially related to the beginning of the Tabberabberan Orogeny (Figure 2) (Burton, 2010; Fergusson et al., 2005a). The S₂ foliation occurs as a differentiated layering of quartz and mica horizons and was observed subparallel to bedding in both regions. Fergusson et al. (2005a) postulated that S₂ developed under the same deformation event that produced isoclinal folds throughout the Girilambone region. S₃ developed axial planar to F₃ folds at both the Kenilworth and Girilambone areas and is defined by a crenulation cleavage in S₂.

S₂ and S₃ fabrics within the Brevelon Tank Quartzite resemble the fabrics described at the Girilambone and Kenilworth sites. S₂ is a strongly developed disjunctive foliation in the quartzite, overprinted by a later S₃ crenulation cleavage, which is interpreted to represent the axial plane orientation of F₂ folds. Similar to Fergusson et al. (2005a), S₃ is interpreted to form subparallel to bedding during the deformation that produced isoclinal folds. Open F₃ folds observed at the Brevelon Tank Quartzite are comparable with the F₃ folds described by Fergusson et al. (2005a) at the Girilambone site. However, S₄, which is axial planar to F₄ folds in the Kenilworth and Girilambone areas, was not observed at the Brevelon Tank site.

The magnetic fabric recognised in gridded aeromagnetic data (dashed black lines in Figure 7) is subparallel to the S₂ orientation recognised at the three field sites. Low intensity magnetic fabrics cannot be directly traced between each field site; however, a change in orientation occurs from ~N–S-trending at the Girilambone site to ~NE–SW-trending at both the Kenilworth area and Brevelon Tank site (Figure 7). This change in orientation of magnetic fabrics resembles the change in orientation of S₂ foliations between field sites, supporting their correlation.

Interpretation of aeromagnetic data

Aeromagnetic data from the eastern Louth-Eumarra Shear Zone show a NE-trending structural grain characterised by a series of moderate- to high-amplitude long-wavelength magnetic bodies, surrounded by low-amplitude anomalies (Figure 8a). The moderate to high amplitude magnetic bodies are inferred to be related to the late Silurian–Early Devonian granitoids of the Tarcoon Plutonic Complex (Figure 8b), which are bounded by two major NE-trending fault lineaments (faults 1 and 2 in Figure 8c).

Figure 6. Observations from the Brevelon Tank Quartzite. (a) Cross-polarised light (XPL) photomicrograph of sample 14-SD-25 highlighting serrated grain boundaries and undulose extinction on quartz grains (sample site 30.46645°S, 146.68734°E). (b) Outcrop of the Brevelon Tank Quartzite showing typical sub-vertical cleavage dashed in red (S₂), photo taken looking towards the south (30.47561°S, 146.68542°E). (c) Photo looking down on a horizontal surface showing S₂ cleavage (dashed in red) being crenulated by S₃ cleavage (dashed in blue) (30.46489°S, 146.69444°E). (d) Outcrop of Girilambone Group meta-sedimentary rocks at the southern extremity of Brevelon Tank Quartzite showing F₂ fold on a horizontal surface with an F₃ axial plane (blue dashed line) dipping 81–142 (30.48929°S, 146.69301°E). (e) Isoclinally folded quartz veins with a fold axial plane dipping 67–225 within the Brevelon Tank Quartzite (30.47635°S, 146.68692°E).
Figure 7. Correlation of the average $S_3$ fabric orientations and magnetic grain between the Brevelon Tank Quartzite, Kenilworth (Burton, 2010), and Girilambone (Fergusson et al., 2005a) areas overlying the total magnetic intensity (TMI-RTP 50 m $\times$ 50 m) data. Equal area lower hemisphere stereographic projections display poles to $S_3$ fabrics from each field area.

Figure 8. (a) Reduced to pole image of total magnetic intensity of the Louth-Eumarra Shear Zone (grid spacing: 50 m $\times$ 50 m). (b) Geophysical—geological interpretation map of the Louth-Eumarra Shear Zone from bedrock geology of the Bourke 1:250 000 map sheet (modified after Hegarty, 2011). (c) Tilt derivative image of gridded aeromagnetic data. Dashed line indicates the boundary of the Compton Downs Granite. (d) Interpreted faults. See Figure 3 for location.
The interpretation of the tilt derivative map of gridded aeromagnetic data indicates an asymmetric shape of plutonic bodies (dashed blue lines in Figures 8c, d, 9a) in the proximity of fault 1. We interpret this asymmetry as a kinematic indicator for dextral shearing along fault 1. In addition, a number of minor faults that offset the plutonic rocks are recognised, based on sharp discontinuities in the tilt derivative map of gridded aeromagnetic data (faults 3–8 in Figures 9a, b). The WNW-trending fault 3, branched off fault 1, seems to displace the easternmost plutonic body (Figure 9a). The orientation of the contacts of the plutonic rock changes from ~NE–SW- to ~E–W-trending along the fault, indicating an apparent dextral movement (Figure 9a). This fault is interpreted as a Riedel shear (R) of fault 1. Farther west, one of the plutonic bodies shows a sinistral offset along a minor ~N-trending fault (fault 4 in Figure 9a).

To the southwestern part of the Tarcoon Plutonic Complex, plutonic rocks (moderate- to high-amplitude bodies in the tilt derivative map; Figure 9b) seem to have been deformed by two parallel NE-trending faults (faults 5 and 6 in Figure 9b). One of these plutonic rocks, presented by dashed lines in Figure 9b, appears to have an ellipsoid shape between these two faults. To the north of this plutonic rock, situated between faults 5 and 6 are minor NW-trending faults (labelled 7 and 8) that offset the southwestern tail of a long plutonic body (Figure 9b). The eastern blocks adjacent to both faults 7 and 8 moved to the NW relative to the western block, indicating an apparent sinistral movement (Figure 9b). Faults 7 and 8 are interpreted as sinistral antithetic shears, which bound clockwise rotating blocks. The presence of NW-trending sinistral antithetic shears and ellipsoid shape of the plutonic rock between faults 5 and 6 might be indicative of the dextral movement along these faults.

Gridded aeromagnetic data of the southern Thomson Orogen shows large ~ENE-trending structures, such as the Culgoa Fault (Hegarty & Doublier, 2015) and fault 1 (Figures 8c, 10). The continuation of fault 1 to the east also shows evidence of dextral movement (Figure 10). A large and continuous NNE-trending moderate-amplitude magnetic structural grain is observed to the east of the eastern Louth-Eumarra Shear Zone (red dashed line in Figure 10). This magnetic anomaly is related to an inferred early Paleozoic plutonic
body. The trend of this plutonic body changes from SSW- to WSW-trending along fault 1, implying that it was deflected and thinned along fault 1 with an apparent dextral movement (Figure 10).

Interpretation of tilt-derivative map of gridded aeromagnetic data shows NNE-trending moderate-amplitude long magnetic bodies in the northeastern part of Figure 10, between the Culgoa Fault and another parallel fault to the north. The orientation of these long magnetic bodies changes from SSW- to SW-trending along the Culgoa Fault to the south, and also along a parallel fault to the north (Figure 10). We interpret these magnetic bodies as a sigmoidal structure formed in a dextral transpressional zone between the Culgoa Fault and the northern fault (Figure 10).

Discussion

Kinematics of the Louth-Eumarra Shear Zone

Gridded aeromagnetic data indicate that large ENE-trending faults in the east Louth-Eumarra Shear Zone dextrally offset Paleozoic rock units (Figure 9). Early Devonian sinistral movement along the Louth-Eumarra Shear Zone was previously suggested to have caused the opening of sedimentary basins (Cobar Basin) 200 km to the southwest (Glen et al., 1996), but no evidence was found in our study to support sinistral kinematics. We note, however, that our kinematic interpretation in the Louth-Eumarra Shear Zone is predominantly based on aeromagnetic imagery, while the 3D subsurface architecture of the faults and rock units remain unconstrained.

The timing of deformation along the Louth-Eumarra Shear Zone is not well constrained. Based on the observation of deformed granites (Figures 8b, c; 9a), at least a component of dextral shearing took place during or after the emplacement of the late Silurian to Early Devonian Tarcoon Plutonic Complex, as indicated, for example, by the dextral offset of the Compton Downs Granite. We emphasise, however, that this deformation may represent a later reactivation of a pre-existing structure that may have experienced a longer history of deformation prior to the late Silurian.

Our field evidence from the Brevelon Tank Quartzite may provide an additional insight into the timing of deformation. The ~NE-trending S3 fabric and F3 fold axial planes (Figure 5) are oblique (35°–40°) to the major ~ENE-trending faults of the Louth-Eumarra Shear Zone, indicating that the folds could have formed during dextral faulting. The age of S3 in the Girilambone region (Figure 7), however, is possibly older, as indicated by a ca 435 Ma 40Ar/39Ar cooling age of metamorphic micas (Fergusson et al., 2005a). This age corresponds to the Ordovician–Silurian Benambran Orogeny and is consistent with conclusions by Burton (2010) from the Kenilworth region,
where the timing of biotite growth within the NE–SW-trending S₂ and S₃ foliations, and staurolite growth in S₃, were attributed to Benambran deformation. Other NE–SW- and E–W-trending shear zones, described by Burton et al. (2012) (e.g. Three Sisters Shear Zone), seem to cross-cut Early Devonian (ca 416 Ma) granites, and may thus indicate younger (Tabberabberan?) reactivation. Assuming that our regional structural correlations (Figure 7) are correct, it is possible that the S₃ foliation at the Brevelon Tank Quartzite had already formed during the Benambran Orogeny (ca 435 Ma) and was rotated from an original ~N–S-orientation (Girilambone field site) to a ~NE–SW-orientation as a result of dextral movement on the Louth-Eumarra Shear Zone after ca 416 Ma.

**Relationships with the Olepoloko and Culgoa faults**

The westward continuation of the Louth-Eumarra Shear Zone is the Olepoloko Fault (Glen, 2005; Glen et al., 2013; Stevens, 2012).
accommodate 100 km of displacement without producing high bulk strain, whereas in subsimple shear (e.g. general shear with vorticity number of 0.82), the bulk strain associated with the same displacement would be even lower (e.g. Fos- sen, 2010, p. 296). This means that, theoretically, very large dextral displacement could have been accommodated over a ~110 km-wide zone between these two major structures. The amount of displacement and shear strain accumulated over the supposed ~110 km-wide shear zone is unknown, but given the suggested width, it is possible that the amount of dextral displacement was substantial. In simple shear, a 100 km shear zone can accommodate 100–200 km of displacement without producing high bulk strain, whereas in subsimple shear (e.g. general shear with vorticity number of 0.82), the bulk strain associated with the same displacement would be even lower (e.g. Fos- sen, 2010, p. 296). This means that, theoretically, very large dextral displacement could have been accommodated along the Louth-Eumarra Shear Zone and Culgoa Fault even if evidence for high strain shear criteria were lacking.

**Implications of kyanite occurrence**

An interesting observation in this study is the recognition of kyanite in a mica-schist (sample 14-SD-03; Figure 4e). Kyanite growth is indicative of relatively high-pressure conditions, and is commonly attributed to crustal thickening. To the best of our knowledge, kyanite has not been reported from the Lachlan Orogen, perhaps because it was an ‘extensional Orogen’ that was continuously subjected to subduction rollback and back-arc extension (Collins, 2002). These processes prohibited crustal thickening and resulted in a ‘hot’ orogen dominated by high-temperature metamorphism and crustal melting.

The recognition of kyanite in the Louth-Eumarra Shear Zone is consistent with previous reports on the occurrence of kyanite in the southern Thomson Orogen (Glen, Korsch, Costelloe, Poudjom Djomani, & Mantaring, 2006), and may indicate a pronounced change in the mode of orogenesis along this boundary. It appears that in addition to the dextral kinematic history recorded in this boundary, the region was also subjected to crustal thickening. The thicker crust recognised in seismic transects north of the Olepoloko Fault (Figure 11b) further supports this suggestion.

**Tectonic implications**

The origins of the Louth-Eumarra Shear Zone and Olepoloko Fault, and their geodynamic significance, remain unknown and could only be resolved with the emergence of additional data. However, we consider a number of models that may provide an insight into the possible geodynamic processes associated with the development of these ~E–W-trending structures. The discussed models follow suggestions put forward by previous authors (Glen et al., 2013; Klootwijk, 2013; Moresi et al., 2014), with an emphasis on the implications of these models on the origin of the Louth-Eumarra Shear Zone and Olepoloko Fault. We note that the models do not necessarily represent alternative explanations, and may in fact complement each other, particularly because each model is applicable to a different period of time.

The first model is schematically illustrated in Figure 12a and is based on Glen et al.’s (2013) interpretation for the earlier (Cambrian) history of the Thomson–Lachlan boundary. In this model, it is assumed that the northwestern part of the Thomson Orogen is underlain by late Neoproterozoic to middle Cambrian oceanic crust. The possible existence of this oceanic domain, referred to as the Barcoo Marginal Sea, was first proposed by Harington (1974) and is still accepted by some researchers (e.g. Fergusson & Henderson, 2015). If the opening of the Barcoo Marginal Sea occurred in an extensional back-arc region, then it is possible that segmentation of the northern and southern Tasmanides has already occurred in the early-middle Cambrian in response to trench retreat (Figure 12a). Importantly, ~E–W-trending structures that currently reside in the southern Thomson Orogen were subjected, according to this model, to lithospheric tearing (e.g. Rosenbaum & Piana Agostinetti 2015; Rosenbaum, Gasparon, Lucente, Peccerillo, & Miller, 2008) and crustal fragmentation. The latter may explain why Neoproterozoic to Cambrian continental blocks are currently found in the Delamerian Belt, Koonenberry Belt, northeast Queensland, and possibly also in the basement of the southern Thomson Orogen (Glen et al., 2013; Figure 12a).

The model shown in Figure 12a has a large number of uncertainties and unresolved problems. First, the oceanic nature of the Barcoo Marginal Sea has recently been challenged by Spaminato et al. (2015b), who suggested, based on results of forward modelling, that the basement of the northwestern Thomson Orogen is more likely composed of thinned Precambrian continental crust. Second, the timing of deformation associated with this model is considerably older than the constraints provided by us, which indicate dextral movement during or after the emplacement of early Silurian and Early Devonian granitoids. In fact, the deformation predicted in this model is older than the exposed rocks, meaning
that the model could only be applicable for explaining the origin of ~E–W-trending structures within the Neoproterozoic (?) subsurface of the southern Thomson Orogen (assuming that such an old basement exists; see question mark in Figure 12a). The major partitioning between the northern and southern Tasmanides, according to Glen et al. (2013), was focused around this Neoproterozoic crustal sliver, which may explain the thickening of the crust north of the Olepoloko Fault (Figure 11b). Nonetheless, whether or not the southern Thomson Orogen is rooted by a Neoproterozoic basement, is a matter of debate, and the evidence provided to support this suggestion has been questioned (Burton & Trigg, 2014).

The second model, shown in Figure 12 (b–d), follows the tectonic reconstruction recently presented by Moresi et al. (2014). The reconstruction is based on the suggestion that a Precambrian microcontinent (VanDieland) collided with the...
Australian continent during the late Cambrian and Early Ordovician (Cayley, 2011). This collision and its possible aftermath in the Silurian and Devonian may contributed to the development of an indentation-related orocline bend in the northwestern part of Lachlan Orogen (Figure 12b, c), which may explain why pre-existing ~E–W-trending structures, such as the Louth-Eumarra Shear Zone and Olepoloko Fault, were subjected to crustal thickening (as indicated by kyanite). We note that the observed dextral kinematics along the ENE-trending Louth-Eumarra Shear Zone (Figure 8c) is kinematically inconsistent with N- or NW-directed indentation. More likely, dextral kinematics was triggered by ~E–W contraction associated with Benambran (Figure 12b) and Tabberabberan (Figure 12d) deformation. If so, the arcuate shape of the Olepoloko Fault farther west would imply an opposite sense of kinematics (i.e. sinistral), which can be tested in future studies.

A major tectonic process highlighted in the reconstruction of Moresi et al. (2014) is the development of an orocline in response to eastward and southeastward trench retreat (Figure 12c). The process of orocline bending is primarily controlled by a combination of continental indentation, trench retreat and slab tearing (Rosenbaum, 2014), and the final shape of oroclines commonly mimics the shape of pre-existing lithospheric discontinuities. Indeed, both indentation and trench retreat, accompanied by widespread back-arc extension, are incorporated in the model of Moresi et al. (2014) for the development of the Lachlan oroclines. The fact that the oroclines are restricted to the area south of the Louth-Eumarra Shear Zone and Olepoloko Fault may suggest that the latter structures acted as a major crustal- or lithospheric-scale discontinuity.

The third model presented in Figure 12e is based on the assumption that ~N–S-trending contractional deformation in central Australia during the Carboniferous Alice Springs Orogeny has affected the kinematics of pre-existing structures within the Tasmanides (Klootwijk, 2013). The model assumes an escape tectonic style of deformation, driven by a far-field collision (e.g., similar to major continental strike-slip systems north and east of the India–Asia collision; Tapponnier et al., 1982). The model is consistent with a general sense of dextral kinematics along the arcuate Olepoloko Fault and Louth-Eumarra Shear Zone (Figure 12e). However, the left bend associated with the latter would imply that this zone was subjected to transpression during the Carboniferous. Given our relatively poor constraints for the timing of dextral faulting (syn- or post-Early Devonian) and the timing of crustal thickening (as indicated by kyanite growth), it is theoretically possible that our field evidence represents Carboniferous transpressional deformation.

Conclusion

Interpretations of faults from gridded aeromagnetic data indicate that major ~ENE-trending faults in the Louth-Eumarra Shear Zone accommodated dextral kinematics. The faults affected ca 416 Ma granitoids of the Tarcoon Plutonic Suite, thus providing a maximum constraint for the age of deformation. Field observations from the Brevon Tank Quartzite, associated with NE-trending folds and foliations, are consistent with the interpretation that the Louth-Eumarra Shear Zone was subjected to dextral movement.

An assessment of the possible tectonic origin and kinematics of the Louth-Eumarra Shear Zone and Olepoloko Fault reveals that these faults may have formed on the expense of pre-existing ~E–W-trending lithospheric-scale structures, which possibly developed already in the Cambrian. The structures may have acted as a northern bound buttressing the development of the Lachlan Orocline in the Silurian, and may have been reactivated during the Devonian Tabberabberan Orogeny and Carboniferous Alice Springs Orogeny.

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Supplementary material

A1. Field and drill-core sample information table.
A2. SEM–BSE images and SEM–EDS spectra from sample 14-SD-03 collected from drill core DDHTE Templestone Anomaly (~30.215023°S, 146.608217°E), 115.9 m depth.

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