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Devonian Crustal Stretching in the Northern Tasmanides (Australia) and Implications for Oroclinal Bending

Rashed Abdullah[1] and Gideon Rosenbaum[1]

[1]School of Earth and Environmental Sciences, The University of Queensland, Brisbane, Queensland, Australia

Key Points:

- Continuation of the Ross-Delamerian Orogen into the northern Tasmanides of eastern Australia is marked by an orogenic-scale bending
- The northern Tasmanides was subjected to bulk crustal thinning and back-arc extension in response to subduction roll-back during Devonian
- Orogenic-scale bending in the Delamerian-Thomson belt was possibly controlled by back-arc extension and slab-tearing

Correspondence to:
R. Abdullah,
r.abdullah@uq.edu.au

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Abstract The Tasmanides in eastern Australia exhibit a number of orogenic curvatures (oroclines), and possibly, a continental-scale bend that defines the continuation of the Delamerian Orogen with the Thomson Orogen. We provide an insight into the geodynamic processes associated with the origin of this orocline. We present interpretations of seismic reflection profiles and potential field data from the Thomson Orogen, which provide information on the crustal architecture and unravel major structures and kinematic relationships. Results show that a large area in the northern Tasmanides is underlain by thinned crust, bounded in the north and south by ~E-W trending geophysical features with apparent sinistral and dextral sense of kinematics, respectively. Within the highly extended crust of the Thomson Orogen, there is evidence for widespread Devonian basins bounded by normal faults. In stark contrast to the southern Tasmanides, where rocks show evidence for an earlier (Silurian) episode of extension and Devonian contractional deformation, no evidence for Silurian synrift sedimentation is observed in the Thomson Orogen. Evidence for ~E-W trending sinistral and dextral crustal-scale shear zones in the northern and southern boundaries of the Thomson Orogen, respectively, may represent tear faults, which were active during the Early Devonian and were possibly accompanied by tear-related magmatism. We suggest that crustal stretching in the northern Tasmanides was associated with Devonian back-arc extension in response to trench retreat, bounded by zones of slab-tearing and crustal segmentation that ultimately led to the development of the Delamerian-Thomson Orocline.

1. Introduction

The Tasmanides in eastern Australia record a prolonged history of convergent-margin tectonism that initiated in the Late Neoproterozoic to Cambrian Ross-Delamerian Orogeny (Flöttmann et al., 1993; Stump et al., 1986) and continued throughout the whole of the Paleozoic and early Mesozoic (Cawood, 2005; Glen, 2005, 2013; Rosenbaum, 2018). Remnants of the Ross-Delamerian Orogen (Figure 1a) are preserved in Antarctica, Tasmania, and South Australia (Gibson & Ireland, 1996) and farther north in the Thomson Orogen (Shaanan et al., 2018; Spampinato et al., 2015a; Spampinato, Betts, et al., 2015; Withnall et al., 1996). The Thomson Orogen is mostly unexposed but contains a number of Neoproterozoic and Cambrian inliers (Anakie, Charters Towers, Greenvale, Barnard, and Iron Range provinces; Figures 1b and 1c and 2) that record evidence for middle to late Cambrian deformation equivalent in time to the Delamerian Orogeny (Fergusson & Henderson, 2013; Withnall et al., 1995, 1996). A continuous fabric linking the Delamerian and Thomson Orogens is not well defined, but the two orogens share an equivalent tectono-stratigraphic history (Shaanan et al., 2018). Accordingly, if the Delamerian and Thomson orogens were originally continuous, as their tectono-stratigraphic similarities suggest, this would require a large orogenic curvature (Figure 1a) herein referred to as the Delamerian-Thomson Orocline (Rosenbaum, 2018). The geodynamic processes associated with this orogenic-scale bending are largely unknown, but the availability of new geophysical and well data from the unexposed basement of the Thomson Orogen provides an opportunity to address this problem.

Geophysical data indicate that the southern Thomson Orogen is underlain by a thick (~40–45 km) crust (Abdullah & Rosenbaum, 2017; Glen et al., 2013), but the central and northern parts of the orogen are characterized by a relatively thin layered crust (Finlayson, 1993; Finlayson, Leven, et al., 1990; Finlayson, Wake-Dyster, et al., 1990; Glen, 2005; Korsch et al., 2012; Milligan et al., 2003; Murray & Finlayson, 1990; Spampinato et al., 2015b). The nature of this basement, however, is unknown, because of the presence of sedimentary cover. It has been interpreted as an attenuated Precambrian continental margin (Glen, 2005; Spampinato et al., 2015a) or, possibly, as an oceanic crust substrate (Glen et al., 2013). The geodynamic processes responsible for crustal thinning are also unknown; they may have occurred in the course of the

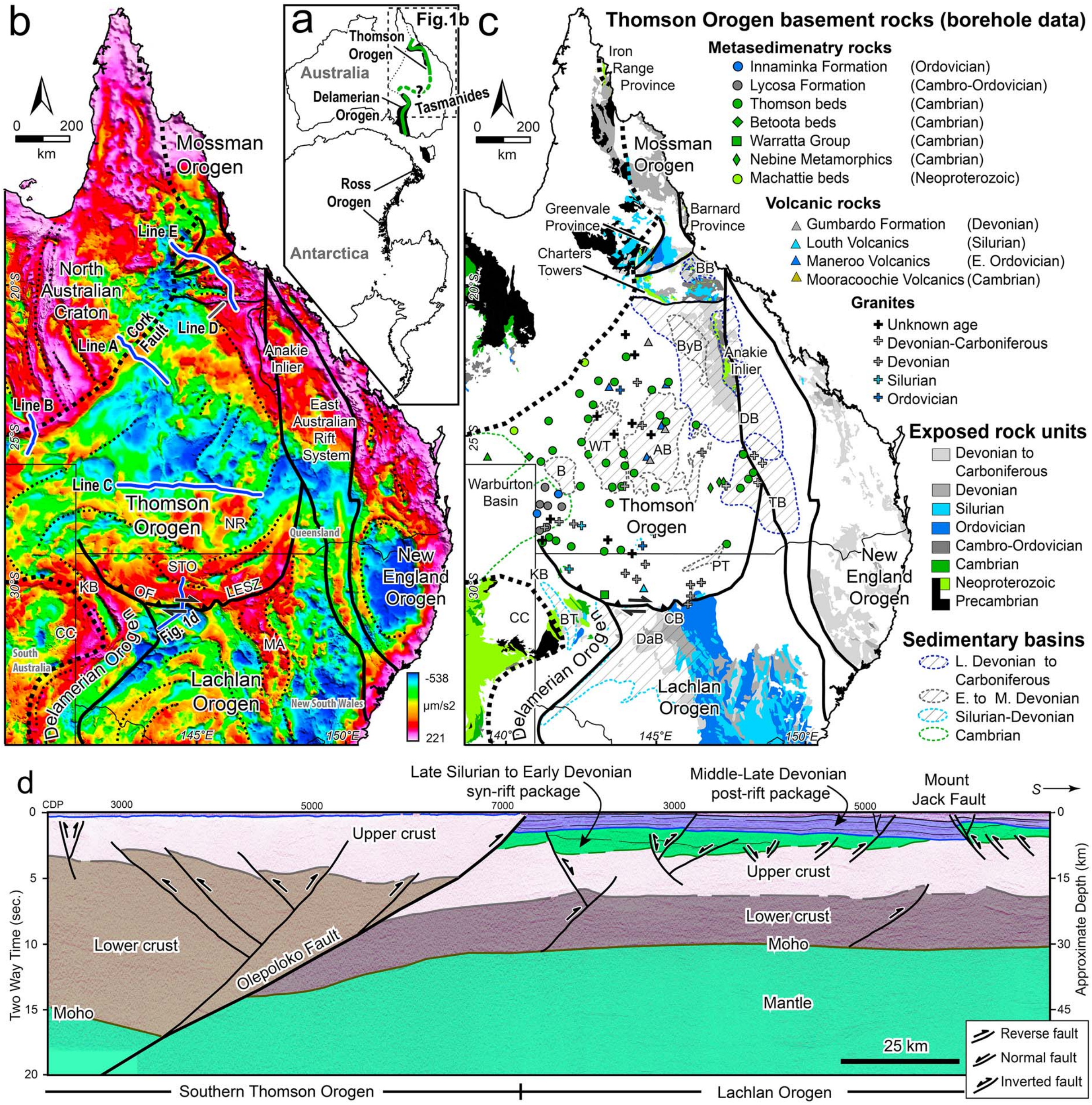

Figure 1. (a) Australia and Antarctica in their eastern Gondwanan configuration (modified after Boger & Miller, 2004), showing the possible northward continuation of the Delamerian Orogen through an orogenic-scale curvature (green line). (b) Bouguer gravity map showing the boundary between cratonic Australia and the Tasmanides (thick dotted lines), major tectonic boundaries (solid black lines), generalized gravity trends (black dotted lines) of eastern Australia, and location of the seismic transects (the blue and grey lines represent deep and shallow seismic transects, respectively). (c) Generalized map of eastern Australia showing exposed geological units and borehole data (borehole information present the lowermost stratigraphic units on the site). (d) Interpreted seismic transect across the Thomson-Lachlan boundary (after Abdullah & Rosenbaum, 2017). (Abbreviations used in maps (b) and (c): AB, Adavale and associated basins [B, Barrolka Trough; WT, Warrabin Trough]; BB, Burdekin Basin; BT, Bancannia Trough; ByB, Belyando Basin; CB, Cobar Basin; CC, Curnamona Craton; DaB, Darling Basin; DB, Drummond Basin; KB, Koonenberry Belt; LESZ, Louth-Eumarra Shear Zone; MA, Macquarie Arc; NR, Nebine Ridge; OF, Olepoloko Fault; PT, Paka Tank Trough; STO, Southern Thomson Orogen; TB, Timbury Hills Basin).

Neoproterozoic rifting of Rodinia (Glen, 2005; Spampinato, Betts, et al., 2015; Veevers, 2000) or during an Ordovician rifting event (*Larapinta Event*) that followed the Delamerian Orogeny (Purdy et al., 2016). Alternatively, the presence of extensive Devonian basins within the central Thomson Orogen suggests that at least part of the crustal stretching was obtained much later. For example, Devonian crustal stretching could have been associated with overriding-plate extension in response to trench retreat of the eastern Gondwana subduction margin (Rosenbaum, 2018).

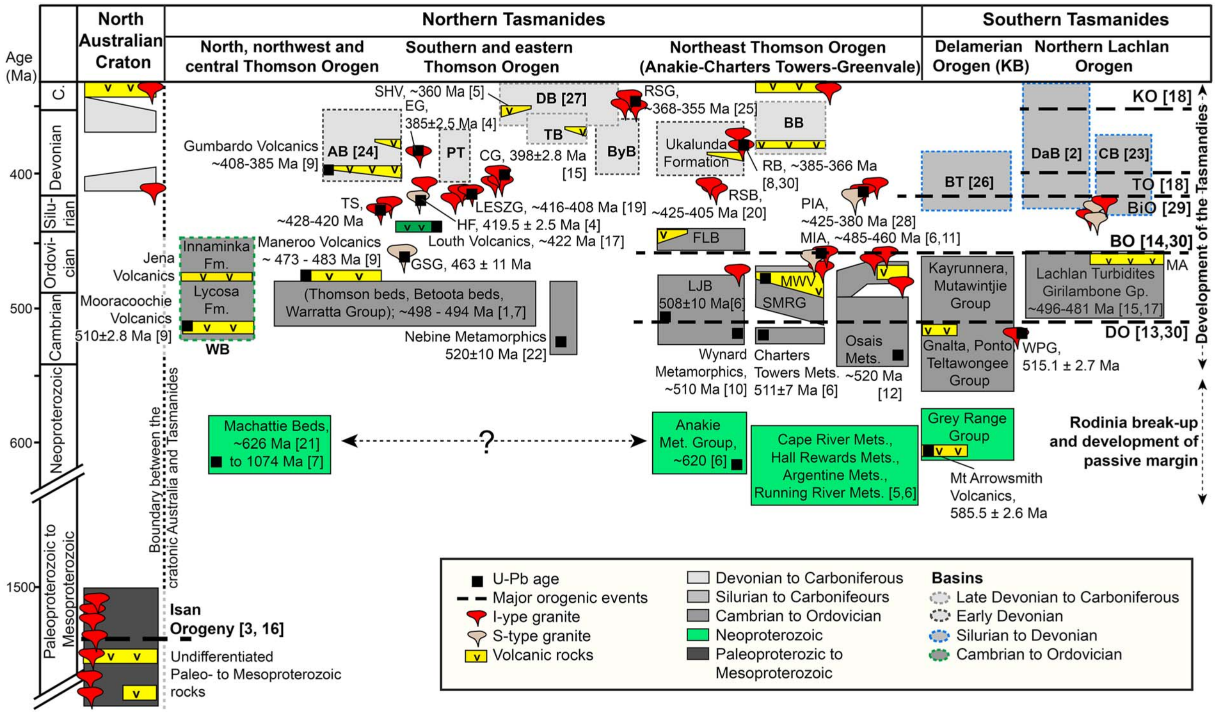

Figure 2. Time-space diagram showing a generalized comparison between the northern and southern Tasmanides and North Australian Craton. (Abbreviations: Basins: AB, Adavale and associated [Warrabin, Barrolka, and Quilpie troughs] basins; BB, Burdekin Basin; BT, Bancannia Trough; ByB, Belyando Basin; CB, Cobar Basin; DB, Drummond Basin; DaB, Darling Basin; PT, Paka Tank Trough; TB, Timbury Hills Basin; Orogenic events: DO, Delamerian Orogeny; Bio, Bindian Orogeny; BO, Benambran Orogeny; KO, Kanimblan Orogeny; TO, Tabberabberan Orogeny; Granites: CG, Conlea Granite; EG, Eulo Granite; HF, Hungerford Granite; TS, Tibooburra suites; GSG, Granite Springs Granite; LESZG, Louth-Eumarra Shear Zone granites; RSG, Roma Shelf granites; RB, Retreat Batholith; RSB, Reedy Springs Granite; PIA, Pama Igneous Association; MA, Macquarie Arc; MIA, Macrossan Igneous Association; WPG, William Peak Granite; others: FBL, Fork Lagoon beds; LJB, Les Jumelles beds; MWV, Mount Windsor Volcanics; SMRG, Seventy Miles Range Group; KB, Koonenberry Belt). Data sources: 1. Armistead and Fraser (2015), 2. Bembrick (1997), 3. Betts et al. (2006), 4. Bultitude and Cross (2012), 5. Cross et al. (2009), 6. Cross et al. (2015), 7. Cross et al. (2016), 8. Crouch et al. (1995), 9. Draper (2006), 10. Fergusson et al. (2001), 11. Fergusson, Henderson, Withnall, et al. (2007), 12. Fergusson, Henderson, Fanning, et al. (2007), 13. Foden et al. (2006), 14. Foster and Gray (2000), 15. Fraser et al. (2014), 16. Giles et al. (2006), 17. Glen et al. (2010), 18. Glen (2005), 19. Glen et al. (2013), 20. Hutton et al. (1997), 21. Kositcin et al. (2015), 22. Kositcin et al. (2015), 23. Mathieson et al. (2016), 24. McKillop et al. (2005), 25. Murray (1994), 26. Neef (2004), 27. Olgers (1972), 28. Purdy et al. (2013), 29. VanderBerg et al. (2000), and 30. Withnall et al. (1995).

Episodes of trench retreat have been shown to play a crucial role in the evolution of the southern Tasmanides (Collins, 2002a, 2002b), leading to tight oroclinal bends (e.g., Lachlan and New England oroclines; Rosenbaum et al., 2012; Moresi et al., 2014). However, the possibility that the northern part of the Tasmanides was also subjected to overriding-plate extension in response to trench retreat (Rosenbaum, 2018) has received relatively little attention. The occurrence of such processes may have controlled oroclinal bending and segmentation of the Phanerozoic fold belts, including the Ross-Delamerian Orogen.

The aim of this paper is to understand the geodynamic processes associated with the origin of the Delamerian-Thomson Orocline. We present new interpretations of potential field data and seismic transects across the northern and central part of the Thomson Orogen. These data allow us to unravel the kinematics of major basement structures and the level of extension related to crustal thinning. The new insights on the crustal structure, in combination with recent results from the southern Thomson Orogen (Abdullah & Rosenbaum, 2017), allow us to develop a new geodynamic model that explains the processes of segmentation and oroclinal bending in the Ross-Delamerian belt.

2. Geological Setting

The tectonic evolution of the Tasmanides was controlled by Phanerozoic subduction processes along the margin of eastern Gondwana (Cawood, 2005). The Tasmanides are commonly subdivided into five orogens: Delamerian, Thomson, Lachlan, Mossman, and New England, and the timing of orogenesis and magmatism generally becomes younger from west to east (Glen, 2005; Rosenbaum, 2018). The dominant structural grain is predominantly ~N-S (Figure 1b), but major ~E-W lineaments also occur, for example, along the southern and northern boundaries of the Thomson Orogen (Figures 1b and 1c). Such structures may provide evidence for orogen-perpendicular structures and segmentation of the plate boundary (Figures 1b and 1d; Abdullah & Rosenbaum, 2017; Dunstan et al., 2016). The ~E-W structures in the southern Thomson Orogen (Olepoloko Fault and Louth-Eumarra Shear Zone; Figure 1b) are commonly considered as the Thomson-Lachlan boundary (Glen et al., 2013), but their origin is a matter of debate (Burton, 2010; Burton & Trigg, 2014). Here we refer to these structures as the boundary between the northern Tasmanides and the southern Tasmanides.

The Thomson Orogen extends from the Cork Fault in the west to the unexposed basement beneath the Permian East Australian Rift System in the east (Figure 1b). The Cork Fault, which represents the boundary between the Precambrian North Australian Craton and the Tasmanides (Glen, 2005; Veevers, 2000), has been interpreted as a reactivated structure that formed along the Neoproterozoic rifted margin of Rodinia (Spampinato et al., 2015b; Spampinato, Betts, et al., 2015). Northeast of the Thomson Orogen, the Mossman Orogen (Figures 1b and 1c) is represented by the Silurian to Late Devonian Hodgkinson and Broken River provinces (Withnall & Henderson, 2012).

The Neoproterozoic to Cambrian basement of the Thomson Orogen is exposed in the Anakie, Barnard, Charters Towers, Greenvale, and Iron Range provinces (Figures 1c and 2). Borehole data from other parts in the Thomson Orogen yielded predominantly Cambrian metasedimentary rocks with minor Ordovician volcanic rocks and abundant late Silurian to Devonian granites (Figures 1c and 2; Purdy et al., 2016). Overlying these rocks are widespread Devonian basins, covering a large area in the central Thomson Orogen (Figures 1c and 2; McKillop et al., 2005). The basal package of these basins (Gumbardo Volcanics) is dated at ~408–385 Ma (Figure 2; Draper, 2006) and provides a constraint on the timing of basin formation. Younger, Late Devonian to Carboniferous basins occur farther east (Figure 1c).

West of the Olepoloko Fault, rift-related Ediacaran and arc-related Cambrian to Early Ordovician metasedimentary packages are exposed in the Koonenberry Belt of the Delamerian Orogen (Figures 1c and 2; Greenfield et al., 2011; Johnson et al., 2016). To the southeast, the Lachlan Orogen (Figures 1c and 2) comprises Cambro-Ordovician turbiditic successions, an Ordovician to Silurian volcanic belt (Macquarie Arc; Figure 1b) and Silurian to Devonian granitic rocks (Foster & Gray, 2000; Fraser et al., 2014; Glen et al., 2010, 2017; VanderBerg et al., 2000). In addition, there are widespread late Silurian to Devonian basins south of the Olepoloko Fault (Darling Basin) and in the Koonenberry Belt (Bancannia Trough; Figure 1c; Bembrick, 1997; Mathieson et al., 2016; Neef, 2004). Interpretation of a deep seismic transect across the Thomson-Lachlan boundary (Figure 1d) suggests that the deposition of the Darling Basin was initiated in a synrift tectonic setting during the Silurian to Early Devonian and was followed by inversion of major structures during the Middle to Late Devonian (Abdullah & Rosenbaum, 2017).

Relatively little is known about the deformation history of the Thomson Orogen. The rocks in the northern inliers (Figure 1c) show evidence for deformation events in the Cambrian and the Silurian (Fergusson & Henderson, 2013; Withnall et al., 1996), which is comparable to the deformation in the Koonenberry Belt of the Delamerian Orogen (Figure 2). In contrast to the Lachlan Orogen where rocks were strongly affected by Devonian contractional deformation (Glen, 2005, 2013), evidence for younger deformation in the Thomson Orogen is relatively rare. Devonian contractional deformation has been recorded in the Hodgkinson and Broken River provinces of the Mossman Orogen (Withnall & Henderson, 2012).

3. Data and Methods

To examine the subsurface geology and to recognize faults and lineaments, we used available borehole information, potential field (gravity and aeromagnetic) data, and 2-D regional seismic reflection profiles. In order to enhance the signal-to-noise ratio in the aeromagnetic data sets, a number of data and image processing algorithms have been applied, using Geosoft's Oasis Montaj™ software. The reduced-to-pole (RTP) algorithm, which has been applied to the total magnetic intensity, gridded data set. This RTP algorithm removes the effects of both inclination and declination of the main field, thus placing anomalies directly above their possible sources, providing that remanence can be ignored (either the Koenigsberger ratio is $\ll 1$ or remanence is close to the present field; Cooper & Cowan, 2005; Swain, 2000). Tilt derivate of the RTP image has been applied in order to enhance geological edges and fault lineaments (Miller & Singh, 1994). A composite image of two different data sets (such as RTP over tilt derivate) has been generated, allowing the correlation of spatially coincident features (Stewart & Betts, 2010). The gridded potential field data sets allowed us to recognize faults or lineaments with the sense of kinematics determined based on the offset and dragging of anomalous features. Lithological and geochronological data from available boreholes and their geophysical responses allowed us to infer basement rock distribution and to construct a solid geology map.

A geological interpretation has been conducted for five regional seismic transects (Figure 1b), four of which are deep (20-s two-way time [TWT]) and one shallow (6-s TWT). Interpretation of these seismic transects provides information on crustal thickness and the kinematics and orientation of the crustal-scale structures. Seismic profile C is a reinterpretation of BMR 01-09-14 (Finlayson, 1993; Finlayson, Leven, et al., 1990; Finlayson, Wake-Dyster, et al., 1990). Seismic transect E (07GAGC1; Figure 1b) was previously interpreted by Korsch et al. (2012). The interpretations of seismic profiles A (14GACF 1), B (14GACF 2), and D (CS86-1) are new and have not been previously published. With the exception of profile C, all seismic sections are migrated and almost free from diffractions or out-of-plane reflections. An average velocity of 6 km/s was assumed to provide approximate 1:1 vertical to horizontal scale. Mantle, lower crust, upper crust, and sedimentary basins were identified based on the reflection configuration, and major faults were interpreted based on reflection terminations and/or offsets.

4. Results

4.1. The Boundary of the Thomson Orogen With the North Australian Craton

Gridded aeromagnetic and Bouguer gravity images (Figures 3a–3c) show that the North Australian Craton is characterized by prominent ~NNW-SSE trending regional geophysical features. To the south, these geophysical features terminate against an ~NE-SW trending negative geophysical anomaly that marks the boundary between the North Australian Craton and the Thomson Orogen. The low magnetic responses in the Thomson Orogen correspond to the low magnetic susceptibilities of the metasedimentary basement rocks at depth.

Structural interpretation of the gravity and magnetic images (Figures 3a–3c) shows that a ~NE-SW trending Cork Fault follows the boundary between the North Australian Craton and the Thomson Orogen (Figure 3d). The interpreted aeromagnetic image (Figure 3b) shows that a number of ~NNE-SSW trending, highly magnetized, narrow linear features are dextrally dragged and obliquely terminate against the Cork Fault. Similar kinematics can be interpreted from large sigmoidal-shaped magnetized bodies along the fault zone (Figure 3b). To the south of the Cork Fault, a number of ~NE-SW trending magnetic lineaments can be identified, showing dextral dragging and offset of ~N-S trending linear magnetic bodies (Figure 3b).

Interpretation of the seismic transects across the boundary between the North Australian Craton and the Thomson Orogen (Figures 1b, 3a, and 4a and 4b) shows a relatively thick undifferentiated crust to the north, associated with the North Australian Craton. This cratonic crust has a seismic signal that is weakly reflective and shows very few coherent reflections, resulting in a homogenous, amorphous character. In contrast, the crust of the northern Thomson Orogen (Figures 4a and 4b) is relatively thin and layered. The lower crust of the Thomson Orogen is characterized by very strong, high amplitude, reflection packages, whereas the upper crust is almost free from reflections. Both North Australian Craton and Thomson Orogen crusts are overlain by high-amplitude, continuous, and parallel to subparallel reflectors, which correspond to the sedimentary successions of Permian-Jurassic basins (Figures 4a and 4b).

Seismic transect A (Figure 4a) shows that the Moho occurs at approximately13- to 13.5-s TWT beneath the undifferentiated cratonic crust that can be identified by moderately strong and high-amplitude reflectors. Identifying the Moho in the northern part of transect B is more difficult but based on the presence of few very weak reflectors with poor continuity, we infer the Moho at ~14-s TWT beneath the nonreflective cratonic crust (Figure 4b). In the northern and western parts of the Thomson Orogen (Figures 4a and 4b), the Moho is defined by the base of lower crust, which is characterized by a set of moderately strong, high-amplitude reflectors with fair continuity.

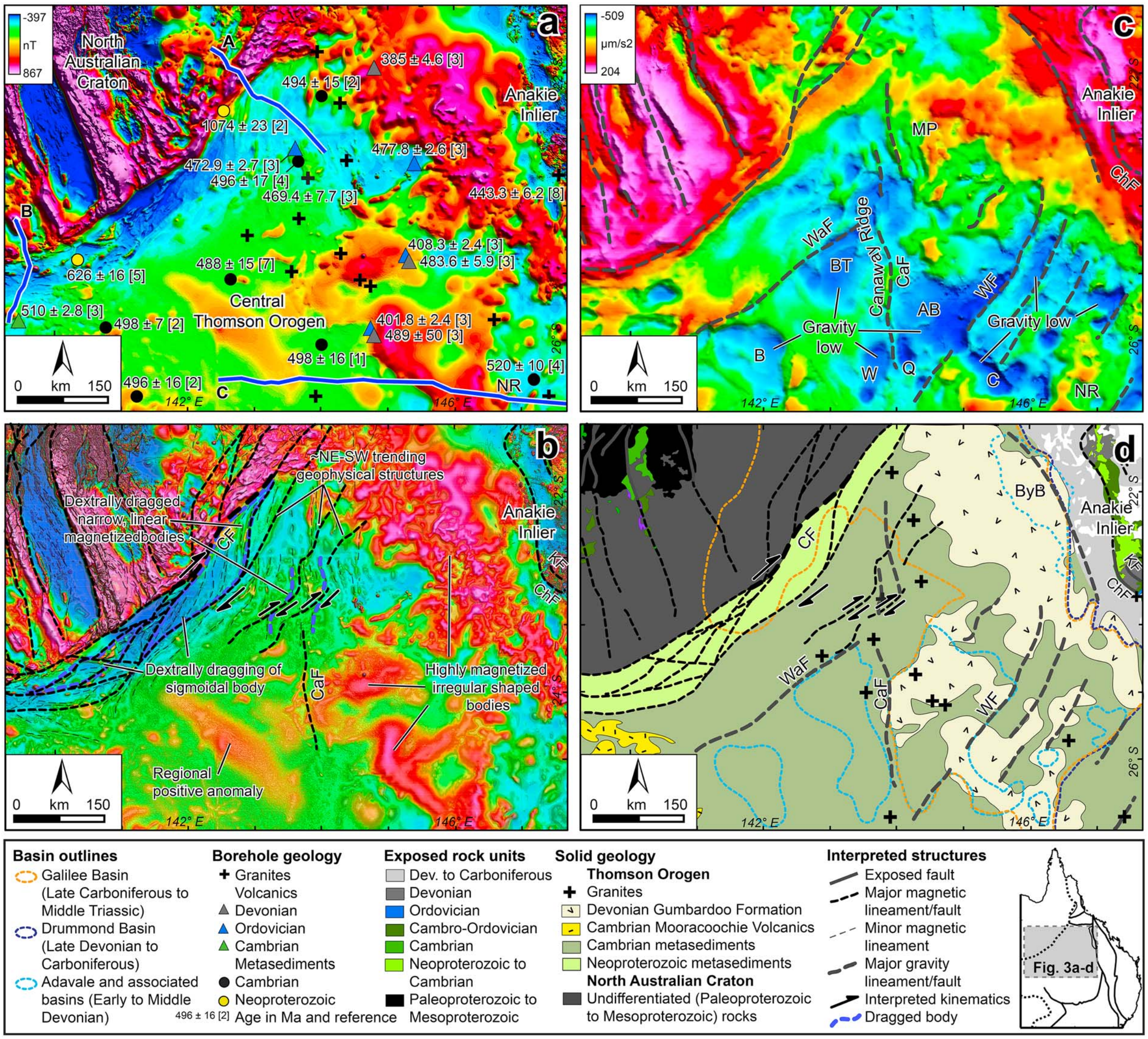

Figure 3. (a) Pseudocolour RTP aeromagnetic image and available borehole information from the study area. Note that the borehole information represents the lowermost stratigraphic units on the site. Data sources: 1. Cross et al. (2015), 2. Cross et al. (2016), 3. Draper (2006), 4. Kositcin, Bultitude, et al. (2015), 5. Kositcin, Purdy, et al. (2015), 6. McKillop et al. (2005), 7. Murray (1994), and 8. Wood (2006). (b) Composite image of RTP aeromagnetic data over tilt derivative, with structural interpretation. (c) Bouguer gravity image, with structural interpretation. (d) Interpreted solid geology map of the area. (Abbreviations: AB, Adavale Basin; B, Barrolka Trough; BT, Barcoo Trough; ByB, Belyando Basin; C, Cooladdi Trough; CF, Cork Fault; CaF, Canaway Fault; ChF, Chinaman Fault; KF, Kettle Creek Fault; MP, Maneroo Plain; Q, Quilpie Trough; WaF, Warbreccan Fault; WF, Warrego Fault; WT, Warrabin Trough).

Along seismic transect A (Figure 4a), the transition from the North Australian Craton to the Thomson Orogen is characterized by a relatively thicker (approximately 7- to 8-s TWT) lower reflective crust and thinner (approximately 3- to 4-s TWT) nonreflective upper crust in the Thomson Orogen. In the southern part of seismic transect A, the reflective lower crust is significantly thinner (approximately 4- to 5-s TWT) and the non-reflective upper crust becomes progressively thicker (approximately 5- to 8-s TWT). Similar thinned lower crust and thick upper crust are also interpreted in the northwestern margin of the Thomson Orogen along seismic transect B (Figure 4b).

The structural interpretation of seismic transect A (Figure 4a) shows that the Cork Fault is a south or southeast dipping crustal-scale structure. This fault is dipping moderately at depth and becomes steeper (>60°) at shallower depths. A similar south dipping major structure (Figure 4b), which coincides with the boundary between the North Australian Craton and the Thomson Orogen, is interpreted along seismic transect B. Both faults show juxtaposition of Late Neoproterozoic to Paleozoic rocks (Thomson Orogen crust in the

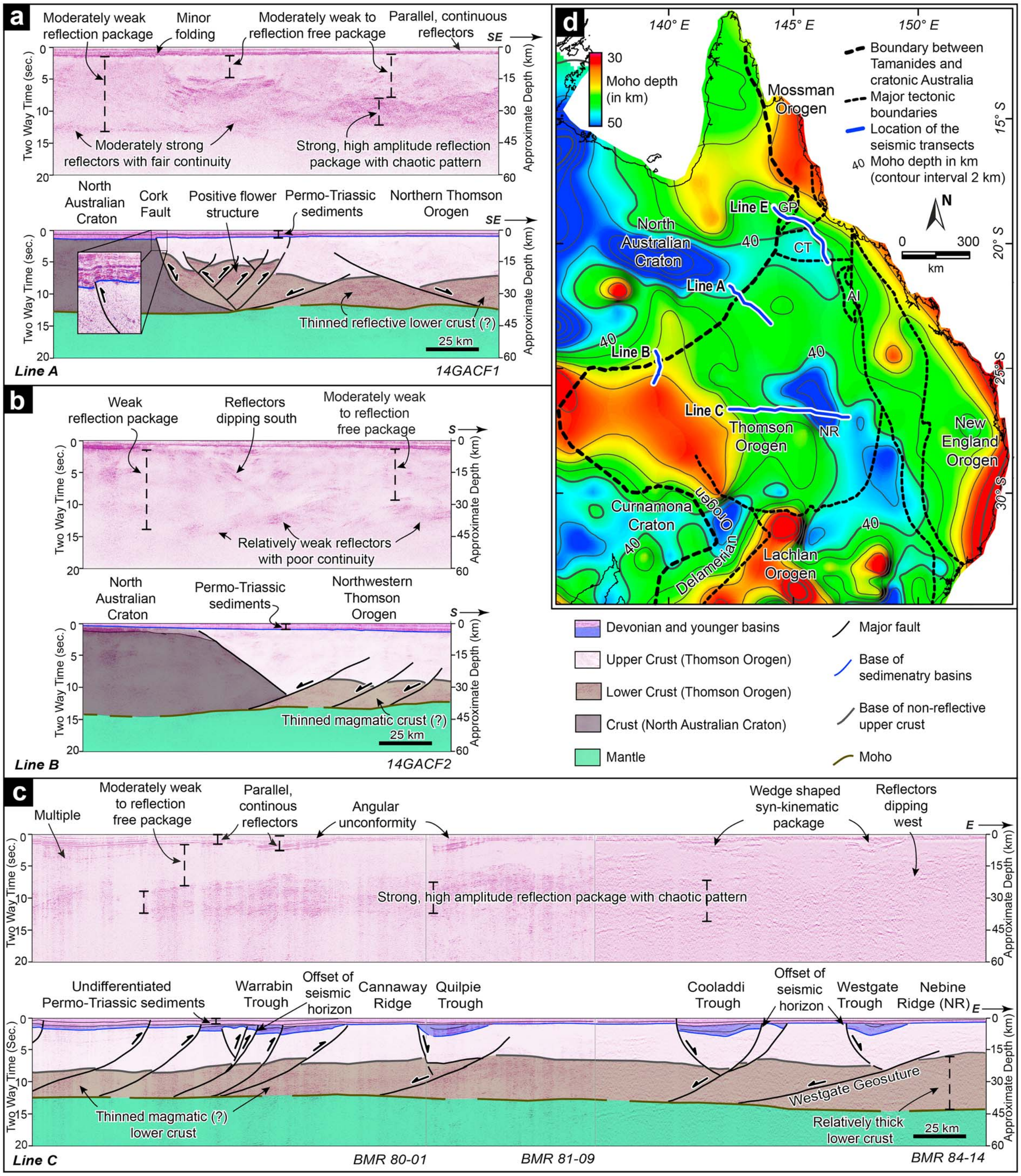

Figure 4. (a–c) Seismic reflection profiles (A-C) and interpretations (see Figure 1b for line locations). (d) Map showing depth of the Moho in eastern Australia and location of the deep seismic transects (modified after; Kennett et al., 2011). (Abbreviations: AI, Anakie Inlier; CT, Charters Towers Province; GP, Greenvale Province).

hanging wall block) against Paleoproterozoic to Mesoproterozoic rocks (North Australian Craton crust in the foot-wall block). These structural relationships suggest normal kinematics along the boundary between the North Australian Craton and the Thomson Orogen, consistent with the forward modeling of the potential field data by Spampinato et al. (2015b). However, at a shallower depth, the Cork Fault can be interpreted as a reverse fault, showing minor folding and small offset near the base of the Jurassic sedimentary package (Figure 4a). To the south of the Cork Fault, the overall structural geometry resembles a positive flower structure (Figure 4a). South of the boundary, a number of normal faults offset the top of the thinned reflective lower crust of the Thomson Orogen (Figures 4a and 4b).

4.2. Central Thomson Orogen

The central Thomson Orogen is the area northwest of the Nebine Ridge and west of the Anakie Inlier (Figure 3a). The area is characterized by a number of gravity depressions, which correspond to the Adavale Basin and its related subbasins and troughs (Barrolka, Barcoo, Cooladdi, Quilpie, Warrabin, and Westgate; Figure 3c). The gridded aeromagnetic image shows a relatively low magnetic response that likely corresponds to the metasedimentary basement of the Thomson Orogen. A number of regional positive anomalies are also present in the area and possibly correspond to moderately deep magnetic sources. The eastern part of the central Thomson Orogen is characterized by highly magnetized irregular-shaped bodies (Figures 3a and 3b) that likely result from the presence of igneous rocks at depth. Based on borehole data, we infer that these magnetic bodies may correspond to the Ordovician Maneroo Volcanics and/or Devonian Gumbardo Volcanics or their equivalent rock units (Figures 2 and 3a).

The Bouguer gravity image (Figure 3c) shows a number of ~N-S and ~NE-SW trending geophysical features in the central Thomson Orogen. Many of these structures correspond to faults (e.g., the Canaway, Warbreccan, and Warrego faults) that bound the basin-related gravity depressions (Figures 3c and 3d). Some of these structures do not have any magnetic expression (Figures 3a and 3b), possibly due to the presence of the irregular-shaped highly magnetized bodies associated with widespread volcanic rocks at greater depth.

The interpretation of seismic transect C (Figure 4c) shows that the central Thomson Orogen is characterized by a distinctive layered crust. The Moho is gently dipping toward the east, reaching a greater depth (~14-s TWT) beneath the Nebine Ridge (Figures 4c and 4d). The thickness of the lower crust is very thin (~4-s TWT) in the west and gradually increases toward the east (approximately 7- to 8-s TWT beneath the Nebine Ridge; Figure 4c).

The structural interpretation of the E-W seismic transect (Figure 4c) shows that faults in the Thomson Orogen penetrate the reflective lower crust and are predominantly dipping to the west. To the west of the Canaway Ridge (seismic line BMR 80-01; Figure 4c), these faults show a component of reverse movement and offset at the top of the nonreflective crust and overlying parallel reflectors (Permian to Triassic sedimentary units). East of the Canaway Ridge (seismic lines BMR 81-09 and BMR 84-14; Figure 4c), faults show a net normal sense of movement and offset at the top of the upper and lower crusts. Parallel to semiparallel reflection packages with occasional onlapping reflection configuration indicate possible synkinematic deposition within the fault-bounded graben or half-graben structures (i.e., the Quilpie, Cooladdi, and Westgate troughs; Figure 4 c). Farther east, a gently west dipping crustal-scale structure (Westgate Geosuture; Finlayson, 1993) separates the relatively thicker reflective lower crust of the southeastern Thomson Orogen (i.e., beneath the Nebine Ridge; Figure 4c) from the central Thomson Orogen.

The interpretation of the shallow seismic transect D (Figure 5) shows that a major west or southwest dipping basement structure separates the northeastern part of the central Thomson Orogen from the exposed parts of the northeastern Thomson Orogen (Charters Towers Province). The lowermost unit is characterized by a seismically weak reflection package that possibly corresponds the metasedimentary Thomson Orogen basement. To the west or southwest of this major fault (Figure 5a), a relatively high-amplitude, poorly continuous reflection package overlies the weakly reflective basement. This high-amplitude but poorly continuous or chaotic reflection package is relatively thin and not uniformly distributed above the metasedimentary basement and can be interpreted as volcanic rocks. Above this inferred volcanic unit, parallel to subparallel reflectors show thickening toward the major fault to the east or northeast (Figure 5). The reflection geometry of this package resembles wedge-shaped growth strata within a half-graben bounded by a major fault to the northeast (Figure 5b). However, due to poor resolution, it is difficult to identify any on-lapping reflectors within this half-graben. Above the growth strata, reflectors are parallel with fair continuity, showing an overall uniform thickness. Borehole information from Campaspe DDH 1 (Figure 5b) suggests that these reflectors correspond to Early Carboniferous and younger sedimentary rocks of the Drummond Basin. The borehole did not intersect the underlying growth strata. We infer that this lower set of reflectors represent a Devonian to Early Carboniferous synkinematic package. East of the major fault,

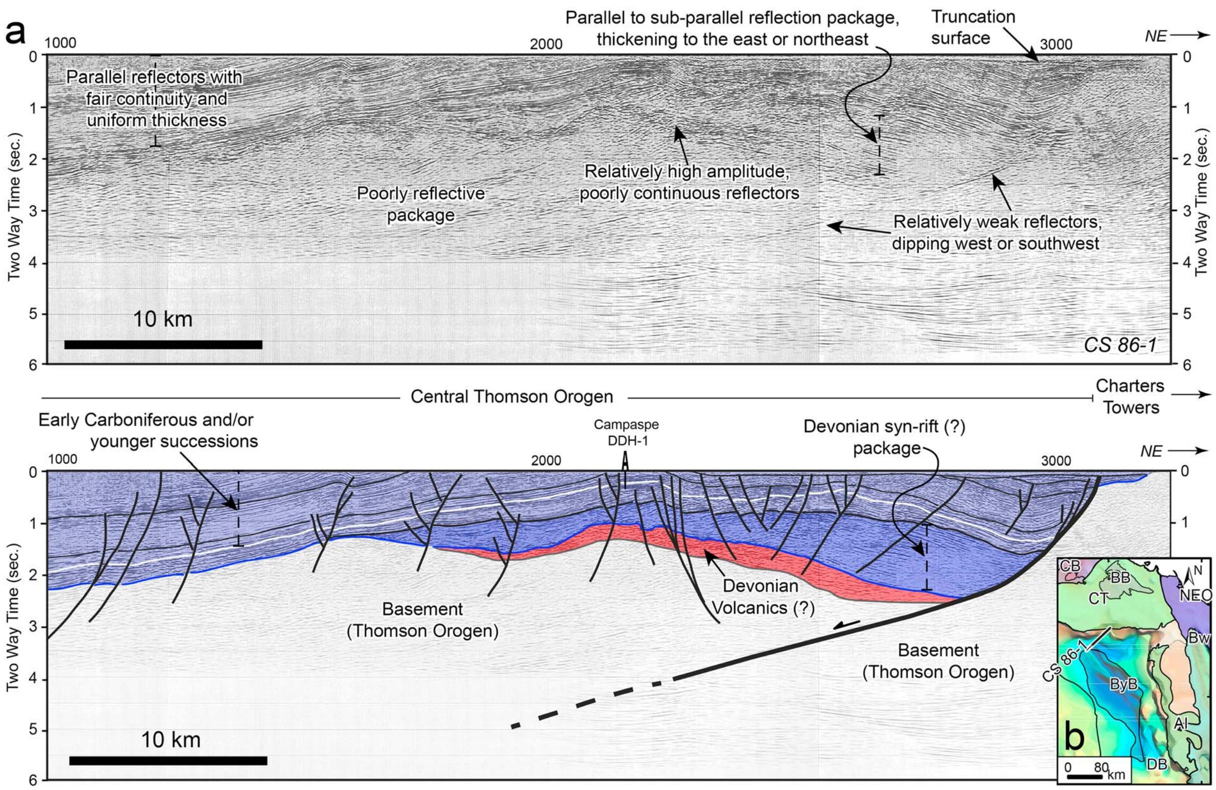

Figure 5. (a) Shallow seismic reflection profile D and geological interpretation showing the basement architecture to the south of the Charters Towers Province. (b) Map showing basement topography and location of the shallow seismic transect. (Abbreviations: AI, Anakie Inlier; BB, Burdekin Basin; ByB, Belyando Basin; Bw, Bowen Basin; CB, Clarke River Basin; CT, Charters Towers Province; DB, Drummond Basin; NEO, New England Orogen).

both the volcanic unit and synkinematic growth strata are absent, and overlying Carboniferous and younger sedimentary rocks are thinned or absent (Figure 5b).

4.3. Northeastern Thomson Orogen

The northeastern Thomson Orogen covers the exposed rock units in the area of the Anakie Inlier, Charters Towers, and Greenvale provinces (Figures 3, 6, and 7). Gridded aeromagnetic images show a number of both high- and low-amplitude magnetic anomalies (Figures 6 and 7). The relatively low magnetic anomalies mostly correspond to exposed metasedimentary rocks, whereas the highly magnetized irregular-shaped bodies correspond to igneous intrusions and volcanic rocks (Figures 6 and 7). Many of these igneous rocks are Silurian to Devonian in age (Figures 6 and 7).

The interpretation of aeromagnetic data shows that the ~N-S structural trend of the Anakie Inlier abruptly changes into ~E-W trending in the Charters Towers Province and then becomes ~NE trending in the Greenvale Province (Figures 6 and 7). A number of major faults (i.e., Chinaman and Kettle Creek faults; Figures 3 and 6) correspond to this ~N-S structural trend in the Anakie Inlier. The Chinaman Fault marks the western and southern boundary of the Anakie Inlier.

A major ~E-W trending structure (Policeman Fault Zone; Figures 6 and 7) may represent the boundary between the eastern Charters Towers Province and Anakie Inlier. Based on seismic interpretation (after Korsch et al., 2012), the Policeman Fault Zone is a south or southeast dipping reverse fault at depth (Figure 6d). Kinematic analysis using potential field data is not conclusive but may indicate a sinistral sense of movement based on the recognition of sigmoidal-shaped magnetized bodies along the Policeman Fault Zone (Figure 7). The Burdekin Basin, which is mainly composed of Devonian sedimentary rocks, overlies the northeastern part of the Charters Towers Province (Figure 6). Interpretation of seismic transect E (Figure 6d) shows that a number of extensional faults offset the base of the Devonian sedimentary package of the Burdekin Basin (after Korsch et al., 2012).

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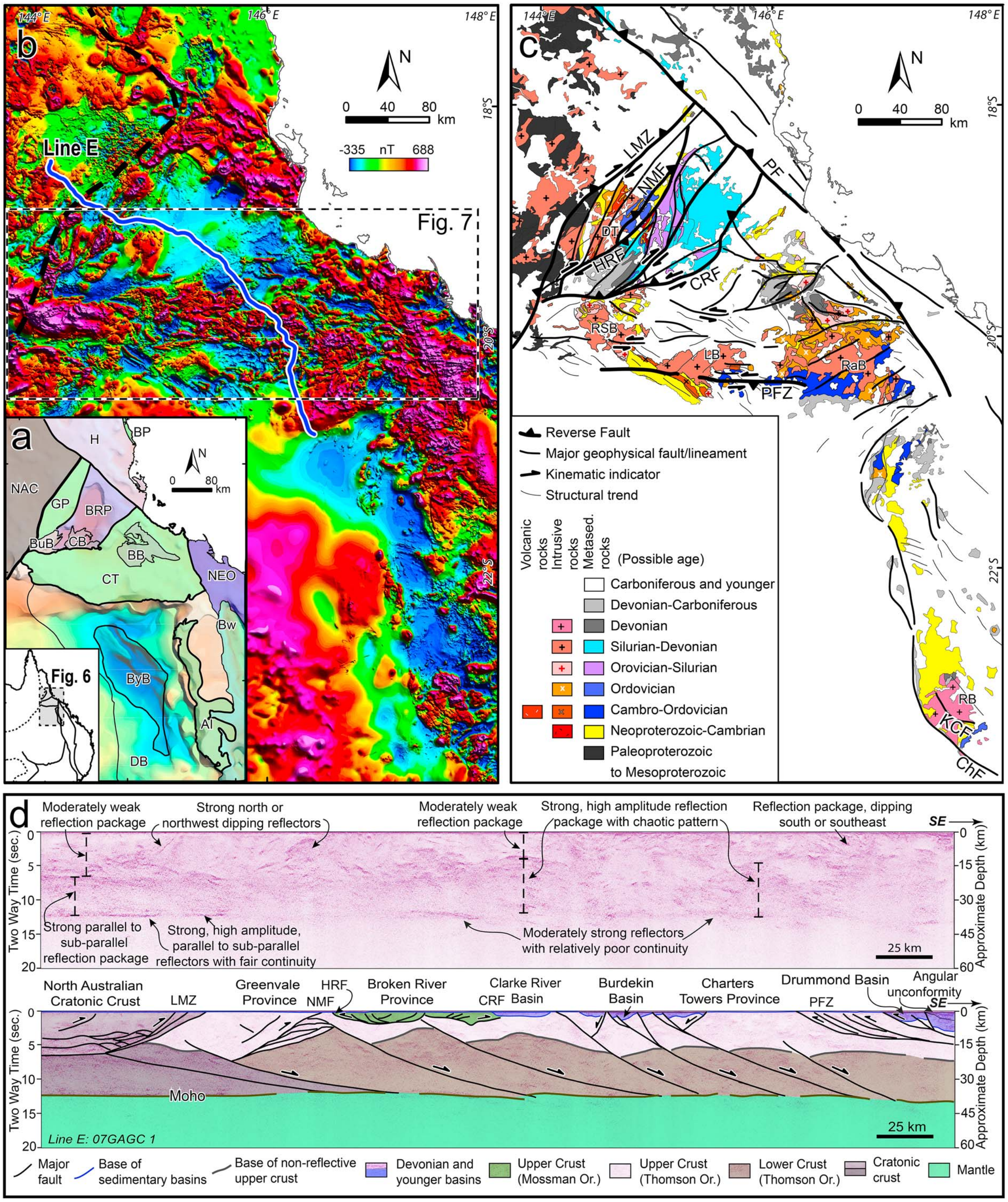

Figure 6. (a) Basement topography, (b) Pseudocolour RTP aeromagnetic, and (c) Geological map of the northeastern Thomson Orogen. (d) Seismic reflection profile E and geological interpretation after Korsch et al. (2012) showing the basement architecture across the northeastern Thomson Orogen. [Abbreviations: AI, Anakie Inlier; BB, Burdekin Basin; BP, Barnard Province; BRP, Broken River Province; BuB, Bundock Basin; ByB, Belyando Basin; Bw, Bowen Basin; CB, Clarke River Basin; ChF, Chinaman Fault; CRF, Clarke River Fault; CT, Charters Towers Province; DB, Drummond Basin; DT, Dido Tonalite; GP, Greenvale Province; H, Hodgkinson Province; HRF, Halls Reward Fault; KCF, Kettle Creek Fault; LB, Lolworth Batholith; LMZ, Lynd Mylonite Zone; NEO, New England Orogen; NMF, Nickel Mine Fault; PF, Parmerville Fault; PFZ, Policeman Fault Zone; RaB, Ravenswood Batholith; RB, Retreat Batholith; RSB, Reedy Springs Batholith).

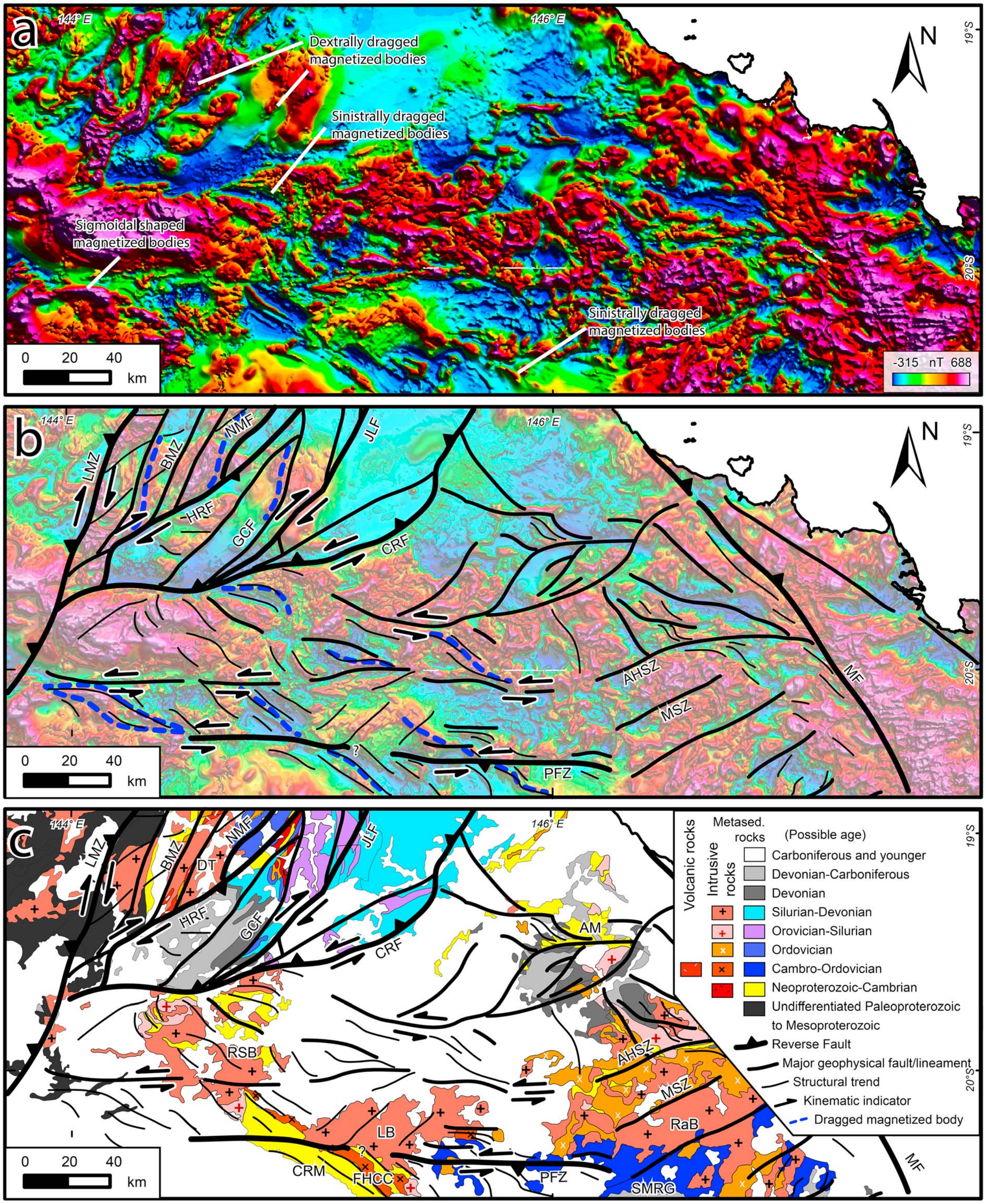

Figure 7. (a) Pseudocolour RTP aeromagnetic image, (b) composite image of RTP aeromagnetic data over tilt derivative (60% transparent) with structural interpretation, and (c) Geological map of the Charters Towers and parts of Greenvale province. (Abbreviations: AHSZ, Alex Hill Zhear Zone; BMZ, Balcooma Mylonite Zone; ChF, Chinaman Fault; CRF, Clarke River Fault; DT, Dido Tonalite; GCF, Gray Creek Fault; HRF, Halls Reward Fault; JLF, Jessey Springs-Lockup Well Fault; KCF, Kettle Creek Fault; LB, Lolworth Batholith; LMZ, Lynd Mylonite Zone; MSZ, Mosgradies Shear Zone; MF, Millaroo Fault; NMF, Nickel Mine Fault; PFZ, Policeman Fault Zone; RaB, Ravenswood Batholith; RB, Retreat Batholith; RSB, Reedy Springs Batholith).

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North of the Charters Towers Province, a curvilinear ~E-W to ~NE trending geophysical structure corresponds to the Clarke River Fault, marking the boundary with the Broken River Province of the Mossman Orogen (Figures 6 and 7). At depth, the Clarke River Fault is a shallowly west dipping reverse fault (Figure 6d; after Korsch et al., 2012). The aeromagnetic image shows evidence of sinistral dragging along the Clarke River Fault (Figure 7b), consistent with previous suggestions (Henderson et al., 2013). A number of other ~E-W trending structures, located in between the Policeman and Clarke River faults in the western Charters Towers Province (Figures 6 and 7), also show evidence for sinistral kinematics.

The dominant ~NE trending geophysical features in the Greenvale Province correspond to a number of fault zones, including (from west to east), the Lynd Mylonite Zone, Balcooma Mylonite Zone, Nickel Mine Fault, and Halls Reward Fault (Figures 6 and 7). Among these faults, the southeast dipping Halls Rewards Fault separates the Greenvale Province from the Broken River Province of the Mossman Orogen. Based on the seismic data interpretation (after Korsch et al., 2012); the Lynd Mylonite Zone is a west dipping reverse fault that separates the Greenvale Province from the North Australia Craton (Figure 6d). Structural interpretation of aeromagnetic data shows evidence for dextral dragging along many of these faults (Figure 7b). To the east, these two faults abruptly terminate against a NW trending geophysical feature (Figure 6) that possibly represents the southern extension of the Parmerville Fault (Vos et al., 2006).

The interpretation of deep seismic transect E (after Korsch et al., 2012) shows a two-layered crust in the northeastern Thomson Orogen (Figure 6d). At depth, the lower reflective crust of the Thomson Orogen is characterized by a series of extensional faults that extend down to the Moho. The upper weakly reflective crust is overlain by Ordovician to Silurian metasedimentary rocks of the Broken River Province and Devonian and younger sedimentary basins belonging to the Clarke River, Burdekin, and Drummond basins (Figure 6d).

5. Discussion

5.1. Structure and Kinematics of the Central and Northwestern Thomson Orogen

The interpretation of potential field and 2-D deep seismic transects reveals that the boundary between the North Australian Craton and the Thomson Orogen is a NE trending crustal-scale fault system (Figures 3 and 4a and 4b). It has previously been interpreted as a SE dipping normal fault (Spampinato, Betts, et al., 2015) that developed in the course of the breakup of Rodinia (Glen, 2005; Veevers, 2000). Our seismic interpretation results (Figures 4a and 4b) show a net normal fault kinematics along this boundary, but we also recognize a broad positive flower-like structure (seismic transect A; Figure 4a) that may indicate a later phase of transpressional reactivation (Harding, 1985; Woodcock & Fischer, 1986; Woodcock & Rickards, 2003). Interpretation of gridded aeromagnetic images (Figures 3a and 3b) suggests that the kinematics associated with the Cork Fault involved a dextral strike-slip component. The presence of minor folding and the evidence of reverse movement at the base of a Permian-Jurassic basin (Figure 4a) indicate a younger episode of inversion or reverse reactivation along the boundary between the North Australian Craton and Thomson Orogen.

Basement faults within the Thomson Orogen are predominantly low-angle and extensional structures (BMR 81-09, BMR 84-14, and CS86-1; Figures 4c and 5) with few minor exceptions to the west, where most of the faults show reverse kinematics (BMR 80-01; Figure 4c). In the east, many of the interpreted crustal-scale structures correspond to ~NNE trending geophysical features in the Bouguer gravity anomaly (Figures 1b and 3b). Evidence for extensional faulting has also been recognized within the lower crust across the Anakie-Charters Towers-Greenvale provinces (Figure 6d; after Korsch et al., 2012). Notably, this extensional deformation is absent in the North Australian Craton, thus suggesting that the boundary operated as a breakaway zone possibly analogous to the Las Vegas fault system in North America (Wernicke et al., 1988).

Activities along faults within the Thomson Orogen may reflect multiple phases of deformation and fault reactivation. Unfortunately, the timing and deformation of these structures are poorly constrained. The thick accumulation of Neoproterozoic to Paleozoic sedimentary rocks in the Thomson Orogen may suggest an early initiation of the boundary fault, possibly during the Neoproterozoic breakup of Rodinia. However, in the central Thomson Orogen, synkinematic packages within fault-bounded grabens, which correspond to the Early Devonian Gumbardo Formation (Draper, 2006; McKillop et al., 2005), indicate a significant amount of extension during the Early Devonian. A Devonian to Early Carboniferous synrift package has also been interpreted along the shallow seismic transect (Figure 5) in the Drummond Basin.

Reverse faults interpreted along the western part of the central Thomson Orogen (BMR 80-01; Figure 4c) show offset at the top of nonreflective crust and overlying parallel reflectors that correspond to Permian to Middle Triassic sedimentary units of approximately uniform thickness. These minor reverse faults were therefore active after the deposition of the Permian to Middle Triassic sedimentary package and were possibly linked to younger orogenic events, such as the last stage of the Permian-Triassic Hunter-Bower Orogeny (Holcombe et al., 1997; Hoy & Rosenbaum, 2017).

5.2. Structure and Kinematics of the Northeastern and Southern Margins of the Thomson Orogen

Interpretation of the seismic transect across the northeastern Thomson Orogen shows that the lower crust is extended (Figure 6d). However, at a shallower depth, major faults have a complex kinematic relationship. Based on the interpretation of aeromagnetic images (Figures 6 and 7), it appears that many of these faults had a strike-slip component with evidence for both sinistral and dextral kinematics. In the Charters Towers Province, E-W trending faults (Policeman Fault Zone and Clarke River Fault) show evidence for sinistral strike-slip movement, whereas in the Greenvale Province, ~NE trending faults (Halls Reward and Jessey Springs-Lockup Well faults) show evidence for dextral kinematics (Figures 6 and 7).

Constraints on the timing of fault movement are limited; however, dragging and sigmoidal-shaped magnetized bodies that correspond to the Silurian-Devonian Reedy Springs Batholith provide a minimum age constraint for the ~E-W sinistral shearing in the northeastern Thomson Orogen (Figure 7). Structural interpretation of the Belyando and Burdekin basins (Figures 5 and 6a and 6d) indicates that extensional faults were likely active during the Devonian.

The aeromagnetic data from the southern Thomson Orogen (Figure 8) show that curvilinear E-W trending structures correspond to relatively long wavelength linear geophysical anomalies (Abdullah & Rosenbaum, 2017). The kinematic analysis indicates a dominantly dextral strike-slip and transpressional movement along these faults (Abdullah & Rosenbaum, 2017; Dunstan et al., 2016), and the structural relationships indicate multiphase reactivation history, with possible deformation during the Benambran (Late Ordovician to Middle Silurian) and Tabberabberan (late Early to Middle Devonian) orogenies (Abdullah & Rosenbaum, 2017).

5.3. Geodynamic Implications

Results of this study highlight three important issues: (1) the possibility that a large-scale orocline is defined by the structure of the Thomson-Delamerian belt, (2) the role of Devonian crustal stretching in the northern Tasmanides, and (3) the kinematics of orogen-perpendicular structures. As discussed below, these findings may have important implications for the geodynamic evolution of eastern Gondwana.

The possible existence of the *Delamerian-Thomson Orocline* (Figure 9a) has been proposed by Rosenbaum (2018) based on the fact that rocks from both the southwestern Tasmanides (Delamerian Orogen, including the Koonenberry Belt) and northeastern Tasmanides (e.g., Anakie, Charters Towers and Greenvale provinces) experienced deformation and metamorphism during the Cambrian Delamerian Orogeny (Foden et al., 2006; Nishiya et al., 2003; Withnall et al., 1996). It is unknown whether or not these two segments are connected (e.g., through an ~E-W *Delamerian* basement underlying the southern Thomson Orogen), and additional kinematic data (e.g., from paleomagnetic studies) are needed in order to test whether, for example, the Koonenberry Belt and Anakie Inlier represent displaced segments of an originally continuous belt (Figure 9b). In any case, the recognition of a large-scale curvature in the Thomson-Delamerian belt (Figure 9a) raises questions about the mechanisms that could have led to this oroclinal bend.

In modern geodynamic settings, the process of oroclinal bending has predominantly been attributed to indentation, plate boundary migration (i.e., trench retreat or advance), and slab tearing (Rosenbaum, 2014, and reference therein). Analogue and numerical experiments have demonstrated that convergent plate boundaries can become progressively curved and/or segmented in response to along-strike variations in the nature of the oceanic subducting plate or the arrival of continental lithosphere at the subduction zone

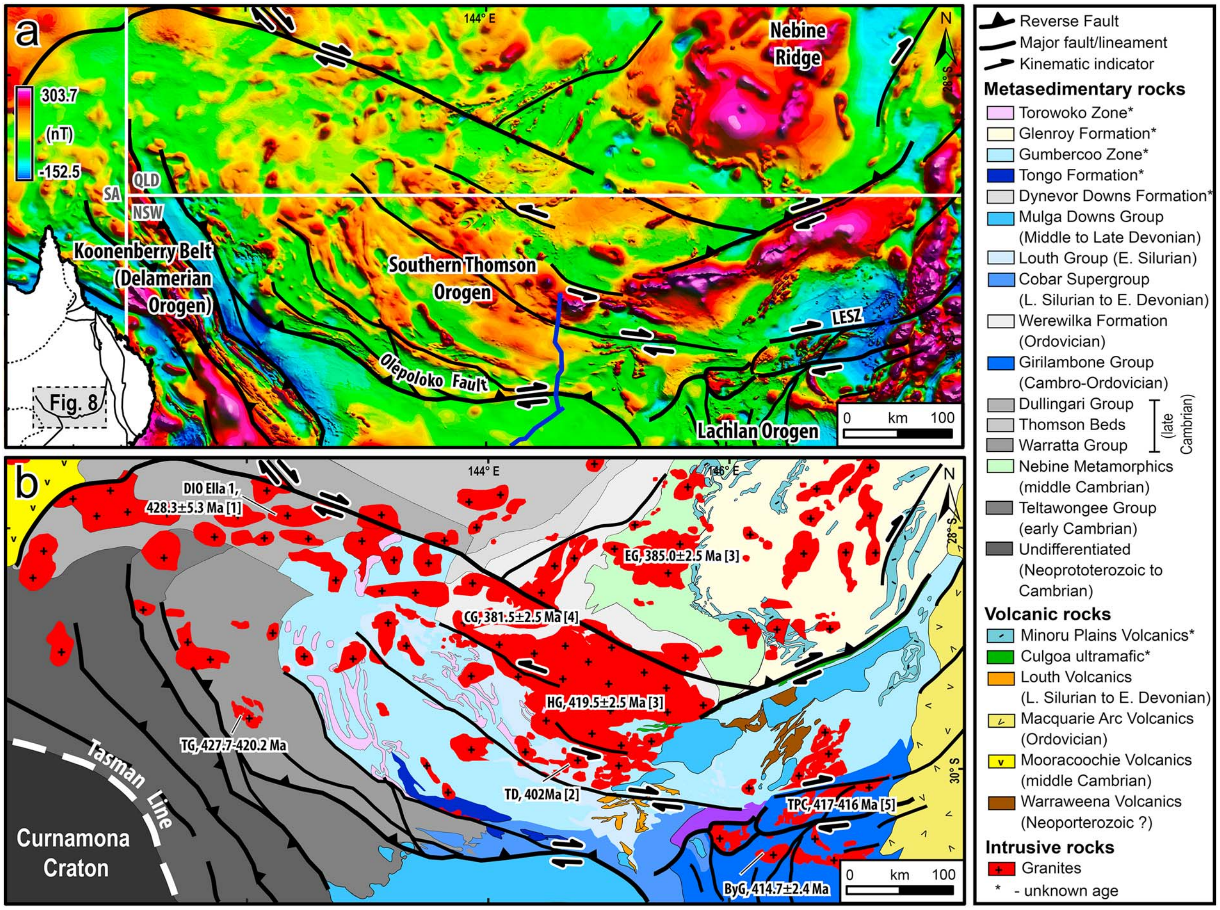

Figure 8. (a) Pseudocolour RTP aeromagnetic image and (b) interpreted solid geology map of the southern Thomson Orogen with structural interpretation (after Abdullah & Rosenbaum, 2017; Purdy et al., 2018). The blue lines represent the location of deep seismic transects 05GATL 1 and 05GATL 2 (shown in Figure 1d). Data sources: 1. Draper (2006), 2. Bodorkis et al. (2013), 3. Bultitude and Cross (2012), 4. Cross et al. (2015), and 5. Fraser et al. (2014). (Abbreviation: ByG, Byrock Granite; CG, Currawinya Granite; EG, Eulo Granite; HG, Hungerford Granite; LESZ, Louth-Eumarra Shear Zone; TD, Tinchelooka Diorite; TG, Tibooburra Granite; TPC, Tarcoon Plutonic Complex).

(Boutelier & Cruden, 2013; Capitanio et al., 2015; Li et al., 2013; Morra et al., 2006; Schellart & Lister, 2004). The overriding plate response to this process is associated with vertical-axis block rotations and oroclinal bending (Bajolet et al., 2013; Capitanio, 2014). In the southern Tasmanides, Moresi et al. (2014) have proposed such a model to explain oroclinal bending during the Silurian (Lachlan Orocline), in response to the combination of trench retreat and indentation (VanDieland microcontinent; Cayley et al., 2011).

In the Thomson-Delamerian Orocline, there is no evidence that indentation played a role during oroclinal bending. However, the recognition of widespread Devonian crustal stretching in the central part of the Thomson Orogen (Figures 4 and 5) may suggest that this area was subjected to back-arc extension in response to trench retreat (Figures 9c and 9d). This area was devoid of Middle Devonian contractional deformation (Tabberabberan Orogeny), which affected large parts of the southern Tasmanides (Fergusson, 2017; VanderBerg et al., 2000). We suggest that this large-scale strain partitioning, which possibly played an important role in the formation of the Delamerian-Thomson Orocline, was ultimately controlled by along-strike variations in the retreating subduction zone (Figure 9c).

Widespread latest Silurian to Devonian magmatism occurs in the northeastern and southern margins of the Thomson Orogen (Figure 9a). Based on structural mapping, kinematic analysis, and geophysical interpretation, it has been suggested that the southern boundary of the Thomson Orogen is a crustal-scale structure that accommodated dextral transpression during the Early Devonian (Abdullah & Rosenbaum, 2017; Dunstan et al., 2016). This Devonian dextral translation and contemporaneous magmatism along the boundary between the northern and southern Tasmanides can possibly be linked to the process of slab

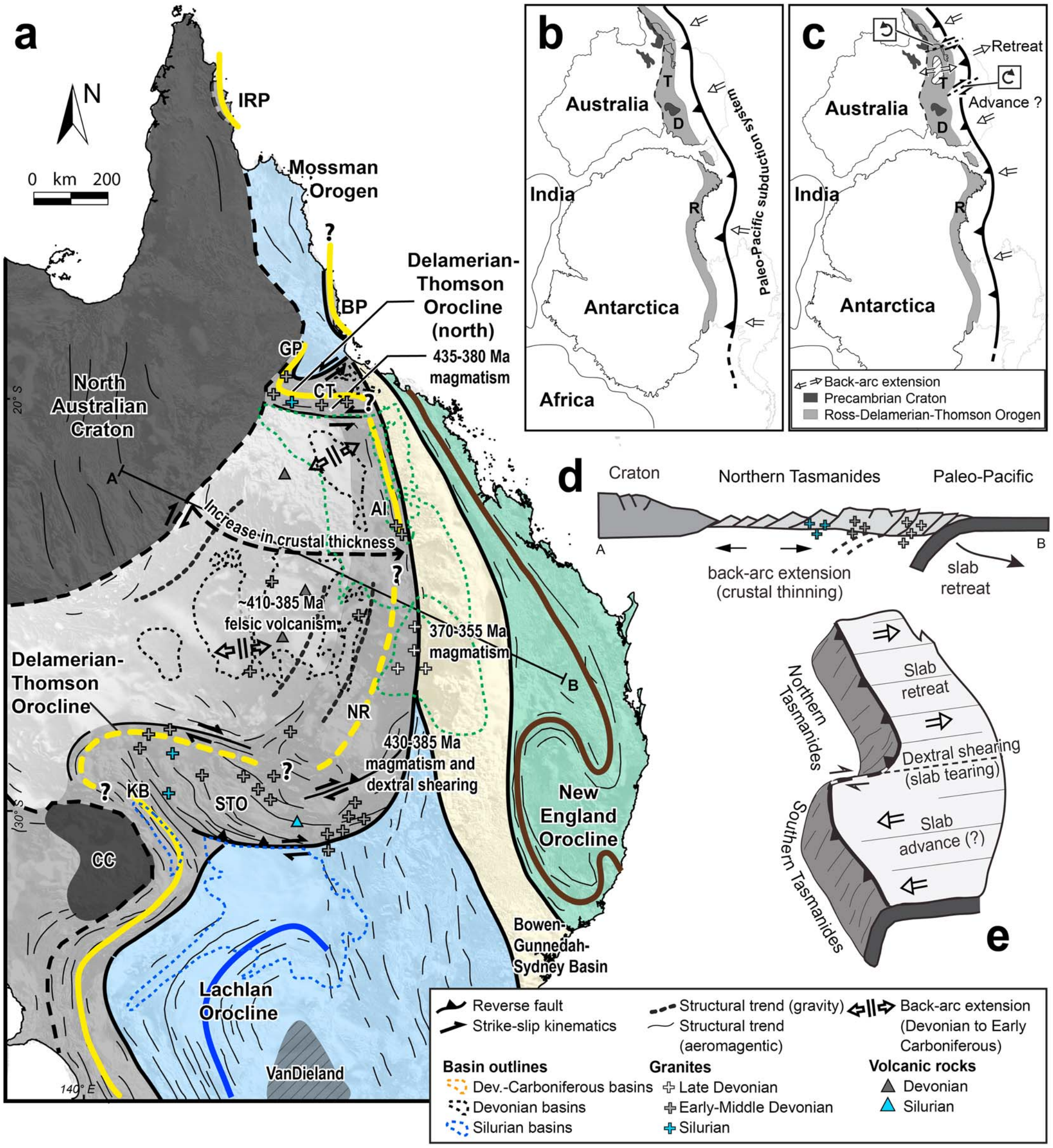

Figure 9. (a) Present day map of eastern Australia showing the inferred Delamerian-Thomson Orocline (yellow line) and evidence for crustal segmentation between the northern and southern Tasmanides. (b) Simplified ~500 Ma reconstruction of the Ross (R)-Delamerian (D)-Thomson (T) Orogen along the margin of eastern Gondwana. (c) Back-arc extension in the Thomson Orogen in response to the along-strike variations of the Devonian subduction system (slab advance and retreat), accompanied by dextral shearing at the southern boundary and sinistral shearing at the northern boundary of the Thomson Orogen. (d) A schematic section across the northern Tasmanides showing the development of west-dipping normal faults within the extended Thomson crust as a result of Devonian back-arc extension and subduction rollback. (e) Schematic 3-D model showing dextral shearing and crustal segmentation between the northern and southern Tasmanides in response to the along-strike variations of slab rollback. (Abbreviations: AI, Anakie Inlier; BP, Barnard Province; CC, Curnamona Craton; CT, Charters Towers Province; GP, Greenvale Province; IRP, Iron Range Province; KB, Koonenberry Belt; NR, Nebine Ridge; STO, Southern Thomson Orogen).

tearing and segmentation that accompanied the development of the Delamerian-Thomson Orocline (Rosenbaum, 2018; Figure 9a).

In the northeast Thomson Orogen (e.g., Charters Towers Province), ~E-W trending structures accommodated sinistral shearing (Figures 6 and 7). Similarly, it is possible that widespread latest Silurian to Devonian magmatism and sinistral shearing was driven by along-strike variations in trench retreat (Figure 9c), giving rise to plate boundary segmentation and oroclinal bending (Figure 9a). Limited paleomagnetic data from the Charters Towers is consistent with block rotations in the northeastern Thomson Orogen, possibly during the late Silurian to Devonian (Musgrave, 2015).

6. Conclusion

The crustal structure of the Thomson Orogen shows evidence for the occurrence of widespread extensional basins above a highly extended lower crust. These extensional basins are bounded by ~NNE trending faults. Devonian synkinematic packages within these basins indicate that the northern Tasmanides were subjected to extension during the Early Devonian. This phase of extensional deformation was coeval with dextral shearing and granitic magmatism along the boundary between the northern and southern Tasmanides. The age distribution of Devonian igneous rocks in the Thomson Orogen becomes younger toward the east, suggesting an eastward retreat of the plate boundary, which may have controlled crustal thinning and extensional faulting. The widespread distribution of Devonian granites and crustal-scale dextral strike-slip faulting at the boundary between the northern and southern Tasmanides may have accommodated the oroclinal bending of the Delamerian-Thomson Orogen in response to slab tearing and crustal segmentation.

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