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Late Cenozoic intraplate faulting in eastern Australia

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Abstract

The intensity and tectonic origin of late Cenozoic intraplate deformation in eastern Australia is relatively poorly understood. Here we show that Cenozoic volcanic rocks in southeast Queensland have been deformed by numerous faults. Using gridded aeromagnetic data and field observations, structural investigations were conducted on these faults. Results show that faults have mainly undergone strike-slip movement with a reverse component, displacing Cenozoic volcanic rocks ranging in ages from ~31 to ~21 Ma. These ages imply that faulting must have occurred after the late Oligocene. Late Cenozoic deformation has mostly occurred due to the reactivation of major faults, which were active during episodes of basin formation in the Jurassic-Early Cretaceous and later during the opening of the Tasman and Coral Seas from the Late Cretaceous to the early Eocene. The wrench reactivation of major faults in the late Cenozoic also gave rise to the occurrence of brittle subsidiary reverse strike-slip faults that affected Cenozoic volcanic rocks. Intraplate transpressional deformation possibly resulted from far-field stresses transmitted from the collisional zones at the northeast and southeast boundaries of the Australian plate during the late Oligocene-early Miocene and from the late Miocene to the
Pliocene. These events have resulted in the hitherto unrecognized reactivation of faults in eastern Australia.

Key words: Cenozoic volcanic rocks, strike-slip reverse faults, far-field stress, eastern Australia, passive margin, intraplate transpressional deformation

1. Introduction

Intraplate contractional or transpressional deformation is commonly attributed to compressional horizontal stress fields, which are transmitted from the plate boundaries and reactivating pre-existing faults in the plate interiors (Etheridge et al., 1991; Ziegler et al., 1995). The Australian plate, for example, is situated far from the plate boundaries (Figure 1a) and is commonly assumed to be a relatively stable continent. Nonetheless, there is widespread evidence that late Cenozoic intraplate transpressional deformation affected different parts of Australia, mainly through the reactivation of earlier faults (Keep et al., 2000; Dickinson et al., 2001; Sandiford, 2003b, a; Keep et al., 2007; Hillis et al., 2008). This intraplate deformation has been interpreted to result from the far-field stresses, which were transmitted from the Australian plate boundaries (Hillis et al., 2008; Muller et al., 2012).

One area where the role of late Cenozoic intraplate deformation is less understood is onshore eastern Australia. Major faults in this area have mainly affected late Paleozoic to early Mesozoic rock units (Figure 1b) (Holcombe et al., 1997b; Babaahmadi and Rosenbaum, 2014), but it is possible that a component of the observed deformation has taken place in the late Cenozoic. This problem can be addressed by focusing on mid-late Cenozoic volcanic rocks, which are widely...
exposed in eastern Australia (Wellman and McDougall, 1974; Cohen et al., 2007; Knesel et al., 2008; Vasconcelos et al., 2008). Therefore, the recognition of structural observations in these rocks provides an opportunity to investigate the kinematics and intensity of late Cenozoic deformation.

The aim of this paper is to investigate whether evidence for intraplate transpressional deformation is recorded in deformational features within Cenozoic volcanic rocks in eastern Australia. We focus on a number of fault systems in southeast Queensland, and use gridded aeromagnetic data and field observations to analyze the kinematics, magnitude and relative timing of deformation. Finally, we discuss our results in the context of the late Cenozoic geodynamic evolution of the Australian plate.

2. Geological Setting

The surface geology of southeast Queensland is dominated by Paleozoic-Mesozoic rock units, which are overlain by Cenozoic volcanic rocks (Figure 1b). The Paleozoic and early Mesozoic rocks belong to the New England Orogen (Figure 1b), and mainly consist of (1) Devonian-Carboniferous supra-subduction units (accretionary complex, fore-arc basin and magmatic arc) (Leitch, 1975; Day et al., 1978; Henderson et al., 1993; Holcombe et al., 1997a); (2) early Permian extensional-related sedimentary and magmatic rocks (Korsch et al., 2009a); and (3) Late Permian to Middle Triassic calcalkaline magmatic rocks. The latter formed during episodic contractional events, collectively referred to as the Hunter-Bowen phase, which was intermitted by an interval of back-arc extension in the Early to Middle Triassic that resulted in the formation of sedimentary basins (e.g., Esk Trough; Figure 1b) (Holcombe et al., 1997b; Li et al., 2012).
Late Triassic and younger sedimentary rocks have supposedly been deposited in post-orogenic localized rift basins (Korsch et al., 1989; Holcombe et al., 1997b). The Devonian-Carboniferous subduction-related elements are generally characterized by N- to NNW-strike orientations, but in the southern New England Orogen, the orogen is tightly curved forming an oroclinal structure (Cawood et al., 2011; Rosenbaum, 2012; Rosenbaum et al., 2012).

Late Triassic and younger sedimentary basins have developed in two major episodes. The earlier episode, which occurred in the early Late Triassic, was associated with a major rifting phase that led to the development of the Ipswich and Tarong Basins (Korsch et al., 1989; Holcombe et al., 1997b). Rifting involved bimodal volcanism in southeast Queensland (Holcombe et al., 1997b), accompanied by major normal faults (Babaahmadi and Rosenbaum, 2014). The second episode of basin formation, from the latest Late Triassic to the Early Cretaceous, was associated with thermal relaxation subsidence that gave rise to the development of the Clarence-Moreton, Surat and Maryborough Basins (Korsch et al., 1989; Hill, 1994; Holcombe et al., 1997b; Korsch and Totterdell, 2009). Subsequently, from the Late Cretaceous to the early Eocene, the eastern Australian margin was subject to continental fragmentation accompanying the opening of the Tasman and Coral Seas (Weissel and Watts, 1979; Gaina et al., 1998a; Gaina et al., 1998b).

Cenozoic intraplate volcanic rocks are distributed over 3000 km throughout the eastern Australian margin (Wellman and McDougall, 1974). This intraplate volcanism is subdivided into three types: central volcanoes, lava field provinces, and high potassium mafic areas (Wellman and McDougall, 1974). The central volcanoes are mostly basaltic but with some felsic lava flows and intrusions, constructing large volcanoes such as Tweed and Main Range (Figure 2) (Wellman and McDougall, 1974; Johnson, 1989). These spatio-temporal distribution of the central volcanoes has been attributed to the northward motion of the Australian plate over a
stationary hotspot(s) (Knesel et al., 2008). Lava field provinces are mostly composed of extensive and thin basaltic lavas, although in some locations their thickness reaches up to 1000 m (Wellman and McDougall, 1974). High potassium mafic areas are observed in central New South Wales as olivine leucitite (Wellman and McDougall, 1974).

In the study area in southeast Queensland (Figure 2), mafic and felsic Cenozoic volcanic rocks are mainly associated with large central volcanoes (Wellman and McDougall, 1974; Johnson, 1989). $^{40}$Ar/$^{39}$Ar ages of volcanic rocks from this region range from 31±0.8 Ma at Maleny in the north to 20.7±0.5 Ma at Main Range volcano in the south (Figure 2) (Cohen et al., 2007; Knesel et al., 2008).

3. Methods

Fault traces were detected using reduced-to-pole gridded aeromagnetic data, provided by Geoscience Australia. We operated a variety of filters in the Fourier domain to enhance short-wavelength and shallow sources, and to highlight magnetic lineaments such as the first vertical derivative and tilt angle derivative filters. The first vertical derivative (1VD) was operated to sharpen short-wavelength sources, and especially fault lineaments (Blakely, 1995). In particular, tilt angle 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 edges of magnetic sources and fault lineaments (Miller and Singh, 1994; Verduzco et al., 2004). The software Intrepid was used to process aeromagnetic data. The gridded aeromagnetic data allowed us to recognize (1) offset and dragging of magnetic anomalies along faults; (2) pronounced structural lineaments; and (3) lensoid and en-echelon structures.
Field work was conducted in accessible exposures of Cenozoic volcanic rocks with the aim of finding faults and their related kinematic indicators. Kinematic indicators used in this study include slickenlines, offset and dragged structures, and Riedel shears (R, P, and Y shears). In the absence of slickenlines, the indicators used to determine the hanging-wall movement in cataclastic fault zones were P-Y shears, which are equivalent to S-C fabrics in ductile shear zones (Doblas, 1998; Lin, 1999; Babaahmadi and Rosenbaum, 2013).

4. Faulting in Cenozoic volcanic rocks

Interpretation of tilt angle derivative of gridded aeromagnetic data indicates that Cenozoic and basement rocks are displaced by three major sets of faults striking (1) NNW to NW, (2) NNE to NE, and (3) N-S (Figure 3). The majority of the faults in southeast Queensland are NNW- to NW-striking sinistral faults, such as the North Pine Fault System (NPFS) and West Ipswich Fault System (WIFS) (Figure 3) (Cranfield et al., 1976; Babaahmadi and Rosenbaum, 2014). NNE- to NE-striking and N-striking faults are dextral (Babaahmadi and Rosenbaum, 2013, 2014) (Figure 3). Faults shown in Figure 3b are classified into three groups based on their inferred Cenozoic activity. Faults shown in black (Figure 3b) do not show evidence for Cenozoic activity. Faults shown in blue (e.g., WIFS, and several segments of the NPFS) do not cut Cenozoic volcanic rocks but have been inferred to have undergone Cenozoic movement based on geological and kinematic analyses, and geomorphological considerations (Cranfield et al., 1976; Hodgkinson et al., 2007; Babaahmadi and Rosenbaum, 2014). The distribution of earthquake epicenters along these major faults may also indicate recent faulting (Hodgkinson et al., 2006, 2007). Faults
shown in red in Figure 3b are those displacing Cenozoic volcanic rocks. Structural observations from these faults are presented below from four areas (Figure 2).

4.1. The Maleny area

Cenozoic volcanic rocks in the Maleny area comprise a succession of thin layered mafic lavas with a total thickness of 180 m (Cohen et al., 2007) (Figures 2, 4a). These rocks appear as small high-amplitude short-wavelength bodies in aeromagnetic data (dashed lines in Figure 4d). Deeper sources are probably related to Triassic volcanic and intrusive rocks and Paleozoic metasedimentary rocks (Figure 4a). Interpretation of the 1VD gridded aeromagnetic data indicates that magnetic anomalies related to Cenozoic volcanic rocks have been displaced by NNW-, NE-, and N-striking faults (Figures 4c, d). NNW-striking faults have dragged magnetic anomalies sinistrally, whereas the strike-slip separation of NE- and N-striking faults is dextral (based on dragging and offset of magnetic bodies; Figure 4d).

Field observations in the western part of the Maleny area show a number of NE-striking faults displacing Cenozoic mafic volcanic rocks (Figures 4a, b, 5). Stereographic analyses of P-Y structures indicate a reverse dextral kinematics for these faults (Figures 4b). Some of NE-striking reverse faults in Cenozoic basalts have been displaced by a younger set of reverse faults (red faults in Figure 5).

4.2. The Ipswich area
Relatively small patches of Cenozoic volcanic rocks are observed in the Ipswich area as some spotted short-wavelength low- and high-amplitude magnetic bodies, overlying Jurassic detrital sedimentary rocks of the Clarence-Moreton Basin (Figures 2, 3, 6a, and black dashed lines in Fig. 6d). Interpretation of the 1VD of gridded aeromagnetic data shows a NNW-striking high amplitude deep magnetic source interpreted as Paleozoic serpentinites which has been cut by a number of major faults such as the WIFS (Figures 3, 6 c, d). Evidence of faulting in Cenozoic volcanic rocks is observed along a NE-striking fault, known in this study as the Redbank Plains Fault (RPF) (Figure 6a-d).

Observations from the RPF show a contact of trachyte overlying basalt, and field evidence that both lithologies have been displaced by a steep, 10 m wide, strike-slip brittle fault zone (Figure 7a). Brittle movement along this fault has produced a volume of incohesive fault gouge (Figure 7b). Kinematic indicators, such as dextral Y and R shears and sinistral R’ shears in the fault zone; indicate a dextral strike-slip movement (Figures 6b, 7c, 8a-c). A minor steep reverse fault surface observed in the fault zone which is interpreted to be kinematically related to the strike-slip movement of the RPF (Figures 6b, 8d). We infer that the NE-striking RPF is an antithetic dextral fault associated with the reactivation of the WIFS during the late Cenozoic. The maximum age of deformation is constrained by $^{40}\text{Ar}/^{39}\text{Ar}$ geochronological data from a nearby outcrop (Figure 2), which indicate that the age of the trachyte is ~26.5 Ma (Cohen et al., 2007).

4.3. The South Ipswich area

In the South Ipswich area, Late Triassic-Jurassic sedimentary rocks are overlain by Cenozoic volcanic rocks (Figures 2, 9a). $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the volcanic rocks range from ~26 to ~23 Ma.
In the tilt angle map of the gridded aeromagnetic data, Cenozoic volcanic rocks appear as small irregular, curved, and short-wavelength bodies (black dashed lines in Figure 9d), which overlie magnetic bodies related to Paleozoic and Mesozoic rocks (Figures 9c, d). Cenozoic volcanic rocks have been displaced by a series of NNW-, N-, and NNE-striking faults (Figures 3, 9c, d). Dragging and offset of magnetic bodies (red dashed lines in Fig. 9d), show that the NNW-striking faults are sinistral and the NNE-striking faults are dextral (Figures 9c, d). In the west, a N-striking fault has dextrally separated a NNW-striking sinistral fault by ~4.8 km (Figures 9c, d). Another offset is observed to the east where a NE-striking fault has dextrally separated a magnetic body related to Cenozoic volcanic rocks by ~1 km (Figures 9c, d).

Field observations indicate that Cenozoic volcanic rocks have been cut by strike-slip reverse faults (Figures 9a-b; 10, 11a-c). A brittle WNW-striking reverse fault zone, in the eastern part of the area, was observed affecting volcanic rocks dated at ~23 Ma (Knesel et al., 2008) (Figures 9a; 10). In the southeastern part of the area, Cenozoic volcanic rocks have been displaced by a series of steep strike-slip reverse brittle faults (Figures 9a-b, 11a-c).

4.4. The Kingaroy area

In the Kingaroy area, widespread Cenozoic volcanic rocks overlie Paleozoic rocks, Permian-Triassic volcanic and intrusive rocks, and Jurassic sedimentary rocks (Figure 12a). Interpretation of a tilt map indicates that the area has mainly been deformed by NW-, N-, and NE-striking faults (Figures 12b, c). The NW- and NE-striking faults have dragged and separated Cenozoic volcanic rocks and older rocks sinistrally and dextrally, respectively (Figures 12b-c). Outcrop
conditions in this area are relatively poor, and our field observations are limited to one location (in a coal mine), where we observed a series of vertical faults affecting Cenozoic volcanic rocks (Figure 11d).

5. Discussion

5.1. Late Cenozoic faulting in the eastern Australian passive margin

Our observations provide evidence for late Cenozoic deformation in eastern Australia. Within this passive margin, there are a series of major faults that mainly affected Paleozoic and Mesozoic rock units (Babaahmadi and Rosenbaum, 2013, 2014). Many of these structures operated as major tectonic boundaries during the formation of the New England Orogen (Murray et al., 1987; Holcombe et al., 1997b; Li et al., 2012). They include NW- and NNW-striking sinistral faults, such as the NPFS and WIFS, and N- and NE-striking dextral faults such as the Demon Fault (Babaahmadi and Rosenbaum, 2013, 2014) (Figures 1, 3). Interpretation of aeromagnetic data indicates that some of these faults have been reactivated and also affected Cenozoic volcanic rocks (Figure 3). Most faults show evidence for a major strike-slip movement and a minor reverse component (Babaahmadi and Rosenbaum, 2013, 2014). These faults have possibly had a significant role in shaping the post-Late Triassic crustal structure of eastern Australia. Notable examples of these post-Late Triassic faults are the NPFS and Demon Fault, which record maximum strike-slip separations of ~8.2 km and ~35 km, respectively (Babaahmadi and Rosenbaum, 2013, 2014).

The major faults discussed above have been reactivated intermittently since the post-Late Triassic. They played an important role in the development of sedimentary basins, such as the
Clarence-Moreton and Maryborough Basins, and the geodynamic evolution of eastern Australia during the Jurassic and Early Cretaceous (Hill, 1994; Holcombe et al., 1997b; Babaahmadi and Rosenbaum, 2013, 2014). Geochronology of fault gouges in the Sydney Basin supports a Jurassic-Early Cretaceous age of brittle faulting (166-119 Ma), followed by a subsequent thermal event associated with the emplacement of magmas in the early stage of break-up of the eastern Gondawana margin (Och et al., 2014). In addition, it has been suggested that Early Cretaceous extensional faulting occurred simultaneously with volcanic activity in central Queensland (Bryan et al. (2000).

The Jurassic-Early Cretaceous sedimentary rocks in the Clarence-Moreton and Maryborough Basins have been folded and displaced by the reactivation of major faults with reverse components (Hill, 1994; Holcombe et al., 1997b). The origin of these contractional structures was likely related either to a mid-Cretaceous contractional event (Hill, 1994; Korsch et al., 2009b), possibly associated with a lithospheric rebound following subduction cessation (Korsch et al., 2009b), or to the far-field stress fields transmitted from the late Eocene to early Oligocene ophiolite obduction in New Caledonia (Babaahmadi and Rosenbaum, 2014).

Babaahmadi and Rosenbaum (2014) suggested that major faults in eastern Australia were active as strike-slip normal faults in response to the oblique opening of the Tasman and Coral Seas from the Late Cretaceous to the early Eocene. Evidence of such activity is the development of Eocene sedimentary basins, such as the Duaringa and Hillsborough Basins, which developed over NNW-striking steep normal faults and have a maximum depth of 1.3 km (Gray, 1976; Gibson, 1989). Results of this study and previous studies (Babaahmadi and Rosenbaum, 2013, 2014) indicate that several major faults have further been reactivated in the late Cenozoic, displacing the Cenozoic volcanic rocks (Figure 3). Our field observations indicate that the
wrench reactivation of major faults in the late Cenozoic gave rise to the occurrence of brittle subsidiary strike-slip and reverse faults (Figures 7, 8, 10, 11).

The exact timing of faulting is not precisely constrained, but the fact that brittle faults displaced Cenozoic volcanic rocks can provide a maximum age constraint for deformation. \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of the deformed volcanic rocks in southeast Queensland range from \(\sim 31\pm0.8\) Ma at Maleny to \(\sim 20.7\pm0.5\) Ma at the Main Range volcano (Cohen et al., 2007; Knesel et al., 2008) (Figure 2). Therefore, the timing of faulting in the Maleny area must be younger than \(\sim 31\) Ma. Moreover, our results show that two phases of faulting have occurred in this area (Figure 5). In the Ipswich area, brittle deformation along the RPF affected a \(\sim 26.5\) Ma trachyte (Figures 6-8), indicating that the activity of the fault is younger than this age. Similarly, considering that the age of the volcanic rocks at the Main Range volcano is \(20.7\pm0.5\) Ma (Figure 3), faulting in this area must have occurred after the early Miocene.

5.2. Origin of late Cenozoic transpressional deformation

Results of this study and other investigations imply that steeply dipping faults in eastern Australia accommodated intraplate transpressional deformation during the late Cenozoic (Babaahmadi and Rosenbaum, 2014). Most of the faults that affected Cenozoic volcanic rocks in the study area have experienced a major strike-slip movement. In addition, kinematic analysis of some of these faults shows that they have a reverse component (Figures 9, 10). Similar reverse strike-slip kinematics is also observed along the NNW-striking NPFS, which displaced Cenozoic volcanic rocks (Babaahmadi and Rosenbaum, 2014). Moreover, faulting and folding have been reported in Cenozoic sedimentary rocks of the Hillsborough, Capel and Faust Basins, and central
Lord Howe Rise (Figure 1a) (Clarke et al., 1971; Gray, 1976; Willcox and Sayers, 2002; Colwell et al., 2010).

We propose that the origin of late Cenozoic intraplate transpressional tectonics in eastern Australia was the far-field compressional horizontal stress fields ($S_{\text{Hmax}}$) transmitted from the plate boundaries. These compressional stress fields were likely intensified during two major collisional events that occurred (1) from the late Oligocene to the early Miocene; and (2) from the late Miocene to the Pliocene.

The earlier phase of deformation, in the late Oligocene-early Miocene, may have been triggered by contractional events along the northeast and southeast boundaries of the Australian plate. These included (1) the initiation of oblique convergence between the Melanesian arc system and the Ontong Java Plateau (OJP) (Petterson et al., 1997; Petterson et al., 1999); (2) arc-continent collision at the northern margin of New Guinea (Hall, 2002; Hill and Hall, 2003); and (3) ophiolite obduction (Schellart, 2007) and the inception of highly oblique convergence in New Zealand (Kamp, 1986; Schellart et al., 2006). The response of the Australian continent to the OJP oblique collision may have resulted in an abrupt deceleration of the Australian plate motion at ~26-23 Ma, as indicated by the spatio-temporal distribution of hotspot-related volcanic rocks in southeast Queensland (Knesel et al., 2008; Cohen et al., 2013). Similarly, the onset of oblique convergence along the northeastern boundary of Australian plate resulted in a westward offset in Cenozoic seamount chains in the Tasman Sea (Knesel et al., 2008; Cohen et al., 2013), possibly due to a possible E-W direction of $S_{\text{Hmax}}$. A numerical paleostress model of the early Miocene shows a dominant ~WNW-ESE direction of $S_{\text{Hmax}}$ over southeast Queensland at that time (Dyksterhuis et al., 2005; Muller et al., 2012), possibly as a result of obduction and collision in New Zealand (Figures 13a,b). Consequently, the geometry and kinematics of fault systems in...
southeast Queensland are generally consistent with both inferred E-W and WNW-ESE $S_{H_{\text{max}}}$. In detail, however, the inferred WNW-ESE orientation of $S_{H_{\text{max}}}$ in southeast Queensland was oblique to major faults during the late Oligocene-early Miocene, and could have produced and reactivated NW- to NNE-striking reverse sinistral faults, and NNE- to NE-striking reverse and reverse dextral faults (Figures 13a, e). Nonetheless, there is no evidence for sinistral movements along N- and NNE-striking faults (Figure 13e). The inferred E-W $S_{H_{\text{max}}}$ could account for reverse sinistral movement along NNW- to NW-striking faults, reverse movement along N-striking faults, and reverse dextral kinematics of NNE- to N-E-striking faults (Figure 13e).

The second stage of compression, from the late Miocene to the Pliocene, could be attributed to a series of successive collisional events that occurred along the northeast and southeast margins of the Australian plate. These events include (1) a sinistral oblique arc-continent collision at the northern margin of New Guinea since the late Miocene (Hill and Raza, 1999; Hill and Hall, 2003); (2) a strong sinistral oblique collision between the Melanesian arc system and the Ontong Java Plateau (OJP) in the Pliocene (Petterson et al., 1997; Petterson et al., 1999); and (3) the kinematic change from strike-slip to transpression in the South Island of New Zealand since ~6.4 Ma (Walcott, 1998) (Figures 13c,d). The modeled paleostress maps show ENE-WSW and WNW-ESE $S_{H_{\text{max}}}$ directions in southeast Queensland in the late Miocene and the Pliocene, respectively (Muller et al., 2012) (Figures 13c,d). The ENE-WSW $S_{H_{\text{max}}}$ in the late Miocene could possibly result in NW-striking reverse sinistral faults, NNW-striking reverse faults, and N- to NE-striking reverse dextral faults (Figure 13f). The WNW-ESE $S_{H_{\text{max}}}$ during the Pliocene could have reactivated NW- and NNW-striking reverse sinistral faults, and NNE- to NE-striking reverse and reverse dextral faults, respectively (Figure 13g).
6. Conclusions

We used gridded aeromagnetic data and field observations to study intraplate deformation in Cenozoic volcanic rocks in southeast Queensland. Our results indicate that Cenozoic volcanic rocks have been displaced by reverse strike-slip faults. Late Cenozoic deformation has mostly taken place due to the reactivation of major faults, which are interpreted to have been active during episodes of basin formation in the Jurassic-Early Cretaceous and later during the opening of the Tasman and Coral Seas in the Late Cretaceous to early Eocene. Faulted Cenozoic volcanic rocks in southeast Queensland range in ages from $31\pm0.8$ to $20.7\pm0.5$ Ma, indicating that the recent phases of faulting in eastern Australia have occurred since the late Oligocene. This intraplate transpressional deformation is construed to be related to far-field stress fields transmitted from collisional events at the northeast and southeast Australian plate boundaries, which were likely intensified during major collisional events during the late Oligocene-early Miocene and the late Miocene-Pliocene.

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Figures

Figure 1. (a) ETOPO1 digital elevation model of the Australian and Pacific plates (Amante and Eakins, 2009), and a simplified tectonic framework showing Mesozoic sedimentary basins in eastern Australia. CMB, Clarence-Moreton Basin; CB, Caledonia Basin; CB, Capricorn Basin; CFB, Capel and Faust basins; CT, Cato Trough; DB, Duaringa Basin; HB, Hillsborough Basin; LB, Laura Basin; LHR, Lord Howe Rise; MB, Maryborough Basin; MP, Marion Plateau; NB, Nambour Basin; NCB, New Caledonia Basin; NC, New Caledonia; OJP, Ontong Java Plateau; QP, Queensland Plateau; SB, Surat Basin; TB, Townsville Basin. (b) Simplified regional tectonic elements of eastern Australia. DF, Demon Fault; ET, Esk Trough; NPFS, North Pine Fault System.

Figure 2. Simplified geological map of the study area based on the 1:500,000 Moreton Geology map (Green et al., 1980). Numbers indicate $^{40}$Ar/$^{39}$Ar ages of volcanic rocks in Ma (Cohen et al., 2007; Knesel et al., 2008). NPFS, North Pine Fault System; WIFS, Western Ipswich Fault.

Figure 3. (a) Tilt angle derivative of gridded aeromagnetic data of southeast Queensland. (b) Interpreted major faults and their kinematics. Black lineaments are faults on which there is no evidence of Cenozoic activity, whereas blue lineaments are faults that have been inferred to have Cenozoic activity but have not cut Cenozoic volcanic rocks. Red lineaments are faults that have affected Cenozoic volcanic rocks. Dashed lines indicate the magnetic bodies related to Cenozoic volcanic rocks. (c) Rose diagram of fault lineaments in southeast Queensland.

Figure 4. (a) Geological map of the Maleny area (after Green et al., 1980) (see Figure 2 for location). (b) Lower-hemisphere equal-area stereographic projection of fault surfaces and their kinematics. (c) The 1VD of gridded aeromagnetic data from the Maleny area, and (d) interpreted
faults. Black dashed lines indicate magnetic bodies related to Cenozoic volcanic rocks; yellow dashed lines and pink areas show dragged and separated magnetic bodies, respectively.

Figure 5. (a-b) NE-striking dextral reverse faults, shown in black, displacing Cenozoic basalts. These faults have been displaced by younger NE-striking reverse dextral faults, shown in red (see Figure 4a for location); Pink areas mark a large separated volcanic fragment and lensoid structures (X: 152°48’, Y: -26°41’). (c-e) Restoration of separated volcanic rocks along two NNE- and NE-striking faults, indicating two possible phases of faulting; Pink areas mark a separated volcanic bomb by older NE-striking thrust fault.

Figure 6. (a) Geological map of the Ipswich area showing the location of the RPF (see Figure 2 for location). (b) Lower hemisphere equal-area stereographic projection of Riedel shear system within the RPF zone. (c) The 1VD of gridded aeromagnetic data of the Ipswich area. (d) Interpretation of the aeromagnetic data showing the WIFS and RPF. Black dashed lines indicate magnetic bodies related to Cenozoic volcanic rocks. Red line shows dragging of magnetic body along the RPF.

Figure 7. (a) The NE-striking dextral RPF, deforming Cenozoic trachyte and basalts (see Figure 6a for location) (X: 152°52’, Y: -27°39’). (b) Fault gouge developed in the RPF zone. (c) A minor NNW-striking fault (R’ shear) that displaced the main fault sinistrally.

Figure 8. Field photographs of the brittle RPF zone (see Figure 7a for locations) showing (a) dextral R and Y shears, (b) dextral dragging of a vein in the RPF zone, (c) dextral displacement of Y shears by an R shear, and (d) a small fault slickenside indicating a vertical reverse movement.
Figure 9. (a) Geological map of the south Ipswich area (see Figure 2 for location); (b-c) Lower-hemisphere equal-area stereographic projection of fault surfaces and their kinematics. (d) Tilt angle derivative of gridded aeromagnetic data of the South Ipswich area. (e) Interpreted faults. Black dashed line indicates magnetic bodies related to Cenozoic volcanic rocks; red dashed lines and yellow-black arrows show fault-related dragging shapes in magnetic bodies.

Figure 10. (a-c) Reverse brittle fault zone, displacing Cenozoic basalts (see Figure 9a for location) (X: 153º06', Y: -28º04').

Figure 11. (a) Minor faults displacing Cenozoic volcanic rocks (see Figure 9a for location) (X: 152º58', Y: -28º20'). (b-c) A steep reverse fault truncating Cenozoic volcanic rocks; (d) A series of parallel N-striking dextral vertical faults displacing Cenozoic basalts (see Figure 12a for location) (X: 151º54', Y: -26º54').

Figure 12. (a) Geological map of the Kingaroy area (see Figure 2 for location). (b) Tilt angle derivative of gridded aeromagnetic data of the Kingaroy area. (c) Interpreted faults and their kinematics. Black dashed lines indicate magnetic bodies related to Cenozoic volcanic rocks. Red dashed lines and yellow-black arrows show fault-related dragging and lensoid shapes in magnetic bodies.

Figure 13. (a-d) Schematic tectonic evolution of the northeast and southeast Australian margins based on models by Hall (2002) and Schellart (2006) during the (a) late Oligocene, (b) early Miocene, (c) late Miocene, and (d) the Pliocene. Blue arrows indicate possible \( S_{H\text{max}} \) directions at these times in southeast Queensland (Muller et al., 2012). Red arrow in (a) indicates an inferred E-W \( S_{H\text{max}} \) from collisional zones at the northeast Australian margin; (e-f) Schematic structural model for the reactivation of faults in response to the modeled \( S_{H\text{max}} \) (Muller et al., 2012) since
the late Oligocene. Red arrows in (e) indicate an inferred E-W $S_{H\text{max}}$. For fault strikes marked by question marks, there is no evidence for such kinematics.
Highlights

2. This intraplate deformation has taken place since the late Oligocene.
3. This young deformation is a substantial revision of previous literature.
4. This deformation occurred due to far-field stress from distant plate boundaries.