

Repeated failure: long-lived faults in the eastern Musgrave Province

Mark J Pawley, Rian A Dutch, Mario Werner and Carmen BE Krapf
Geological Survey of South Australia, Department of State Development

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Introduction

Aeromagnetic images of the Musgrave Province are characterised by a series of laterally continuous, approximately east–west-striking, magnetically low lineaments (Fig. 1), which have been interpreted as faults (Major and Connor 1993). These structures have been divided into two main types: divergent thrusts that occur closer to the boundaries of the province, e.g. the Woodroffe and Everard thrusts, and steeper, strike-slip structures that are generally found along the axial core of the province, e.g. the Mann, Echo, De Rose and Wintiginna faults (Fig. 1; Aitken et al. 2009; Korsch and Kositsin 2010; Lambeck and Burgess 1992).

The east–west-trending faults appear to have a complex history, with movement interpreted to have occurred at different times. In the western part of the

province, east–west faulting is interpreted to have accompanied the c. 1085–1040 Ma Giles Event (Coleman 2009; Glikson et al. 1996). However, most movement on these structures is interpreted to have occurred during the c. 600–530 Ma, dextral transpressional Petermann Orogeny, when pre-existing steeper structures were reactivated and the thrusts formed. This resulted in a crustal-scale flower structure that exhumed high-grade rocks in the core of the orogeny, and the development of pull-apart basins (Fig. 2; Aitken and Betts 2009; Aitken et al. 2009; Camacho et al. 1997; Camacho and McDougall 2000; Edgoose, Scrimgeour and Close 2004; Hand and Sandiford 1999; Lambeck and Burgess 1992). The faults are also interpreted to have been reactivated during the c. 450–300 Ma Alice Springs Orogeny, with fluid flow resulting in local epidote and silica alteration (Connor et al. 2006).

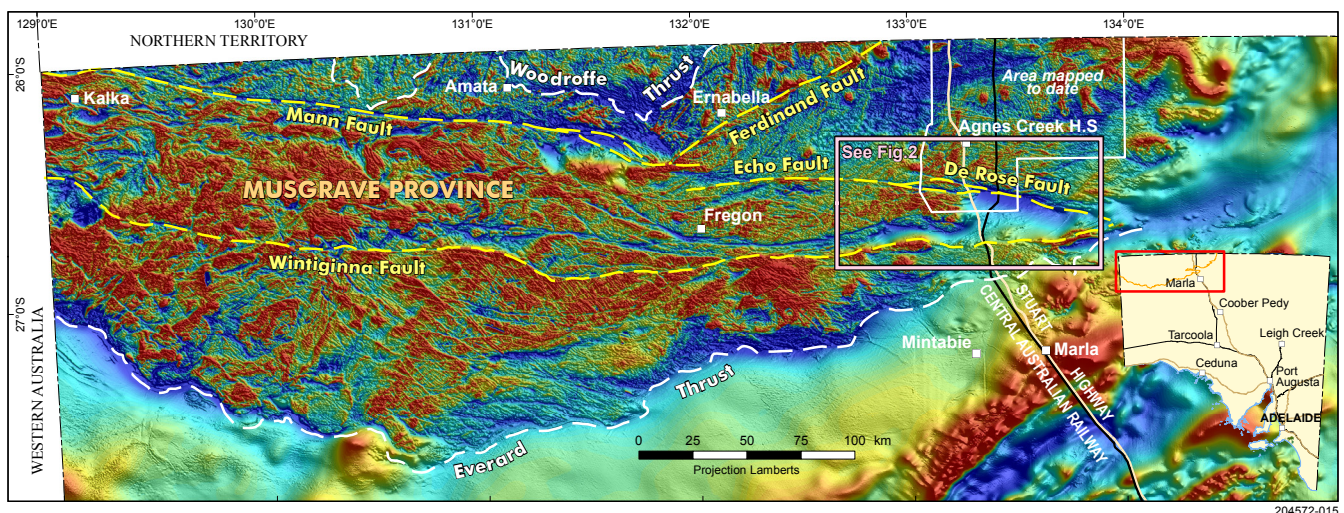


Figure 1 Total magnetic intensity reduced to the pole (TMI-RTP) image of the South Australian portion of the Musgrave Province showing some of the prominent, laterally continuous, east-striking, magnetically low lineaments that correspond to faults. The yellow dashed lines are the steep structures and the white dashed lines are shallower thrusts. The white box shows the area that has been mapped so far during the current Geological Survey of South Australia program.

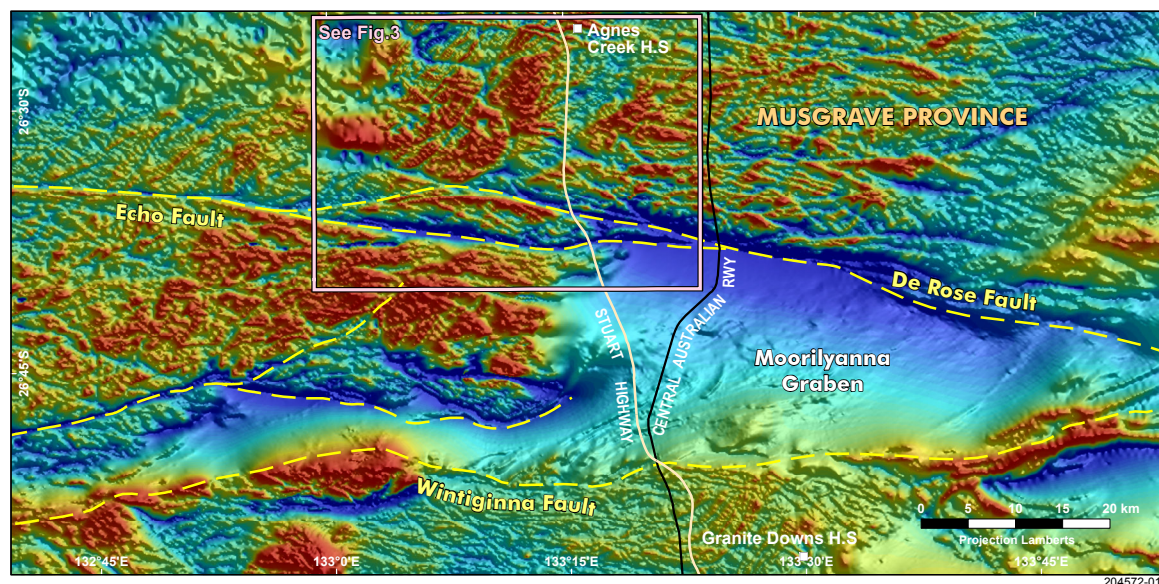


Figure 2 TMI RTP image showing the step-over between the overlapping De Rose and Echo faults, and the Moorilyanna Graben, which both have a geometry that suggests an apparent dextral sense of shear.

Recent mapping from the eastern Musgrave Province¹ provides evidence for multiple reactivation of the Echo – De Rose fault system which lies along the core of the orogen (Fig. 1). The new observations provide information about several different deformation events, as well as time constraints on the development of the crustal architecture. The observations also suggest that these structures channelled several stages of fluid flow. In particular, they appear to have influenced the ascent of mafic magmas which is relevant for Ni–Cu sulfide exploration in the region.

Geological setting and previous work

The eastern Musgrave Province predominantly comprises c. 1680–1550 Ma magmatic arc rocks (Dutch et al. 2013; Smits et al. 2014; Wade et al. 2006) that were deformed during the c. 1220–1120 Ma Musgravian Orogeny (Edgoose, Scrimgeour and Close 2004; Jagodzinski and Dutch 2013; Major and Conor 1993; Smithies et al. 2010). The Musgravian Orogeny was a regional amphibolite to granulite facies metamorphic event that resulted in partial melting of the protoliths in the eastern Musgrave Province to form the gneisses of the Birksgate Complex (Major and Conor 1993; Walsh et al. in press). The gneissosity in the eastern part of the province is generally north-northeast-striking, which in conjunction with intrafolial folds and melt-filled shear bands, suggests the area underwent east-southeast to west-northwest-directed

shortening during the Musgravian Orogeny (Pawley et al. 2013; Reid et al. 2013).

The Musgravian Orogeny was accompanied by intrusion of the c. 1200–1140 Ma, anhydrous, charnockite series Pitjantjatjara Supersuite (Camacho and Fanning 1995; Smithies et al. 2010). Based on aeromagnetic data, Aitken and Betts (2008) recognised a northeast-trending grain in the Musgravian Orogeny that was interpreted to represent a northeast-trending orogenic belt. However, despite these interpretations there is still uncertainty about the tectonic setting of the Musgravian Orogeny. Based on the long-lived, widespread nature of the event, and the high-temperature granites of the Pitjantjatjara Supersuite, it is considered to have been associated with extension and/or upwelling in an intracontinental setting (Smithies et al. 2010; Smithies et al. 2011; Walsh et al. in press). Alternatively, based on work from the western end of the province, it has been interpreted to represent an ultra-hot orogen that initiated in the back-arc region of the Mount West Orogeny (Smithies et al. 2013).

These rocks were subsequently intruded and overlain by c. 1085–1040 Ma rocks of the Giles Event (Edgoose, Scrimgeour and Close 2004; Glikson et al. 1996) which includes the variably deformed mafic-ultramafic layered intrusions of the Giles Complex, bimodal volcanics and associated rift sediments of the Bentley Supergroup (WA) and Tjauwata Group (NT, WA), the Alcurra Dolerite and minor granitic intrusions and felsic dykes (Howard et al. 2011). The Giles Event is interpreted to form part of the Warakurna large igneous province which affected much of central and western Australia (Wingate, Pirajno and Morris 2004).

¹ Undertaken as part of the 'Mapping the Musgrave Province' project funded through the PACE 2020 initiative, theme 1.1 Pathways to Prospectivity – New Frontier Mapping.

Giles Event aged deformation has been recognised in the western Musgrave Province, with Glikson et al. (1996) describing steep, southeast- to east-striking high-strain zones that were associated with uplift and erosion of more than 12 km of crust. Coleman (2009) also recognised steep, east-striking shear zones with vertical movement in the western Musgrave Province. The vertical movement is interpreted to have occurred after the intrusion of the layered mafic bodies of the Giles Complex, and resulted in the uplift and exposure of the mafic intrusive rocks before the eruption of c. 1070 Ma rhyolite flows of the lower Bentley Supergroup (Coleman 2009).

The eastern Musgrave Province was intruded by dykes of the c. 825–760 Ma Amata Dolerite (Dutch et al. 2013; Werner et al. 2014), which is a correlative of the Gairdner Dolerite that intrudes the Gawler Craton (Goode 1970; Wingate et al. 1998; Zhao, McCulloch and Korsch 1994).

The Musgrave Province was deformed by the Petermann Orogeny which has been constrained between 600 to 530 Ma (Camacho et al. 1997; Camacho and McDougall 2000; Raimondo et al. 2009; Raimondo et al. 2010; Scrimgeour and Close 1999; Wade, Hand and Barovich 2005). This is a major intracratonic event that resulted in the reactivation of several crustal-scale, east–west-trending shears and faults, and the formation of thrusts and widespread mylonitic shear fabrics. Divergent thrusting resulted in the uplift of the central axis of the Musgrave Province as a crustal-scale flower structure, and the exhumation of high-grade metamorphic rocks from beneath the Centralian Superbasin (Aitken and Betts 2009; Camacho et al. 1997; Camacho and McDougall 2000; Clarke et al. 1995; Edgoose, Scrimgeour and Close 2004; Hand and Sandiford 1999; Korsch et al. 1998; Lambeck and Burgess 1992; Raimondo et al. 2010; Zhao, McCulloch and Korsch 1994). Reactivation of the steep faults accommodated dextral strike-slip movement, which resulted in pull-apart basins, such as the Moorilyanna Graben near the eastern margin of the province (Fig. 2; Aitken et al. 2009; Lambeck and Burgess 1992). Localised partial melting is also interpreted to have occurred during the Petermann Orogeny, with anatexis restricted to between the Mann Fault and the Woodroffe Thrust in the central and western part of the province (Edgoose, Scrimgeour and Close 2004; Gregory et al. 2009; Raimondo et al. 2009; Raimondo et al. 2010; Scrimgeour and Close 1999; Walsh et al. 2013). Wade et al. (2008) proposed that the current east–west-striking structural architecture was established during the Petermann Orogeny with the exhumation of the high-grade rocks along the core of the province.

The De Rose and Echo fault system was active during the Petermann Orogeny (Scrimgeour and Close 1999), when it formed the northern boundary of the Moorilyanna Graben (Fig. 2). This is a strike-slip, pull-apart basin that was filled with clastic sediments of the Moorilyanna Formation (Gravestock et al. 1995; Preiss, Korsch and Carr 2010), with the overall geometry of the graben suggesting it formed during dextral strike-slip movement. Furthermore, it has been proposed that Petermann-aged displacement on the De Rose and Echo fault system dextrally deflected a northeast-trending grain on the aeromagnetic images (Fig. 3) which has been interpreted as the structural grain of the Musgravian Orogeny (Aitken and Betts 2008; Wade et al. 2008).

It is proposed that minor reactivation of some of the Petermann-aged structures near the southern margin of the Musgrave Province occurred during the Ordovician-aged Alice Springs Orogeny (Conor et al. 2006; Hand and Sandiford 1999; Hoskins and Lemon 1995; Korsch et al. 1998). Conor et al. (2006) observed that the Petermann-aged mylonites and pseudotachylites of the northeast-trending, sinistral Ferdinand Fault on the EATERINGINNA 1:100 000 map sheet (northwest of the current study area), were overprinted by epidote–quartz alteration, with fluid flow focused along the reactivated structures. Conor et al. (2006) also recognised a chlorite alteration that overprinted the epidote alteration in the Ferdinand Fault.

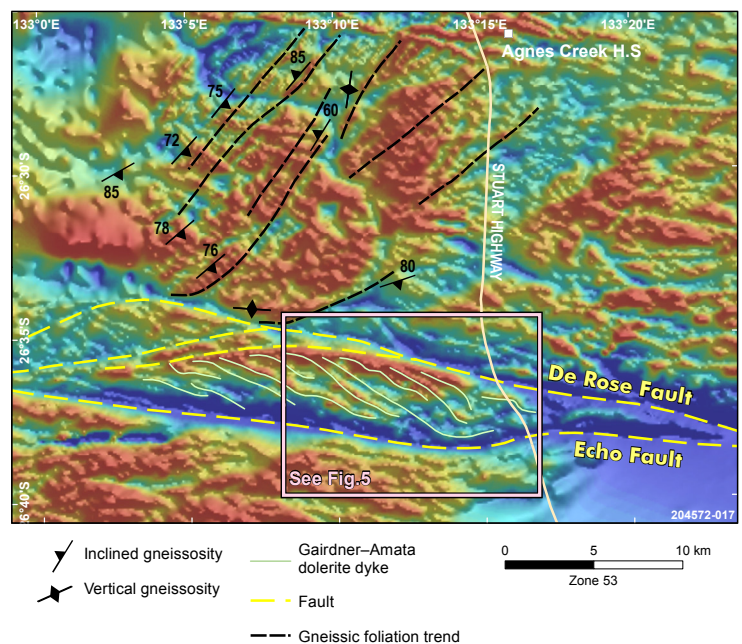


Figure 3 TMI RTP image showing the north-northeast-striking grain that corresponds with the gneissosity, which is dextrally deflected against the Echo Fault. The northeast-striking magnetic grain within the rhomboid corresponds to the sigmoidal dykes of the Gairdner–Amata dolerite.

New observations from recent mapping

De Rose and Echo fault system

The study area (Fig. 1), located at the eastern margin of the Musgrave Province, is crossed by the east–west-trending De Rose and Echo faults which are prominent on aeromagnetic images of the Musgrave Province (Figs 1, 2). The eastern De Rose Fault can be traced from the eastern margin of the province for almost 100 km. The western Echo Fault, which can be traced for about 150 km, is subparallel to, and located about 5 km to the south of the De Rose Fault. The two faults overlap for about 30 km, with their fault tips stepping across to merge and form an asymmetric rhomboid that has apparent dextral displacement (Fig. 2). Gneisses in the vicinity of the faults have undergone pervasive epidote and silica alteration (see below in the section on ‘Alteration and the fault zones’) that has destroyed most of the primary textures. Consequently, interpretations of their kinematic history are dependent on large-scale geophysical or external features, such as the geometry of the step-over, deflection of layering, and geometry of the synkinematic Moorilyanna Graben.

The new mapping indicates that the magnetic grain is similarly orientated to the foliation developed in the Birksgate Complex which is defined by a well-developed gneissosity with parallel leucosomes. Immediately north of the De Rose Fault, the gneissosity is steeply dipping and east- to northeast-striking, before curving to north-northeast-striking over a distance of about 10 km (Fig. 3). This implies

that dextral shearing occurred along the De Rose and Echo fault system after the development of a Musgravian-aged layering, although this could have occurred either late in the Musgravian Orogeny, or during a subsequent event.

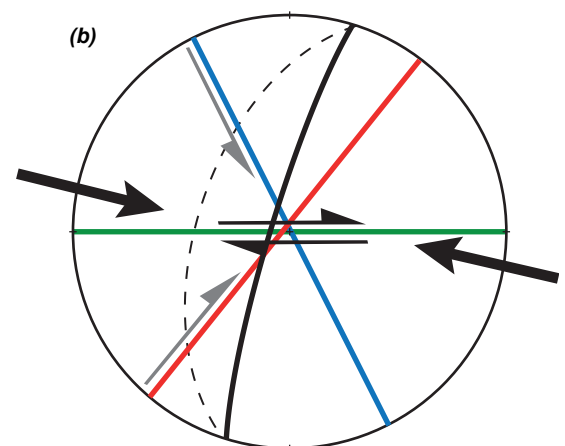
At one location, the north-northeast-striking gneissosity is cut at a high angle by a steep, east-striking, small-scale (<1 cm wide) dextral shear zone that deflects the layering (Fig. 4). The shear is filled with melt that is texturally continuous with the leucosomes parallel to the gneissosity, suggesting that it formed late in the Musgravian Orogeny, after the gneissosity and leucosomes had formed, but while a component of melt was still present in the rock. While this location was not sampled, nearby migmatitic gneisses that were analysed using the SHRIMP (sensitive high resolution ion microprobe) returned Musgravian metamorphic ages, with no evidence for younger zircon growth (Jagodzinski and Dutch 2013; Jagodzinski, Dutch and Reid in prep).

The principal stress axes responsible for the melt-filled dextral shear are consistent with the approximately west-northwest to east-southeast-directed shortening proposed for the Musgravian-aged structures in this area (Fig. 4b; Pawley et al. 2013; Reid et al. 2013). This could mean that after the formation of the widespread gneissosity under pure shear conditions, there was a switch to localised strain that was partitioned into the east-striking dextral shear zones. The switch in behaviour may reflect the change in rheology as the rocks cooled towards the end of the Musgravian Orogeny.



Photo 414234

Figure 4 (a) Narrow, east-trending, melt-filled, dextral shear zone that deflects the gneissosity. The tip of the scribe points towards the north. (Photo 414234) (b) Stereonet showing the geometric relationship between the proposed shortening direction during the Musgravian Orogeny (large black arrows), the early Musgravian-aged gneissosity and extensional shear bands that reflect pure shear conditions, and the overprinting melt-filled, dextral shear zone, which would be a late Musgravian structure.



Early Musgravian-aged structure

- Average gneissosity (n = 495)
- - Reverse shear band (n = 1)
- Average sinistral shear band (n = 5)
- Average dextral shear band (n = 3)

Later Musgravian-aged structure

- Overprinting melt-filled dextral shear (n = 1)

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Dykes and the De Rose and Echo fault system

Two main dolerite suites can be distinguished in the easternmost Musgrave Province, with each forming dykes that have different orientations and widths. It is possible to determine their relationship with the De Rose and Echo fault system as both dolerite suites have been recognised within the rhomboid.

The first set of dolerite dykes are prominent on the aeromagnetic, Landsat, and ortho-images of the rhomboid formed by the De Rose and Echo faults (Fig. 5). The dykes are up to 100 m wide and sigmoidal, curving from northwest-striking in the centre of the rhomboid, to approximately

east–west-striking at the tips, where they are aligned subparallel to the faults bounding the rhomboid. The geometry of the dykes suggests that the tips of the dykes were rotated by $\sim 30^\circ$ in an anticlockwise direction during a phase of sinistral shearing.

Mapping of the gneisses in the rhomboid, however, reveals a different story. If the dyke tips had been rotated during sinistral shearing, then the gneissosity hosting the dykes should have undergone a similar amount of anticlockwise rotation. Yet field observations reveal that the orientation of the gneissosity is relatively consistent along the dykes, regardless of the dyke orientation (Fig. 5). In the northern part of the rhomboid, the gneissosity has locally changed orientation, but in a clockwise manner that is consistent with dextral displacement. There is also some local transposition of the layering along the faults, but this is not widespread. Essentially, the gneissosity in the rocks hosting the dykes within the rhomboid did not significantly change orientation during faulting.

The sigmoidal dykes are composed of a mid Neoproterozoic group of low La/Nb, low Mg, high Fe–Ti dolerites that have been dated at c. 825 Ma (zircon and baddeleyite U–Pb SHRIMP age; Glikson et al. 1996; Wingate et al. 1998; Zhao, McCulloch and Korsch 1994) and c. 760 Ma (Sm–Nd/Rb–Sr isochron age; Dutch et al. 2013). These dolerites are likely part of the Gairdner–Amata dolerite suite (Dutch et al. 2013; Werner et al. 2014).

The second set of dykes within the rhomboid is relatively minor and comprises olivine dolerite which forms thin (generally < 10 m wide) dykes that are typically aligned subparallel to the bounding faults (i.e. $080\text{--}110^\circ$ -striking). It is unlikely that these dykes were re-oriented by dextral faulting during the Petermann Orogeny as the host gneisses do not exhibit any rotation. Instead, based on the parallel alignment of these dykes with the De Rose and Echo faults, it is possible that the emplacement of the dykes reflects a structural control, which may correspond to faulting, or fault reactivation, during the Giles Event at c. 1080–1040 Ma.

The olivine dolerites form a late Mesoproterozoic suite of olivine-bearing, high-La/Nb, high Mg, low Fe–Ti dolerites which have a Sm–Nd isochron age of 1110 ± 56 Ma (Dutch et al. 2013; Werner et al. 2014). This suite would likely correspond to the c. 1075 Ma Alcurra Dolerite of the Giles Complex, and the poorly age-constrained Kullal Dyke Suite of the west Musgrave Province that has a Sm–Nd mineral-whole rock isochron age of c. 1000 Ma (Glikson et al. 1996; Howard et al. 2011; Zhao and McCulloch 1993a; Zhao and McCulloch 1993b).

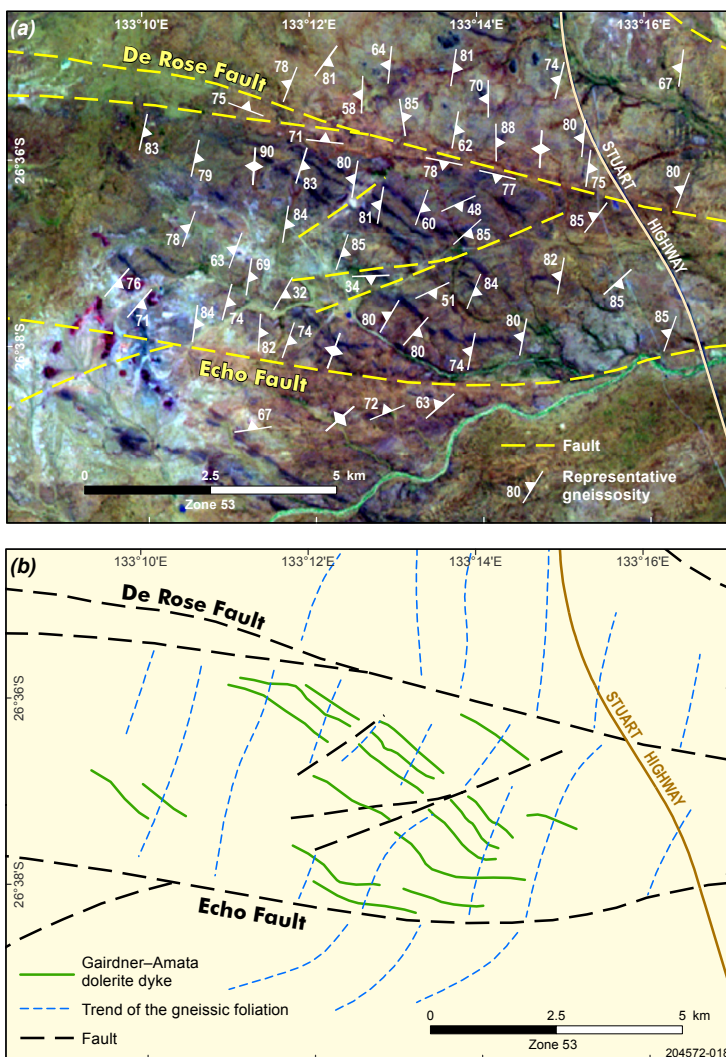


Figure 5 (a) Landsat 5 Thematic Mapper image of the central part of the rhomboid, with the apparently deflected, sigmoidal dolerite dykes showing up as the northwest-trending dark parallel lines. The representative structural measurements show the relatively uniform orientation of the gneissic layering, despite the orientation of the dykes. (b) Diagram of the same area, showing the relationship between the gneissosity and dykes of the Gairdner–Amata dolerite within the rhomboid.

Alteration and the fault zones

The new mapping reveals that epidote–silica alteration occurs locally within the eastern Musgrave Province in two main forms. First, there is intense, pervasive epidote–silica alteration that is spatially associated with the large-scale magnetically low lineaments (Fig. 6). The altered rocks are medium grained, green and massive, with locally preserved primary textures (Figs 7a, b, c). They typically form low, rubbly angular outcrop that is distinct from the more rounded, bouldery outcrop and platforms of the unaltered basement rocks. The alteration mineral assemblage is dominated by epidote (often zoisite) and silica with minor leucoxene and hematite, while trace amounts of calcite infill fractures. No opaque minerals, including magnetite, are observed in the altered rocks, despite being ubiquitous in the unaltered rocks, suggesting there was comprehensive replacement of the magnetic minerals. The alteration assemblage is interpreted to have occurred under moderately low pressure–temperature conditions (greenschist facies; SA Geodata rock sample number 1961427; Mason 2013).

Magnetic susceptibility measurements (in SI units) of hand samples reveal that the altered rocks have values of $0.33\text{--}0.54 \times 10^{-3}$ (average 0.41×10^{-3}). This is significantly lower than the unaltered basement rocks, with the leucocratic gneisses having values of $2.95\text{--}12.90 \times 10^{-3}$ (average 4.29×10^{-3}) and the melanocratic gneisses of $3.35\text{--}69.70 \times 10^{-3}$ (average 36.71×10^{-3}).

The De Rose and Echo faults are the main structures to host the epidote–silica alteration; however, other altered structures have been recognised in the study area. To the south of the Echo Fault is a network of east-southeast to northeast-striking aeromagnetic lows that coincide with outcrops of weathered basement rocks (Fig. 6) and are also interpreted as faults. One of the sigmoidal Gairdner–Amata dolerite dykes, ~ 1 km to the north of the Echo Fault, has undergone minor northeast- and northwest-trending faulting with locally pervasive epidote–silica alteration in the vicinity of these structures. Alteration is typically less common to the north of the De Rose Fault, with low aeromagnetic features, also interpreted to be faults, lacking an alteration overprint. The one exception is a northwest-striking, low aeromagnetic anomaly to the north of De Rose Hill (just north of the De Rose Fault: Fig. 6) that is characterised by epidote–silica alteration. Consequently, it appears that the greatest proportion of alteration occurs along, and to the south of, the De Rose Fault.

Second, the epidote occurs as discrete, millimetre-wide veins that are either parallel to the east–west-striking faults (Fig. 7d), or parallel to the margins of dykes near the main faults (Fig. 7c). The latter relationship suggests that strain during reactivation was partitioned along the rheological contrast represented by the boundaries (Fig. 7d). At one outcrop within the rhomboid, the altered gneisses are cut by a series of millimetre-wide, epidote–silica-filled, east-striking sinistral faults that contain millimetre-scale angular blocks of the gneiss (Fig. 7c).

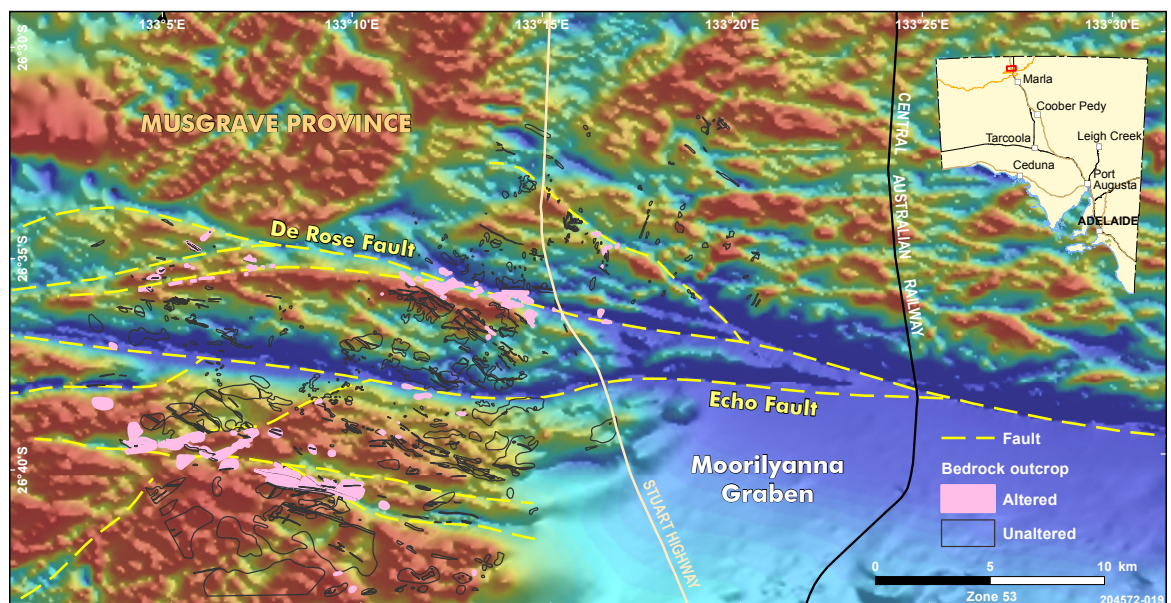


Figure 6 TMI RTP image showing the correlation between the low magnetic anomalies and the mapped outcrops of epidote and silica altered rocks.



7 (a) Rock with pervasive epidote alteration that is cut by veins of epidote and silica. The rock locally has a vuggy texture. (Photo 414235)



7 (b) Altered gneiss that is cut by an epidote vein aligned subparallel to a sigmoidal dolerite dyke. (Photo 414236)



7 (c) Altered gneiss with the layering sharply cut at a high angle by sinistral faults that are filled with epidote and silica. The faults contain the angular gneissic fragments within the epidote and silica groundmass. (Photo 414237)



7 (d) An east-trending epidote vein aligned subparallel to the De Rose Fault. (Photo 414238)

Figure 7 Epidote–silica alteration within the eastern Musgrave Province.

Discussion

Fault history

Based on the new observations, the Echo and De Rose faults are interpreted to be long-lived structures with a history of reactivation. The relative timing of these events can often be determined by the relationship between the faults and the dykes that are prevalent in the area.

Was there Musgravian-aged faulting?

There is no direct evidence for large-scale, east–west-faulting during the c. 1220–1120 Ma Musgravian Orogeny, with most structural (Pawley et al. 2013; Reid et al. 2013) and geophysical data (Aitken and Betts 2008) suggesting that the Birksgate

Complex is dominated by a northeast-trending Musgravian-aged grain. However, the presence of the small, melt-filled dextral shear (Fig. 4) represents indirect evidence. The textural continuity of the gneiss-parallel leucosome with the melt in the shear suggests that they both formed during the same event, the Musgravian Orogeny. This is supported by the available geochronology which indicates that metamorphism occurred during the Musgravian Orogeny with no evidence for Petermann-aged anatexis and zircon growth (Jagodzinski and Dutch 2013; Jagodzinski, Dutch and Reid in prep). Migmatitic rocks are also interpreted to have formed during the Petermann Orogeny, when the faults focused fluid flow and promoted local partial melting (Camacho et al. 1997; Edgoose, Scrimgeour and Close 2004; Raimondo et al. 2010;

Scrimgeour and Close 1999). However, these rocks are reported from the western and central parts of the Musgrave Province, with no record of high-grade deformation from the eastern end of the province. In the east, the Petermann Orogeny appears to have resulted in localised greenschist-facies fabrics and shear zones (Edgoose, Scrimgeour and Close 2004).

The approximately northwest–southeast-directed shortening principal stress axes responsible for the melt-filled shear are consistent with those proposed for the other Musgravian-aged structures in this area (Pawley et al. 2013; Reid et al. 2013). This could mean that after development of the widespread northeast- to north-northeast-striking gneissosity there was a switch to localised strain that was partitioned into the east-striking dextral shear zones. This switch in behaviour may reflect the change in rheology as the rocks cooled towards the end of the orogeny. Consequently, east–west-faulting may have initiated in the eastern part of the province during the Musgravian Orogeny.

Faulting between the Musgravian and Petermann orogenies

Based on the relations between the De Rose and Echo fault system and the dykes in the rhomboid, it is possible to reach some conclusions about the timing of displacement on the faults.

The thin, east-trending dykes within the rhomboid have been interpreted as part of the c. 1085–1040 Ma Giles Complex (Dutch et al. 2013; Werner et al. 2014). Given the parallel alignment of these dykes with the De Rose and Echo faults, it is possible that dykes were following a structural control that may correspond to faulting, or fault reactivation, during the Giles Event.

So far Giles-aged deformation hasn't been recognised in the eastern Musgrave Province, although it has been recognised in the west part of the province. Glikson (1996) described steep, southeast- to east-striking high-strain zones that accommodated uplift and erosion of more than 12 km of crust. Similarly, Coleman (2009) also recognised steep, east-striking shear zones with predominantly vertical movement. These structures were interpreted to have occurred after the intrusion of the layered mafic bodies of the Giles Complex, and resulted in their uplift and exposure before the eruption of c. 1070 Ma rhyolite flows of the lower Bentley Supergroup, which is the eruptive component of the Giles Event (Coleman 2009).

Consequently, there is the possibility that the parallel alignment of the east-trending dykes of the Giles Complex with the De Rose and Echo faults may reflect Giles-aged deformation in the eastern part of

the province. This hypothesis will be evaluated as the current mapping program progresses to the west.

The sigmoidal dykes (Fig. 5), which are interpreted to be part of the c. 825–760 Ma Gairdner–Amata dolerite suite (Dutch et al. 2013; Werner et al. 2014), appear to be sinistrally deflected by the dykes bounding the rhomboid, whereas the host gneissosity is uniformly oriented despite the orientation of the dykes. If the dolerite was intruded synkinematically as en echelon dykes that were rotated during progressive shearing, this would require the gneissosity to also show a corresponding rotation, which it does not. The lack of evidence for rotation of the gneissosity in the host suggests instead that the dykes may have been emplaced with the sigmoidal geometry representing the primary shape of the intrusion. If this is the case, it would suggest that the De Rose and Echo faults existed prior to magma intrusion, forming discontinuities that locally influenced the location and shape of the conduits for the ascending magma. Since the Gairdner–Amata dolerite is interpreted to be c. 825–760 Ma (Dutch et al. 2013; Werner et al. 2014), it would appear that the De Rose and Echo faults existed prior to the intrusion of the mid Neoproterozoic dykes.

Faulting in the Petermann Orogeny

The De Rose and Echo faults were active during the Petermann Orogeny when they formed the northern boundary of the Moorilyanna Graben (Fig. 2) which is a strike-slip, pull-apart basin that was filled with clastic sediments of the Moorilyanna Formation (Gravestock et al. 1995; Preiss, Korsch and Carr 2010). The overall geometry of the graben suggests that it formed during dextral strike-slip movement. Furthermore, the De Rose and Echo fault system dextrally deflects a northeast-trending grain on the aeromagnetic images (Fig. 3) which has been interpreted as the structural grain of the Musgravian Orogeny (Aitken and Betts 2008; Wade et al. 2008). This interpretation is supported by the new mapping which indicates that the aeromagnetic grain is parallel to the foliation observed in the outcrops of the Birksgate Complex gneisses (Fig. 3).

Reactivation during the Alice Springs Orogeny

The Ordovician-aged Alice Springs Orogeny is interpreted to have resulted in the reactivation of Petermann-aged structures along the southern margin of the Musgrave Province (Conor et al. 2006; Hand and Sandiford 1999; Hoskins and Lemon 1995; Korsch et al. 1998). Conor (2004) recognised a late-stage assemblage of epidote, quartz and altered feldspar that was typically associated with brecciated fault zones to the northwest of the current study area. This alteration

was interpreted to have occurred during the Alice Springs Orogeny (Conor et al. 2006).

Based on the similarity of the epidote and silica alteration within the fault zones of the current study area to the alteration recognised by Conor (2004), the De Rose and Echo faults are interpreted to have also been reactivated during the Ordovician Alice Springs Orogeny and experienced the same fluid flow. The small-scale, apparent sinistral fault that is filled with epidote (Fig. 7d) suggests that there may have been a component of sinistral displacement during this event. Furthermore, the network of altered structures south of the Echo Fault (Fig. 6) suggest that there is a broad zone of brittle deformation where faults were either reactivated, or formed, during the Alice Springs Orogeny. The scarcity of observed alteration to the north of the De Rose Hill Fault suggests that reactivation during the Alice Springs Orogeny was restricted to the south of this structure. Alternatively, the spatial distribution of the alteration may suggest that the fluids were sourced from the graben, which would also imply reactivation of the structures bounding the basin.

The pervasive epidote–silica alteration tends to obliterate any earlier textures within the fault zones. This can make it difficult to recognise primary textures, or determine kinematic indicators at the outcrop scale. Instead, it has been necessary to look at the larger scale features, such as deflected foliation or offset markers (whether measured in the field or interpreted based on geophysical data) and basin geometry, to understand the kinematic history of these structures.

It is also possible that the fluids responsible for the alteration may have scavenged metals from the basement rocks (whether they be the gneisses of the Birksgate Complex or the dolerites) and the basin fill in the nearby Moorilyanna Graben. Consequently, the altered structures may represent underexplored mineral targets.

Implications of long-lived faulting

The observations of the De Rose and Echo fault system and the interpretation presented in this study have two main implications for the understanding of the Musgrave Province.

First, the early (i.e. at least pre-c. 825–760 Ma) initiation of the large-scale faults, which can be traced on aeromagnetic images for almost 200 km, suggests that the east-trending architecture of the province was established relatively early in the history of the province. This indicates that the 600–530 Ma Petermann Orogeny, rather than being responsible for this grain, reactivated and exploited a pre-existing east–west-striking structural grain. Furthermore, since the De Rose

and Echo fault system contains an asymmetric rhomboid with apparent dextral displacement, which influenced the geometry of the Gairdner–Amata dolerite dykes, it appears that at least one phase of pre-c. 825–760 Ma fault development involved apparent dextral displacement.

Second, the De Rose and Echo fault system appears to have influenced the distribution and emplacement geometry of the Gairdner–Amata dolerite dykes. The faults may have acted as conduits for the mafic magma ascending through the crust; an interpretation supported by seismic images which indicate that the De Rose and Echo fault system forms part of a crustal-scale system (Korsch and Kositsin 2010). Understanding the structural controls on the transfer and emplacement of mafic magmas may help companies target potential Ni–Cu mineralisation.

Summary

The observations and interpretations presented in this paper have a number of implications for the geological evolution of the eastern Musgrave Province and its mineral potential:

- The field-based constraints on the Echo and De Rose fault system indicate that these structures formed relatively early, i.e. prior to c. 825–760 Ma, and could be as old as the Musgravian Orogeny.
- These faults were demonstrably reactivated during the Petermann and Alice Springs orogenies.
- The early (i.e. pre-c. 825–760 Ma) initiation of the large-scale faults, which can be traced on aeromagnetic images for almost 200 km, suggests that the east-trending architecture of the province was established relatively early and is not a product of the Petermann Orogeny.
- The large-scale structures appear to have influenced the transfer of mafic magma, possibly acting as magma conduits through the crust. This has implications for understanding the structural controls on the distribution of mafic magmas that may host Ni–Cu mineralisation.
- The epidote–silica alteration indicates that the structures were reactivated during the Alice Springs Orogeny and accommodated significant fluid flow. These fluids may have scavenged base metals from the basement and basin fill.
- The epidote–silica alteration has generally obliterated any earlier textures within the fault zones making it difficult to recognise primary textures or outcrop-scale kinematic indicators. Instead, it is necessary to look at larger scale features to understand the kinematic history of the altered structures across the province.

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FURTHER INFORMATION

Mark Pawley
 Mark.Pawley@sa.gov.au
 +61 8 8463 3115