Multiply reactivated crustal-scale structures and a long-lived counter-clockwise *P–T* path: New insights into the 1.5 billion year tectonothermal evolution of the eastern Arunta Region, central Australia

Anett Weisheit[1,2], Barry L Reno[3], Eloise E Beyer[1], Jo A Whelan[3] and Matthew McGloin[3]

Introduction

The geological evolution and metallogenic potential of the eastern Arunta Region has been a focus of the Northern Territory Geological Survey's (NTGS) regional mapping program since the early 2000s. Since 2013, detailed geological mapping of the Jervois Range, Jinka and Dneiper[4] map areas (**Figure 1**) carried out under the *Creating Opportunities for Resource Exploration (CORE)* initiative has led to a revised model for the geological evolution of this part of the eastern Arunta Region. In parallel, detailed studies on copper, tungsten, and polymetallic base metal mineralisation focus on constraining the timing of mineralisation and its genetic relationship to host stratigraphy, deformation, and metamorphism (McGloin and Weisheit, 2015; McGloin *et al* 2016).

In light of this new work, this abstract presents a new understanding of the tectonothermal history of the

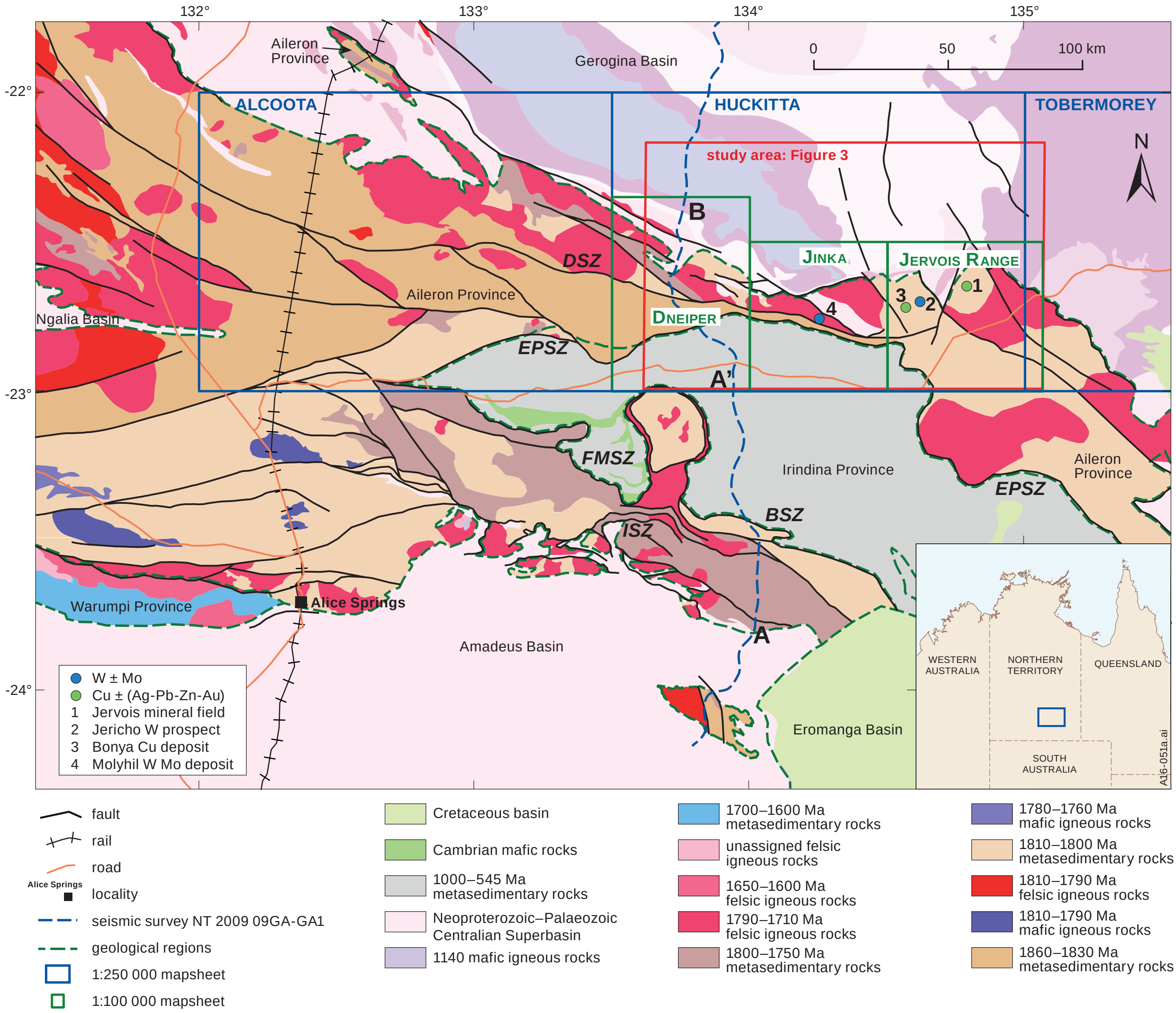

Figure 1. Schematic interpreted geological-tectonic map of part of the Arunta Region including the Palaeoproterozoic Aileron Province and the Neoproterozoic to Palaeozoic Irindina Province. The Arunta Region is unconformably overlain by Neoproterozoic to Palaeozoic sedimentary rocks of the Georgina and Amadeus basins. A network of west-northwest trending shear zones caused the juxtaposition of the provinces during the ca 450–300 Ma Alice Springs Orogeny (Collins and Teyssier, 1989); DSZ = Delny Shear Zone, EPSZ = Entire Point Shear Zone, FMSZ = Florence-Muller Shear Zone, ISZ = Illogwa Shear Zone, BSZ = Basil Shear Zone. The location of the study area and of the Georgina Basin–Arunta Region deep seismic reflection line, 09GA-GA1, as well as the locations of mineral deposits and occurrences mentioned in the text are shown (**Figure 3**).

[1] Northern Territory Geological Survey, GPO Box 8760, Alice Springs NT 0871, Australia
[2] Email: anett.weisheit@nt.gov.au
[3] Northern Territory Geological Survey, GPO Box 4550, Darwin NT 0801, Australia
[4] Names of 1:250 000 and 1:100 000 mapsheets are shown in large and small capital letters, respectively, eg HUCKITTA, Jervois Range.

HUCKITTA (**Figure 1**) area with focus on the structural evolution. Due to the lack of continuous outcrop in this highly weathered area, the regional structural interpretation presented herein integrates field structural data collected by NTGS geologists with airborne magnetic and gravity data.

Regional geology

The Arunta Region in central Australia preserves evidence of a complex polytectonic and polydepositional history that spans ca 1.5 billion years from the Palaeoproterozoic through to the Palaeozoic. In HUCKITTA and western TOBERMOREY, the Palaeoproterozoic Aileron Province comprises a supracrustal succession that has been subjected to regional high-thermal-gradient metamorphism, deformation, and various episodes of related felsic and mafic magmatism between ca 1810 and 1690 Ma (eg Scrimgeour 2013, and referenced therein; **Figure 1**).

The weakly folded and unmetamorphosed Georgina Basin unconformably overlies the northeastern margin of the Aileron Province; it records evidence for widespread deposition beginning in the Neoproterozoic (Kruse *et al* 2013, and references therein). The Irindina Province, an age-equivalent supracrustal succession to the Georgina Basin, experienced metamorphism up to granulite facies during the ca 480–460 Ma Larapinta Event (eg Buick *et al* 2001, 2005). The juxtaposition of the Aileron and Irindina provinces and the Georgina Basin along major fault and shear zones occurred during the Ordovician to Carboniferous Alice Springs Orogeny between ca 450 and 300 Ma (eg Scrimgeour 2013, and referenced therein).

Tectonothermal evolution

Palaeoproterozoic

The oldest rocks exposed in Jervois Range and Jinka are the Bonya Metamorphics, a sequence of clastic and chemical metasedimentary rocks comprising various meta-mudstones, meta-sandstones, marbles, and calc-silicate rocks. They are interpreted to have been deposited in a high-thermal-gradient, extensional back-arc environment active until ca 1790–1780 Ma (Reno *et al* 2015).

The Bonya Metamorphics were intruded by syn-depositional, bimodal igneous units that outcrop in Jervois Range, including: the Attutra Metagabbro, King's Legend Amphibolite, and related mafic dykes; 10s–100s m thick layers of felsic Mascotte Gneiss (Reno *et al* 2015); and volumetrically minor occurrences of meta-(sub)-volcanic rock (McGloin *et al* 2016). In Jervois Range and south in ILLOGWA CREEK, ca 1780–1770 Ma I-type granitoids are locally calc-alkaline or are characterised by a high-Al, high-Sr, low-Ti geochemical signature; they have been interpreted to have been derived from the fractionation of arc-type magmas and/or partial melting of pre-existing intrusions which were emplaced in an arc setting (Zhao and McCulloch 1995). In Jervois Range, the influx of mafic and felsic magma into the active sedimentary basin between ca 1790 and 1780 Ma (Reno *et al* 2015) provided a heat source that initiated regional high-thermal-gradient metamorphism and fluid flow (**Figure 2a**). These events are interpreted to be contemporaneous with syngenetic base metal mineralisation at the *Jervois mineral field* (**Figure 1**). This stratabound mineralisation is sediment-hosted but spatially and temporally associated with the bimodal igneous rocks (McGloin and Weisheit 2015; McGloin *et al* 2016).

The rocks observed in Jervois Range remained at temperatures 50–100 °C below the solidus during high-thermal-gradient metamorphism in the Palaeoproterozoic, whereas evidence of partial melting is observed in meta-sedimentary and meta-igneous rocks to the west in Jinka and Dneiper, and in ALCOOTA (Beyer *et al* in prep; **Figure 1**). Partial melt derived during super-solidus metamorphism between ca 1780 and 1730 Ma is interpreted to have accumulated to form felsic igneous bodies observed throughout the area, for example the Jinka and Marshall granites (Reno *et al* 2015).

The extensive high-temperature metamorphism and continuing igneous intrusion resulted in crustal-scale thermal weakening, progressive regional deformation, and subsequent strain localisation in the study area (**Figure 1**). The main structure in HUCKITTA is the east-west trending, sub-vertical to south-dipping Delny Shear Zone (**Figure 1, 3a**). Co-planar, granulite-facies proto-mylonites and mylonites in the eastern Delny Shear Zone in Jervois Range evidence a dominant dip-slip, south side-down movement. Monazite interpreted to have grown within the proto-mylonite fabric yielded a $^{207}Pb/^{206}Pb$ age of 1759 ± 13 Ma (2σ; Reno *et al* 2016; **Figure 3a**). This age is within uncertainty of a $^{207}Pb/^{206}Pb$ monazite age obtained from monazite aligned within the main foliation of cordierite–biotite schists close to the north-northeast-trending Jervois Fault zone in central Jervois Range (1757 ± 9 Ma, 2σ; Reno *et al* 2016; **Figure 3a**).

Deformation of this cordierite–biotite schist occurred during the regional progressive D_2 event that is interpreted to have formed the main foliation S_2 in all meta-sedimentary and most magmatic rocks of the Aileron Province in Jervois Range (McGloin and Weisheit 2015; Weisheit *et al* 2015). The steep to sub-vertical S_2 foliation and cm- to m-scale shear zones formed axial planar to asymmetric, cm- to km-scale, isoclinal shear folds (**Figure 2b**) with shallowly to moderately plunging fold axes and a steep stretching lineation, indicating extension in sub-vertical direction. Nearly-co-planar cm- to km-scale asymmetric shear-folds with moderately to steeply plunging fold axes overprinted D_2 structures during a regional D_3 event in Jervois Range. Sub-vertical extension and strain localisation during the progressive D_3 event likely led to the formation of the steeply east-southeast-dipping Jervois Fault zone (**Figure 3a**). Normal dextral movement along this structure resulted in 10 km-scale drag folds with steeply-plunging axes in the footwall (Bonya area) and hanging wall ("J-Fold", see McGloin and Weisheit 2015) of the Jervois Fault zone.

An overprinting of S_2 fabric in the Jervois Fault zone observed in outcrop- and thin section-scale resulted in fabric rotation and intrafolial folds cut by an S_3 shear fabric (**Figure 2c**). This shear fabric does not continue into the overlying Georgina Basin; shearing therefore pre-dates the basin's deposition. The similarity in style and only slight variation in orientation and scale of D_2 and D_3 structures are interpreted to result from a single progressive deformation event during minor changes in the direction of an extensional stress field. Based on this structural interpretation that D_2–D_3 are progressive, the aforementioned monazite age from S_2-foliated cordierite–biotite schist provides a maximum age constraint on this progressive event that eventually resulted in initiation of the Jervois Fault zone. This interpretation will be tested by dating monazite in S_3 shear fabric in a sample from the Jervois Fault zone.

During a progressive D_2–D_3 deformation in Jervois Range, the normal movement in the eastern Delny Shear Zone in this area would have occurred contemporaneously with the normal movement along the Jervois Fault zone, suggesting at least in Jervois Range, an extensional stress field at that time. Additionally, cross-cutting relationships between the north-northeast trending Jervois Fault zone and the north-northwest trending Charlotte, Bonya, and Lucy Creek Fault zones suggest contemporaneous movement along these structures (**Figure 3a**). The geometric relationship between the eastern extension of the Delny Shear Zone and the Jervois, Bonya, Charlotte, and Lucy Creek Fault zones is typical of a primary fault with high-angle Riedel and splay faults (Ramsay and Huber, 1987 and referenced therein; **Figure 3a)**.

The initiation of the primary and secondary fault and shear zones in an extensional setting brought the Palaeoproterozoic rocks in the hanging walls to peak-pressure conditions after

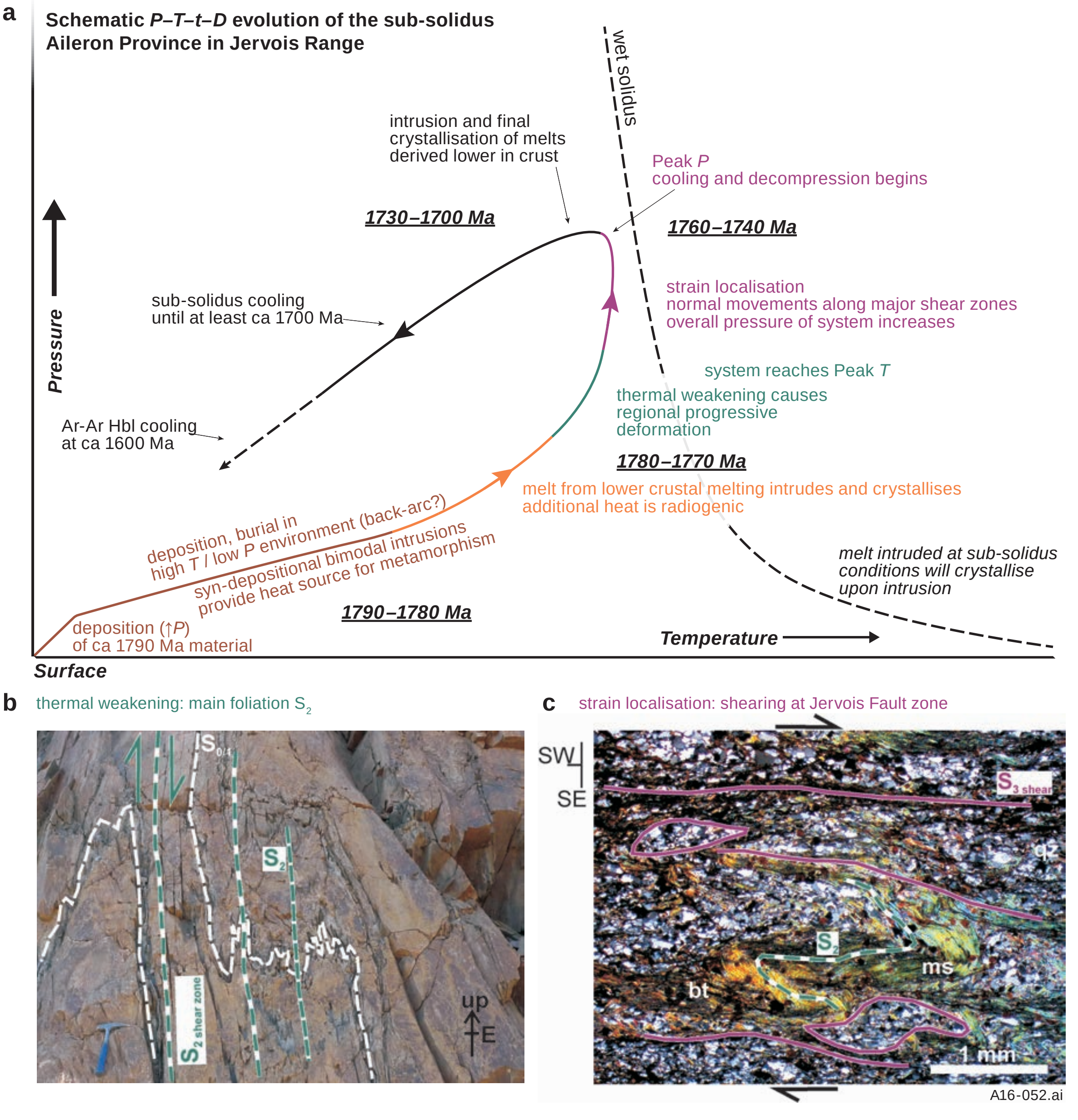

Figure 2. (**a**) Schematic pressure–temperature metamorphic evolution of Aileron Province rocks in Jervois Range during the Palaeoproterozoic. This long-lasting sub-solidus metamorphic cycle can be directly linked to progressive deformation of meta-sedimentary and meta-igneous rocks in the study area. Burial, thermal weakening due to magmatism, and strain localisation are the main driving forces of this counter-clockwise pressure–temperature path. (**b**) Outcrop photo taken of quartzitic meta-sedimentary rocks in the Jervois mineral field (see **Figure 1**). The $S_{0/1}$ foliation is folded into vertical shear folds with sub-horizontal to shallowly plunging fold axes. A schistose to gneissic S_2 foliation and cm- to m-scale shear zones developed axial planar, indicating southeast-down movement. (**c**) Photomicrograph of a sample taken from the Jervois Fault zone close to the contact with the overlying Georgina Basin. The muscovite±biotite S_2 foliation is overprinted by a biotite–muscovite–quartz S_3 shear fabric indicating southeast-down along the north-northeast trending Jervois Fault zone.

ca 1750 Ma (Reno *et al* 2016). The cessation of regional deformation and cooling of the regional system below solidus temperatures resulted in the crystallisation of undeformed granites and pegmatites, including the Jinka Granite in JINKA between ca 1730 and 1710 Ma. Crustal fluid flow initiated by magmatic crystallisation and metasomatism was focused in the regional and local foliation and fold structures, leading to the formation of epigenetic Cu and W mineralisation (eg Bonya Cu deposit, Jericho W prospect, Molyhil W-Mo deposit; **Figure 1**), as well as extensive alteration, and brecciation zones (McGloin and Weisheit, 2015; McGloin *et al* 2016).

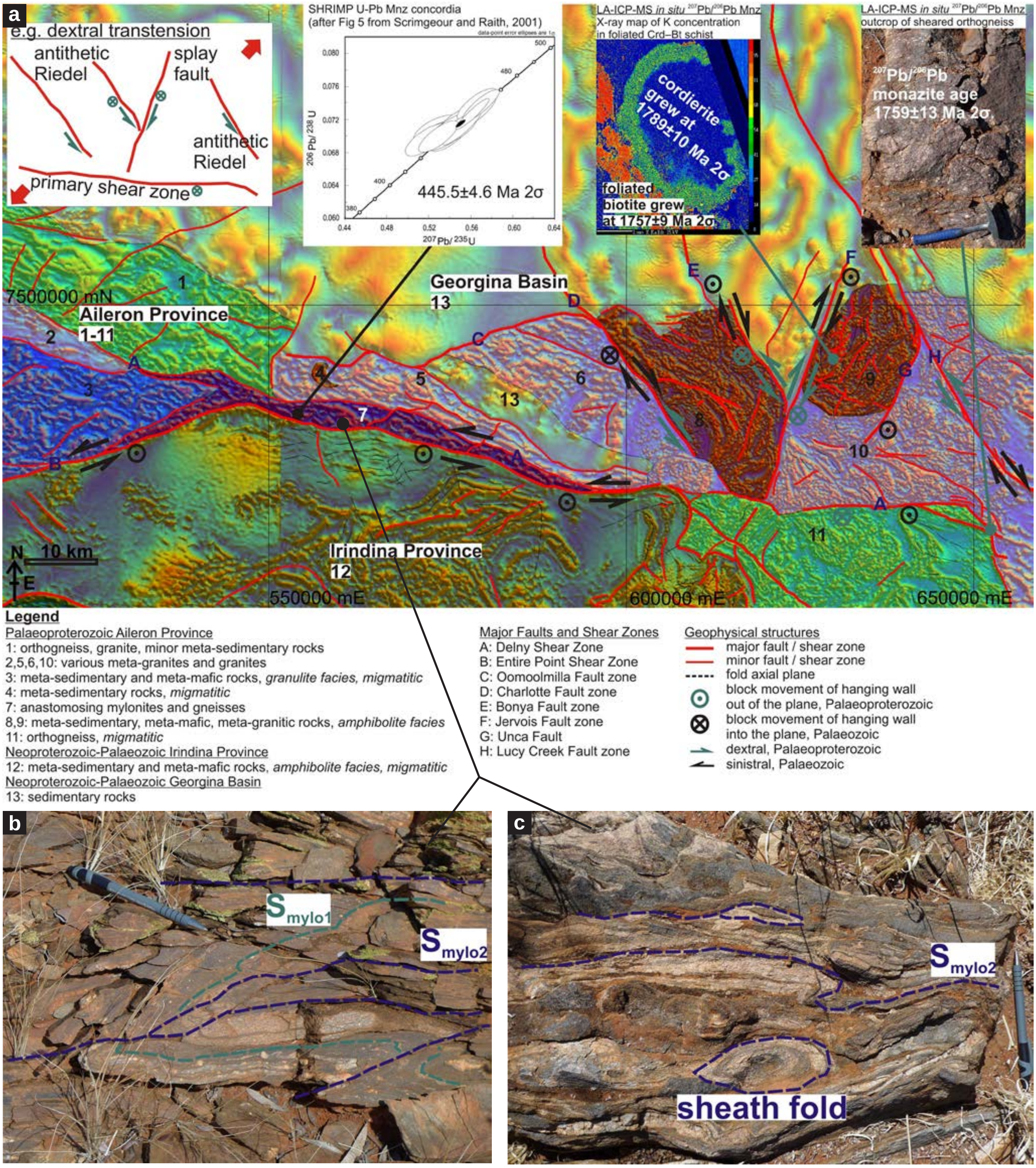

Figure 3. (**a**) Tilt derivative of the total magnetic intensity image overlain by colour coded interpreted geological-geophysical domains (numbers) of the study area in the eastern Arunta Region (**Figure 1**). Major and minor faults and shear zones (letters) and their interpreted sense of movement during the Palaeoproterozoic (green) and the Palaeozoic (black) are shown. The locations of key samples targeted for monazite geochronology are highlighted, and the geometric relationship of primary and secondary faults and shear zones is sketched. (**b**) Outcrop photo of an asymmetrically folded mylonitic S_{mylo1} rock in the Delny Shear Zone in JINKA. A mylonitic axial planar foliation S_{mylo2} developed only locally in this fold, but forms m- to 100 m-scale anastomosing shear zones elsewhere in this area. Pen points towards north. (**c**) Outcrop photo of dm-scale sheath fold structures in anastomosing S_{mylo2} mylonites in the Delny Shear Zone on JINKA. Sheath folds are structures commonly found in high strain zones. Pen points towards north.

The ca 1790–1700 Ma metamorphism in the study area is interpreted to follow a counter-clockwise pressure–temperature path beginning with 1) burial and syn-depositional magmatism in a high-thermal-gradient setting between ca 1790 and 1780 Ma; followed by 2) peak-temperature conditions due to intrusions of lower crustal melt at ca 1780–1770 Ma, combined with continued radiogenic heat production; 3) increasing pressure at high-temperature conditions in the hanging walls of normal shear zones at ca 1760–1740 Ma; and 4) slow cooling and melt crystallisation starting at ca 1730 Ma and continuing until at least ca 1700 Ma (**Figure 2a**).

This new interpretation of the late Palaeoproterozoic evolution of the Aileron Province rocks in the study area (**Figure 1**) differs from existing models that propose a number of discrete tectonothermal events (eg Scrimgeour 2013 and references therein; Reno *et al* 2015). Discrete events previously interpreted to have affected the eastern Aileron Province (eg Stafford, Yambah, Strangways) are interpreted here to represent a single ca 100 my counter-clockwise pressure–temperature evolution.

Neoproterozoic and Palaeozoic

Secondary shear zones that likely initiated during the Palaeoproterozoic were multiply reactivated during Neoproterozoic and Palaeozoic regional stress regimes. North-northwest trending faults such as the Lucy Creek and Bonya faults (**Figure 3a**) were active in a Neoproterozoic extensional regime as normal faults in half graben settings, leading to the deposition of the basal successions of the Georgina Basin (Greene 2010). The Georgina Basin sedimentary rocks unconformably overlie the Aileron Province, demonstrating that the basement rocks in HUCKITTA were exposed at the surface by the Neoproterozoic.

The Irindina Province, south of the Entire Point Shear Zone (**Figure 1, 3a**), experienced granulite facies metamorphism and melt crystallisation at ca 480 and ca 460 Ma, respectively (eg Buick *et al* 2001). Progressive simple shear folding and stretching structures (**Figure 4b**) indicate an extensional setting at this time that resulted in the deep burial of the Irindina Province rocks. An extensional setting is supported by the voluminous, rift-related tholeiitic Riddock Amphibolite which was emplaced throughout the Irindina Province during the Cambrian (Whelan *et al* 2010). Deep seismic reflection survey 09GA-GA1 shows that the Irindina Province is bound by the Entire Point Shear Zone in the north and the Basil Fault in the south and sits in the core of a crustal-scale flower structure (Ramsay and Huber, 1987 and references therein) that extends for ~ 80 km south of the Entire Point and Delny shear zones (Korsch *et al* 2011; **Figure 4a**). Normal movement (transtensional, negative flower) along the primary shear zones of this flower structure (Illogwa Shear Zone, Basil Fault, Entire Point Shear Zone and Delny Shear Zone; **Figure 4a**) is likely to be responsible for the high-grade metamorphism in the Irindina Province at ca 480–460 Ma.

Shear structures, such as shear bands and mantled porphyroclasts observed in mylonites (S_{mylo2}) in the Delny Shear Zone in HUCKITTA, indicate a phase of reverse movement overprinting previous proto-mylonitic to mylonitic (S_{mylo1}) structures (**Figure 3b**). At the eastern Delny Shear Zone in JERVOIS RANGE, reverse movement is restricted to mylonitic quartz veins that formed sub-parallel to the 1759 ± 13 Ma proto-mylonites and mylonites in this area (see above; Reno *et al* 2016). In contrast, the Delny Shear Zone in JINKA and DNEIPER is characterised

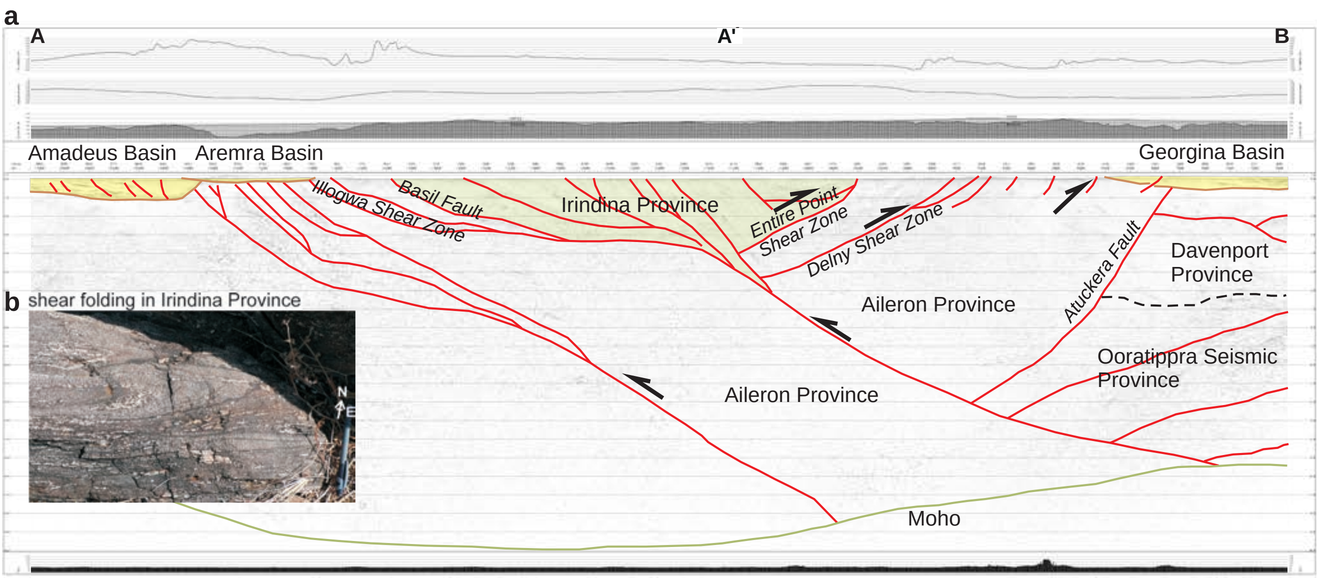

Figure 4. (**a**) Section of the migrated Georgina Basin – Arunta Region deep seismic reflection line 09GA-GA1 shot in 2009 (image from Geoscience Australia). Location of the line is shown in Figure 1. The seismic interpretation is based on Korsch *et al* 2011, and reveals a crustal-scale flower structure with positive and negative characteristics. The Irindina Province rocks in the core of this structure are overprinted by wide-spread shear folding that likely occurred during high-grade metamorphism at ca 480–460 Ma (Buick *et al* 2001). Latest movement on the primary shear zones (black arrows) occurred during the Alice Springs Orogeny at ca 450–300 Ma (Scrimgeour and Raith 2001). (**b**) Outcrop photo of layered meta-sedimentary rock in the Irindina Province in JINKA. Shear fold structures indicate progressive deformation in an extensional setting.

by anastomosing amphibolite and greenschist facies proto-mylonites and mylonites that record progressive deformation structures, including several generations of asymmetric folds, rotation of fold axes, sheath folds (**Figure 3c**), and strain localisation, resulting in cm-km sized boudins that preserve older proto-mylonitic to mylonitic structures (**Figure 3b**). The overall sense of shear in the Delny and Entire Point shear zones in JINKA and DNEIPER during the Palaeozoic is interpreted to be sinistral, with south-side-up, reverse movement.

Monazite that formed in a mylonitic fabric of a sample from the anastomosing part of the Entire Point Shear Zone preserves an U–Pb concordia age of 445 ± 5 Ma (2σ), interpreted to record the initiation of the ca 450–300 Ma Alice Springs Orogeny (Scrimgeour and Raith 2001; **Figure 3a**). It remains to be tested whether evidence for Palaeoproterozoic movement is preserved in the proto-mylonitic to mylonitic boudins in this part of the Delny and Entire Point shear zones. Regional sinistral transpression and wrenching during the Alice Springs Orogeny (Collins and Teyssier 1989; Teasdale and Pryor 2002) reactivated the crustal-scale negative flower structure; reverse movement along the primary shear zones (**Figure 4a**) resulted in the juxtaposition of high-grade Irindina Province rocks with the Aileron Province. Contemporaneously, the reactivation of most Neoproterozoic graben faults and the Jervois Fault zone as reverse faults caused minor folding and brecciation in the unmetamorphosed Georgina Basin and brittle juxtaposition with the Aileron Province. Fault and shear zone activity during the Alice Springs Orogeny has characteristics of a primary regional shear system accompanied by Riedel and splay faults, that is here interpreted to have been initiated in the Palaeoproterozoic (**Figure 3a**).

Conclusion

Interpretation of field observations and structural and geophysical data sets coupled with new monazite geochronology and pressure–temperature estimates suggests major east, north-northeast, and north-northwest trending extensional structures in the study area could have developed during a long-lasting Palaeoproterozoic metamorphic cycle. Progressive deformation and the activity along the shear zones influenced the counter-clockwise metamorphic path of the basement rocks in the hanging walls of the primary and secondary structures. Most shear zones were reactivated as brittle faults during Neoproterozoic and Ordovician extension, and again in ductile and brittle regimes during compression in the Alice Springs Orogeny. This indicates repeated strain localisation at pre-existing zones of weakness during this long-lasting, ca 1.5 billion year evolution of this part of the central Australian crust.

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