# Structural evolution of the S-bend region, east Albany–Fraser Orogen

by

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The margins of Archean cratons have long been recognized as important zones of intense deformation, enhanced magmatism and economically important mineralization. Understanding the tectono-metamorphic and magmatic evolutions of these margins is therefore paramount in establishing temporal and structural frameworks for the formation of these mineral systems. The Albany–Fraser Orogen is an important and prospective example of Archean craton margin modification and deformation. This is because it hosts the Tropicana gold mine within the reworked Archean rocks of the Tropicana Zone, and the Nova–Bollinger Ni–Cu deposit within the mafic to ultramafic, Mesoproterozoic granulite facies rocks of the Fraser Zone. The linear orogen is approximately 1200 km long and is situated along the southern and southeastern margins of the Yilgarn Craton, with the transition zone between the two marked by the Jerdacuttup Fault and the Cundeelee Shear Zone. The eastern extent of the east Albany–Fraser Orogen is marked by the Rodona Shear Zone, an east- to southeast-dipping thrust system that separates the orogen from the Proterozoic Madura Province (Spaggiari et al., 2014a).

The S-bend region (Fig. 1) is informally named as such due to its apparent S-fold geometry and is one of the most structurally complex regions within the orogen. It is an asymmetric interface between the reworked Archean rocks of the Northern Foreland, the Paleoproterozoic orthogneiss-dominated rocks of the Biranup and Nornalup Zones, and the Mesoproterozic interlayered mafic and felsic gneisses of the Fraser Zone (Spaggiari et al., 2014b). This region consists of multiple fold generations affecting a series of faults and shear zones, marking an important regional-scale crustal architecture that provides insight into the structural relationships between these tectonic units, and their evolution. The tectonic units within and adjacent to the S-bend region preserve differences in their structural grain and evolution, and are described below.

## Structural evolutions preserved internally within tectonic units

### The Biranup Zone

The structural grain of the Biranup Zone to the southwest of the S-bend (Figure 1, area a) is defined by northwest-trending gneissic layering subparallel to the axial traces of folds and shear zones. The folds are upright, isoclinal, gently northwest or southeast plunging, and affect the gneissic layering and layer-parallel leucosomes. Stretching lineations on the axial planar foliation are subparallel to the fold axes, and also parallel to the long axes of boudins of the foliation. This suggests that folding and stretching may have been synchronous, and both symmetric and asymmetric boudins are present. Open, moderately to steeply northeast-plunging folds deform the earlier folds resulting in the formation of Type 3 fold interference patterns (Fig. 2a; Ramsay, 1962). Leucosomes are commonly in situ and show different structural relationships. Some are deformed by, or axial planar to, northwest-trending $F_1$ folds. Others are axial planar to northeast-trending $F_2$ refolds. This indicates that partial melting occurred before or during local $F_1$ folding, and also during local $F_2$ folding.

To the south and southeast of the Fraser Zone, the structural grain of the Biranup Zone is defined by regional-scale, northeast-trending fold axial traces (Fig. 1, area b). Several northeast-trending folds in this eastern section of the Biranup Zone refold pre-existing folds resulting in both Type 2 and Type 3 interference patterns (Ramsay, 1962). This indicates the refolding of two prior fold generations. The presence of northeast-trending boudins suggests the development of the northeast-trending folds in the centre of the S-bend might also have been associated with a significant component of subhorizontal, strike-parallel stretching. A steeply east-plunging, regional-scale fold (Fig. 1, area c) is manifest in interlayered felsic and mafic gneisses of this section of the Biranup Zone and might represent either a second generation fold, or, alternatively, passive folding within a regional-scale boudin neck adjacent to the shear zone boundary.

### Northern Foreland

Early deformation in metasedimentary and metamafic rocks of the Northern Foreland to the northwest of the S-bend produced gently south-plunging, overturned, west-verging isoclinal folds and approximately north–south striking, west-directed thrusts (Fig. 1, area d). These are refolded about near-orthogonal, moderately east-plunging, open folds. This fold overprinting history is bounded to either side by two east-dipping thrusts that have been

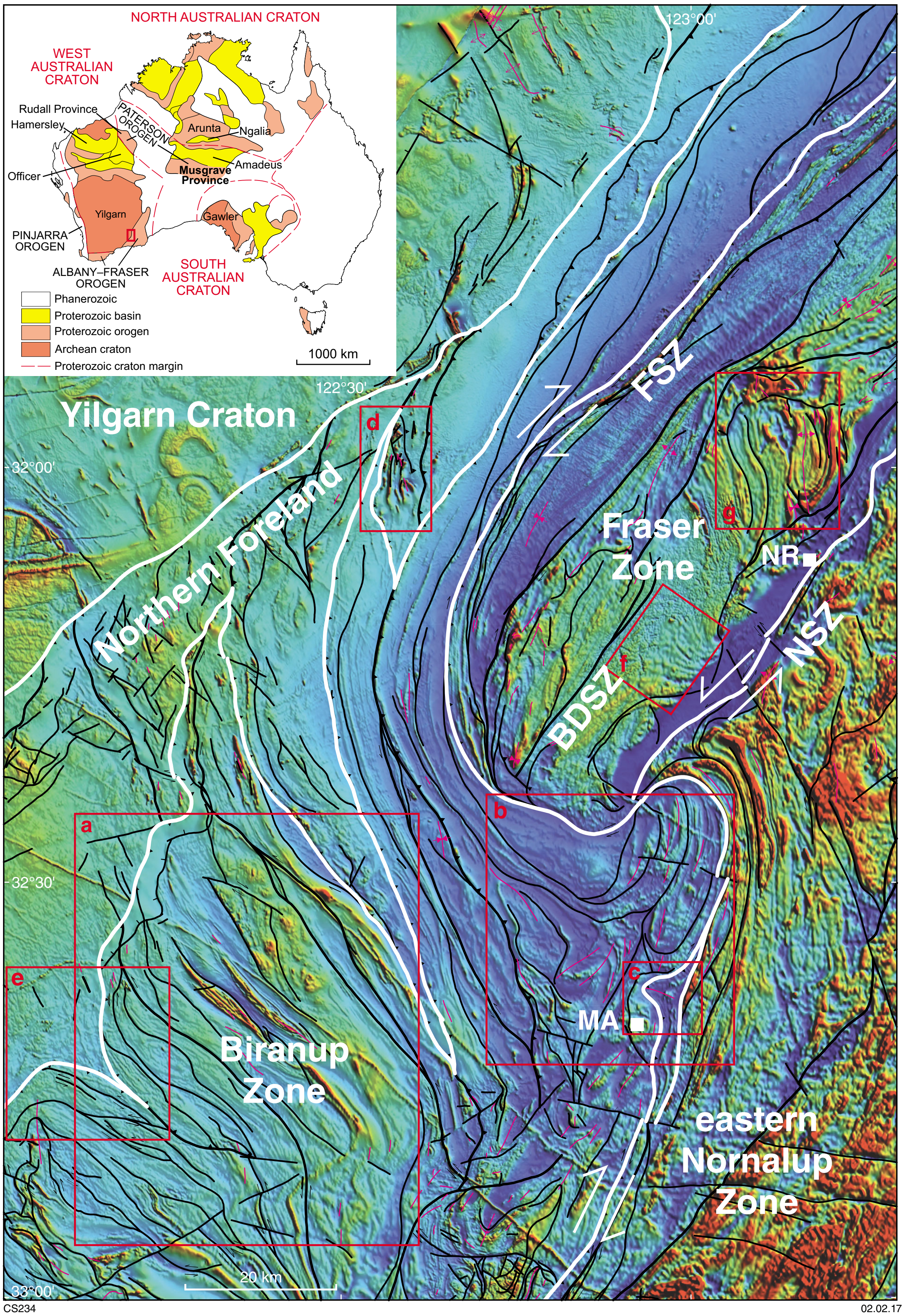


**Figure 1.** Reduced-to-pole aeromagnetic image showing the structural relationship between the four tectonic units in the S-bend region. FSZ = Fraser Shear Zone; NSZ = Newman Shear Zone; BDSZ = Browns Dam Shear Zone; NR = Newman Rock; MA = Mount Andrew. Areas a–g mark the positions of key structural domains described in the text.

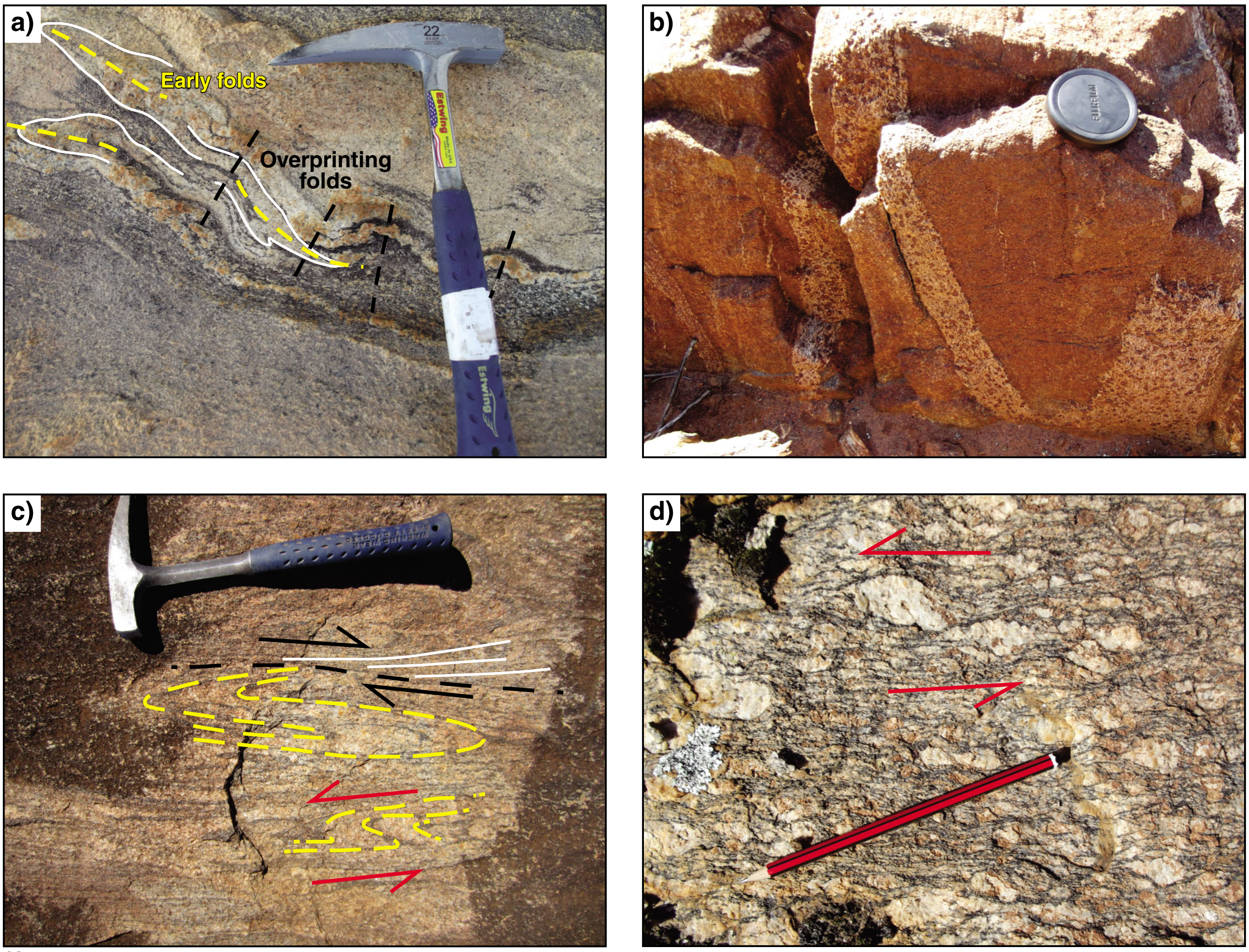


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**Figure 2.** **a) Plan view of early northwest-trending isoclinal folds of gneissic layering and leucosomes (solid white lines show layering; dashed yellow lines show axial traces) in the Biranup Zone, refolded about steeply northeast-plunging, open folds (dashed black lines show axial traces). Hammer head points north; b) a gently northeast-plunging antiform and synform pair in interlayered garnet-bearing sedimentary gneiss, metagabbro and metagranite on the northwestern margin of the Fraser Zone. Photo faces due northeast; c) plan view of asymmetric folds (yellow dashed lines) showing an early sinistral shear history preserved along the Fraser Shear Zone near the centre of the S-bend, overprinted by subsequent discrete dextral shear zones (black dashed line). White markers show the progressive rotation of previous structures into the discrete dextral shear. Hammer head points north; d) plan view of the dominant northeast–southwest striking mylonitic foliation of the Newman Shear Zone. Large sigma-type feldspar porphyroclasts indicate sinistral strike-slip shear sense. Pencil tip points north.**

folded about the S-bend. Along strike to the northeast, an eastward-dipping thrust has been folded about a series of east-trending folds with tighter interlimb angles. The bounding thrust between the Northern Foreland and the Biranup Zone has a curved trace, as interpreted from aeromagnetic data (Fig. 1, area e). This suggests that the margin between the two units has been deformed about northwest-trending folds that parallel the structural grain of this section of the Biranup Zone.

## Fraser Zone

The northeast-trending Fraser Zone may be subdivided along the Browns Dam Shear Zone into a northwestern and a southeastern domain (Fig. 1). The northwestern domain is dominated by interlayered paragneiss, metagabbro and metagranite. The northeast-trending structural grain of this domain is defined by the layering and a layering-parallel foliation. Folds are tight to isoclinal, and gently to steeply doubly plunging (Figs 1, 2b). The more competent mafic layers form centimetre- to metre-scale boudins that indicate stretching subparallel to the northeast-trending axial traces of the folds. The southeastern domain is dominated by metagabbroic rocks. Aeromagnetic data show folded magnetic horizons interpreted to represent a 10 km-wide, northeast-trending open fold affecting the magmatic layering within the metagabbroic rocks (Fig. 1, area f). To the northeast of this fold, a series of approximately north-trending magnetic horizons are interpreted to reflect folded and sheared magmatic layering (Fig. 1, area g). The northeast-trending structural grain that dominates the Fraser Zone wraps around this structure.

This structure may be interpreted as a regional-scale boudin whose orientation might have been rotated from its original northeast trend into its current north trend during shearing. Alternatively, this north trend may represent the preservation of an older generation of structures that pre-date the northeast structural grain of the Fraser Zone.

## Kinematic history of shear zones bounding the Fraser Zone

The Fraser Shear Zone (FSZ) is a wide zone of mylonitic to ultramylonitic foliations that mark the boundary between the Biranup and Fraser Zones (Fig. 1). Kinematic indicators associated with subhorizontal to gently plunging stretching lineations suggest a protracted history of dextral strike-slip kinematics. The dominant mylonitic foliation contains asymmetric dextral boudins that are overprinted by narrow dextral shear zones that lie at a low angle to the foliation. However, relatively lower strain areas preserve evidence of an earlier sinistral shearing history (Fig. 2c). Large delta-type garnet porphyroclasts and the asymmetries of isoclinal, often rootless, folds indicate sinistral shear sense along the gneissic layering. These earlier structures are truncated by narrow discrete dextral shear zones at low angles to the gneissic layering.

The northeast-trending Newman Shear Zone (NSZ) separates the Fraser Zone from the eastern Nornalup Zone and toward the southern end of the Fraser Zone, coincides with a remarkably low-intensity aeromagnetic signature (Fig. 1). Stretching lineations on the dominant mylonitic foliation vary significantly from steeply plunging to subvertical at localities such as Newman Rock (Fig. 1), to gently plunging and subhorizontal elsewhere along strike. Sinistral and southeast-side-up relative motion can be interpreted from kinematic indicators (e.g. Fig. 2d). Displacement along the shear zone appears to have produced a regional-scale drag fold that affects a series of northeast-trending folds and faults in the Biranup and eastern Nornalup Zones (northeast corner of area b in Figure 1), accentuating the S-bend's geometry. Within the NSZ, narrow, discrete, approximately north-trending sinistral shear zones locally branch out of the mylonitic foliation. Their shear sense and angular relationship with the mylonitic foliation are compatible with representing subsidiary synthetic R shears. However, a series of discrete, approximately east-trending dextral shear zones locally deform the mylonitic foliation and may correlate with other similarly oriented dextral shears that overprint northeast-trending folds in the Biranup Zone.

## Conclusions and future directions

The S-bend of the East Albany–Fraser Orogen is an important regional-scale crustal interface between four lithologically and structurally distinct tectonic units. The structural evolution of the S-bend region preserves at least three regionally significant orientations of folds and associated structures: north–south trending, northwest–southeast trending and northeast–southwest trending. A history of gently south-plunging folds near-orthogonally overprinted by moderately east-plunging folds in the Northern Foreland may correlate with an analogous relationship observed in metagabbros and orthogneisses of the Biranup Zone in the S-bend (Fig. 1, area c). The northeast-trending folds that dominate the structural grain of the Fraser Zone appear to correlate with similarly oriented northeast-trending folds in the Biranup Zone that refold earlier northwest-trending folds.

Rheological contrasts and deformation partitioning may have contributed toward the differential preservation of structural orientations throughout the S-bend region. While at least three generations of folding are preserved in the centre of the S-bend just north of Mount Andrew (Fig. 1), elsewhere, evidence of earlier structures and their relative timing has been largely erased during their transposition into parallelism with the dominant northeasterly structural grain during ongoing or subsequent deformation. We interpret that the northwesterly trending structures of the Biranup Zone were preserved due to their proximity to the relatively competent metagabbro-dominated Fraser Zone. The regional-scale S-fold geometry may therefore have developed by the overprinting of multiple structures oriented at high angle to one another, as opposed to a straightforward sinistral shear development as might be expected to produce such geometry. The FSZ preserves a dextral shear-dominated kinematic evolution. However, an earlier history of sinistral kinematics is locally preserved. The FSZ is interpreted as a relatively old structure that was later folded about the S-bend with associated northeast-trending folds. Younger sinistral and east-side-up components of relative motion along the NSZ subsequently produced an apparent regional-scale drag fold that overprinted northeast-trending folds, accentuating the S-bend geometry.

The determination of the structural evolution for the S-bend region represents an important step toward a holistic tectono-metamorphic and magmatic framework for the east Albany–Fraser Orogen and the economically important mineralization that it hosts. Future work will combine oriented microstructural analysis with the field- and aeromagnetic-based structural observations, thermodynamic modelling, and in situ dating of microstructurally constrained accessory phases to establish the pressure–temperature–time–deformation (P–T–t–d) histories of the different tectonic units.

## References

Ramsay, JG 1962, Interference patterns produced by the superposition of folds of 'similar' type: Journal of Geology v. 70, p. 466–481.

Spaggiari, CV, Kirkland, CL, Smithies, RH, Occhipinti, SA and Wingate, MTD 2014b, Geological framework of the Albany–Fraser Orogen, *in* Albany–Fraser Orogen seismic and magnetotelluric (MT) workshop 2014: extended abstracts *compiled by* CV Spaggiari and IM Tyler: Geological Survey of Western Australia, Record 2014/6, p. 12–27.

Spaggiari, CV, Occhipinti, SA, Korsch, RJ, Doublier, MP, Clark, DJ, Dentith, MC, Gessner, K, Doyle, MG, Tyler, IM, Kennett, BLN, Costelloe, RD, Fomin, T and Holzschuh, J 2014a, Interpretation of Albany–Fraser seismic lines 12GA-AF1, 12GA-AF2 and 12GA-AF3: implications for crustal architecture, *in* Albany–Fraser Orogen seismic and magnetotelluric (MT) workshop 2014: extended abstracts *compiled by* CV Spaggiari and IM Tyler, Geological Survey of Western Australia, Record 2014/6, p. 28–51.