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Contact between tightly-folded Proterozoic quartz-mica schists and phyllites (Keith Schist) and the overlying massive Permian diamictite (Wynyard Tillite). The irregular, uncomfortable contact between the underlying schists and the diamictite is well exposed to the left of the waterfall. Campbells Rivulet; 372825 mN, 5439215 mE (GDA94), looking NE. Photo Credit - Carl Jackman.

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Structural Geology of the Keith River - Lyons River area, NW Tasmania

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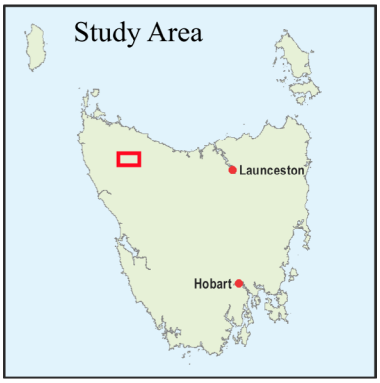


ABSTRACT

The Proterozoic rocks of the Keith River - Lyons River area span the northern Arthur Metamorphic Complex (AMC). The main lithological units of the AMC are, from east to west, the Oonah Formation, Keith Schist, Victory Springs Formation, Champion Schist and Bird Phyllite. These units share transitional metamorphic, interpreted low angle faulted, and possible conformable or unconformable contacts. At a regional scale a major north-plunging fold, or a large north-tilted block, is contained within the high-strain core of the AMC. Five deformation episodes can be observed at outcrop-scale. Three early deformational episodes are likely related to the Middle Cambrian Tyennan orogeny, manifested as early, high-strain events which caused isoclinal folding and development of schistose axial planar fabric. A rotational shear component, apparent as shear bands, suggests north over south or sinistral transport. Subsequent D3 deformation within the AMC likely occurred during the later stage of the Tyennan Orogeny. This event folded and tightened the various stacked lithostratigraphic units to form non-cylindrical asymmetric folds. These were later subject to generally northwest-directed, potentially Devonian compression (D4) and tilting. At a regional scale, late-stage north-plunging folds are inferred along the highest strain zone of the northern AMC. This area is a locus for Mesozoic or early Cainozoic faults, and a half-graben also extends along this zone, which is also in the core of the AMC. A late stage (D5) folding event may be partly related to Devonian compression, although the timing and nature of this folding event is largely unclear.

1.0 Introduction

The Keith 1:25 000 digital geological map sheet (400 km^2) includes parts of Keith, Lyons and upper Arthur Rivers in northwest Tasmania (Figure 1). The most notable feature of geological interest in the area is a moderately exposed section across the northern segment of the Arthur Metamorphic Complex (AMC), which is obscured to a greater extent by Permo-Carboniferous and Cainozoic cover to the north and immediate south. Several historic or active prospects fall on the Keith sheet, particularly within the Keith River Gossan Zone; commodities recorded include silver-lead, copper, gold, magnesite and talc.

An early investigation of the local regional geology (McNeil 1961) was followed by publication of the Burnie 1:63 360 (Gee et al. 1967) and St Valentines 1:50 000 (Baillie et al. 1986) geological map sheets, which together overlap with the eastern third of the Keith sheet. Most of the remaining area was mapped in 1990-93 by D. B. Seymour and J. L. Everard for the Trowutta 1:50 000 map sheet (Everard et al. 1996). In 2016-17, most of the southern margin of the Keith sheet was

mapped, and numerous new or more detailed traverses made elsewhere, by G. Cumming and C. Jackman. All mapping was digitised and used to compile the Keith 1:25 000 geological map sheet (Cumming and Jackman 2018). A small inaccessible area around the upper Lyons River remains unmapped.

This report briefly outlines the geological setting of the region (Section 2, Figure 1), and the general features of six major mapped lithological units, from east to west (Section 3, Figure 2). The structural geology of each unit, based on field observations, is then described in detail (Section 4). Measurements of bedding, compositional banding, foliations and mesoscopic folds (axial surfaces and plunges) were used to construct form-line maps, and cross-sections, and a sequence of five deformation events are defined (in Section 5). Finally, the implications of the new data are discussed in terms of the overall regional context of the Arthur Metamorphic Complex (Section 6).

All grid references in the text (and map grids) are GDA94 datum and are MGA co-ordinates in Zone 55. All structure measurements are positioned and referred to in relation to true north. The abbreviation "D" refers to deformation event, where D1 relates to the first deformation event, D2, the second deformation event (and so forth). "F" refers to fold generation, where F1 folds are related to the first folding event (or D1); F2 are related to the second folding event (or D2) and so on. S0 refers to bedding, S1 refers to the earliest cleavage or foliation, S2 is the second foliation (etc.). The abbreviation Sm indicates modal schistosity. Structural Regions are made up of sub domains, and these are abbreviated to "Dm" in the text.

2.0 Regional Geology of the Arthur Metamorphic Complex

The Arthur Metamorphic Complex (AMC) is a 5-10 km wide, 100 km long, high-strain metamorphic belt which trends northeast from Ahrberg Bay on the west coast, to near Wynyard on the north coast of Tasmania (Figure 1). It is derived from lithologically diverse protoliths with Proterozoic depositional ages, but the main deformation and metamorphism, once considered to have also been Proterozoic, has been demonstrated to be Cambrian (Turner 1992; Turner et al. 1998). The AMC is intersected by numerous faults, spanning several generations, and large segments are obscured by Permo-Carboniferous and Cainozoic cover rocks.

The metamorphism and deformation of the AMC is attributed to the Cambrian Tyennan Orogeny, during which an east-facing oceanic island arc collided with a Proterozoic passive continental margin (Berry and Crawford 1988). During this event, parts of the arc were obducted westwards or south-westwards over a passive margin. These are preserved as allochthonous remnants (boninitic and arc tholeiitic volcanics, associated ultramafic cumulates and sedimentary sequences) east of the AMC. Parts of the passive margin were also partially subducted and then rapidly exhumed during post-collisional crustal re-equilibration (Meffre et al. 2000). These are preserved as the western Tasmanian metamorphic complexes, the largest of which is the AMC.

Throughout its length, the AMC is flanked to the east by a Neoproterozoic quartz turbidite sequence, the Oonah Formation. The main unit to the west of the northern AMC is the Mesoproterozoic Rocky Cape Group, but in the Corinna-Savage River area a Neoproterozoic volcano-sedimentary unit, the Ahrberg Group, unconformably overlies the Rocky Cape Group. In that area the contact between the Ahrberg Group and the Arthur Metamorphic Complex is faulted, but the AMC contains mafic schist and amphibolite units (termed the Timbs Group by Turner 1992 and the "eastern Ahrberg Group" by Holm and Berry, 2002; Holm, 2002) which are considered to be metamorphosed equivalents of the Ahrberg Group. Proximal to the eastern margin, the southern AMC also includes the Bowry Formation; a distinctive unit characterised by early high-pressure metamorphism (Holm, 2002), which also hosts the Savage River magnetite deposits.

Although relationships between lithostratigraphic units in the southern and northern AMC require further study, some units in the Keith and Lyons River area can be loosely correlated with the Timbs Group. Newly published U-Pb detrital zircon data (Mulder et al. 2020) also supports the correlation, long suspected on lithological grounds (e.g. Turner, 1989), of the recently defined Victory Springs Formation with the Bowry Formation.

3.0 Lithostratigraphic units of the study area

The major Proterozoic lithostratigraphic units in the Keith and Lyons River area strike northeast-southwest (Figure 3), and are described in detail below. Intensity of deformation and metamorphism ranges from weak to very strong. Individual units do not form a stratigraphic sequence, and contacts between each are either transitional metamorphic, faulted, inferred unconformable or undetermined. Contacts between the Victory Springs Formation and the Champion Schist are obscured by a partly fault-bounded block of Permo-Carboniferous strata.

To the northeast, the Oonah Formation, Keith Schist and Victory Springs Formation are obscured by Permo-Carboniferous strata, although the Oonah Formation also crops out in the Burnie area. The Champion Schist and Bird Phyllite can be traced north-eastward to the Lapoinya area (where Gee et al. 1967 referred to them as the Keith Metamorphics), and isolated exposures assigned to the Champion Schist crop out in the Inglis River near Wynyard. The Jacob Quartzite can be traced to the north coast.

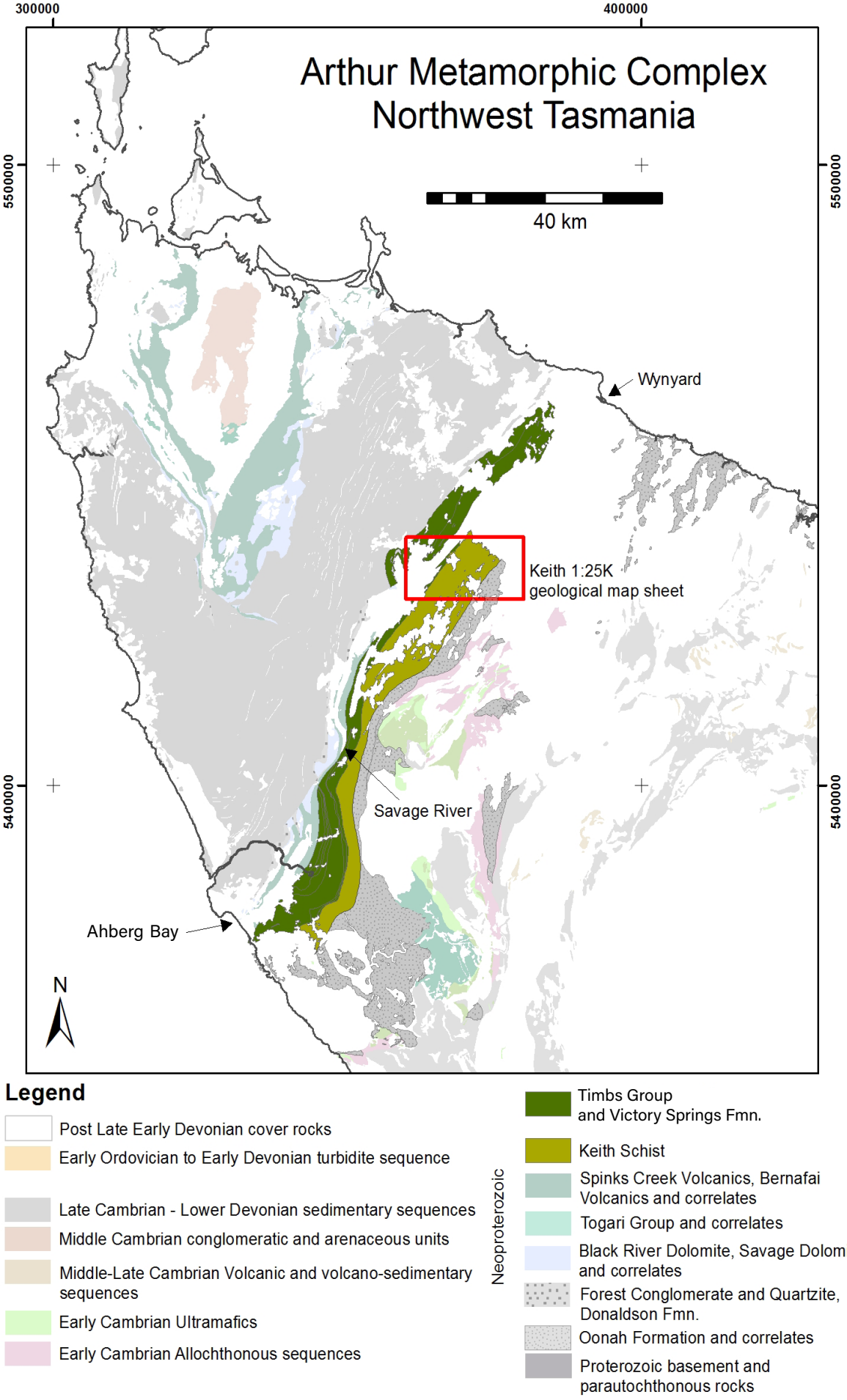


Figure 1. Summary geological map based on 1:25 000 geological compilation showing the extent of the Arthur Metamorphic Complex (in dark green), the main lithological host to the Savage River iron ore body, and the magnesite deposits at Keith is the Bowry Formation. Extensive post Early Devonian cover rocks obscure the AMC to the north, but it outcrops near the coast at Wynyard.

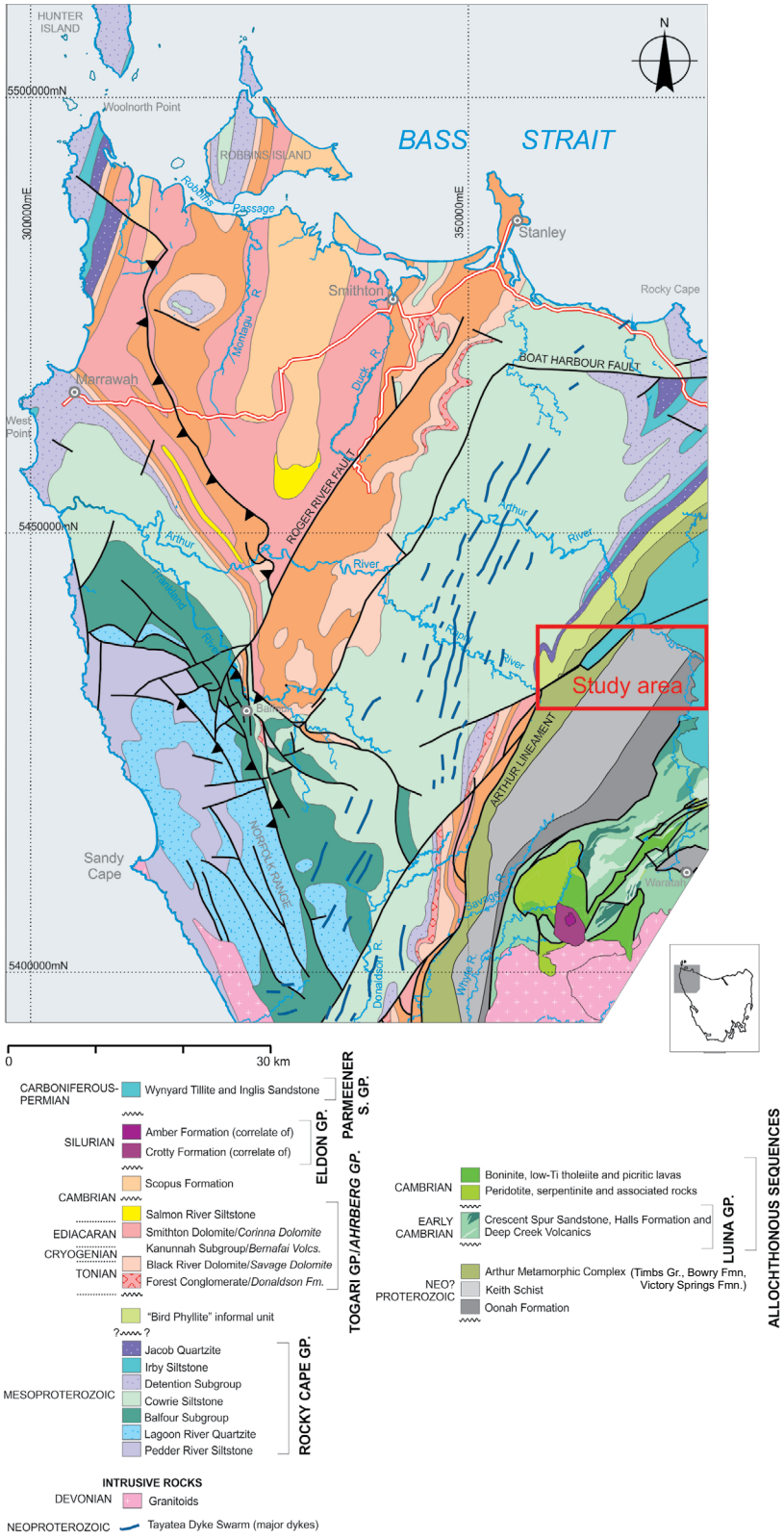


Figure 2. Regional geological map of far northwest Tasmania showing the extent of the Arthur Metamorphic Complex and the study area (adapted from Calver et al. 2014).

These units have not been identified to the southwest due to the inaccessibility of the country and Cainozoic basalt cover.

Oonah Formation

The Oonah Formation forms an east-dipping, northeast-trending belt up to 3.5 km wide in the southeast of the study area (e.g. in the Arthur River upstream of the confluence of the Hellyer River, and on adjacent forestry roads; Figure 3). It is composed mainly of massive quartz sandstone with rare, thinly-bedded to stratified, ripple-laminated sandstone and minor greywacke, pelitic siltstone and mudstone. In Halfway Creek, large boudins of silicified dolostone are enclosed within grey-green, pale brown weathered, fine-grained phyllite.

In the east, the unit has a weak slaty cleavage which gradually increases to a strong phyllitic schistosity in the west. Metamorphic grade is of prehnite-pumpellyite to lower greenschist facies. The contact between the Oonah Formation and Keith Schist mostly appears to be a transitional metamorphic boundary, but in a few outcrops rocks of contrasting metamorphic grade are juxtaposed by vertically dipping, northeast-southwest-trending faults. It is probable that, within the mapped area, these units are locally tectonically intercalated as fault-bound blocks.

Mulder et. al. (2018) obtained a U-Pb apatite age of 733 ± 9 Ma from a syn-sedimentary dolerite within the Oonah Formation at Burnie, 40 km northeast of the Keith area, and used detrital zircon and monazite data to support a correlation with the base of the Togari Group (in the Smithton area) and the Ahrberg Group. This interpreted correlation provides at least an approximate depositional age for the Oonah Formation in the study area.

Keith Schist

The Keith Schist consists of quartz-mica schist with lesser quartzite, phyllite, and rare dolostone. The terms Keith Schist and Oonah Formation have previously been used by Geological Survey geologists to define areas of differing strain in the AMC and the Keith Schist has been differentiated from the Oonah Formation due to its higher strain intensity. The dominant schistosity in the Keith Schist is parallel to bedding and has similar orientations to that in the Oonah Formation. Isoclinal folds and a well-developed schistosity are present in both, although the Keith Schist has been subject to higher metamorphic grade (greenschist to amphibolite facies), which increases to the west (as observed along the Keith River). However, within the Keith Schist there are pod-like zones, up to 2 km across, which are less intensely metamorphosed, and in which primary sedimentary features are preserved.

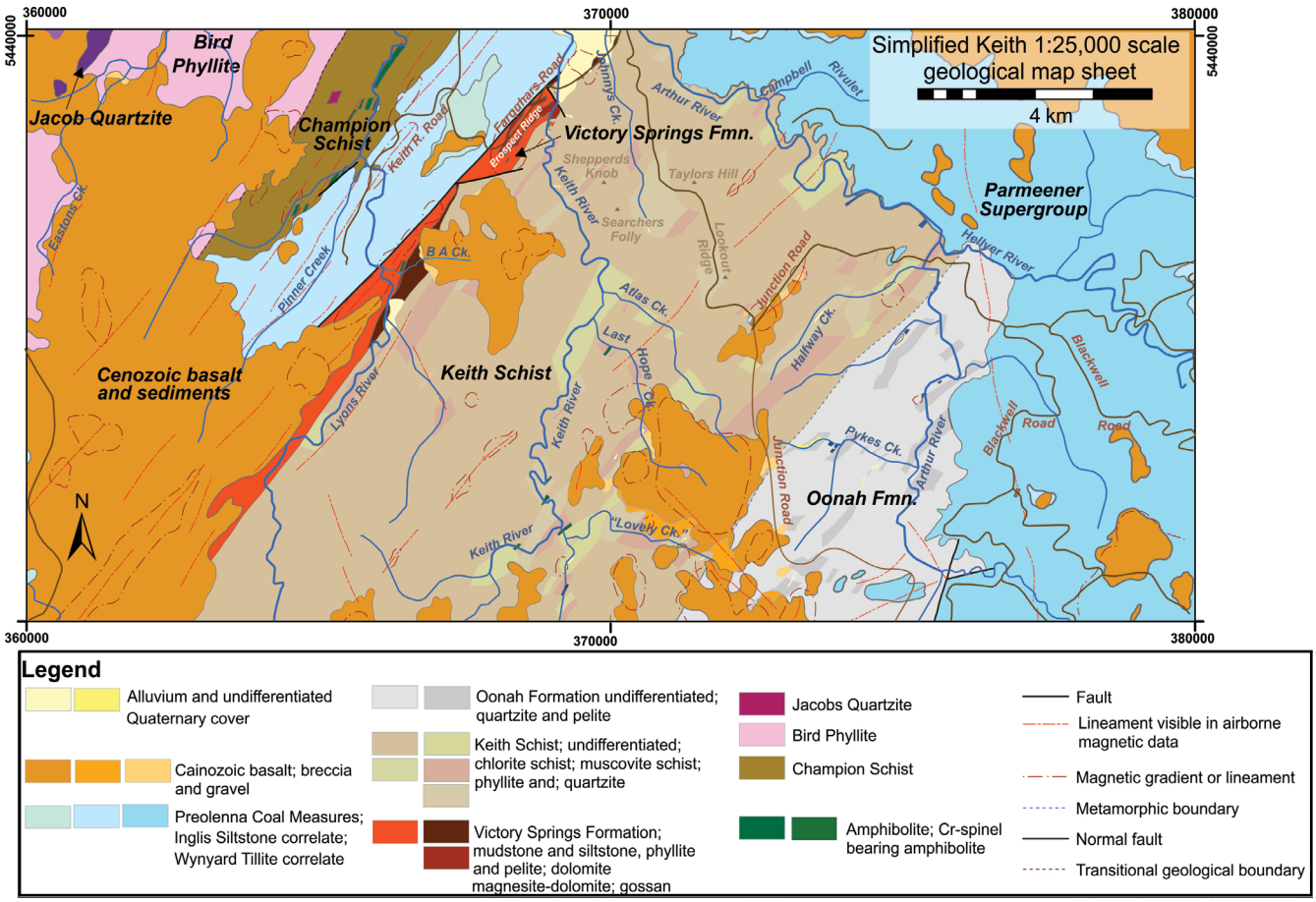


Figure 3. Summary geological map of the Keith 1:25 000 scale map sheet, northwest Tasmania, showing the key Neoproterozoic units within and surrounding the Arthur Metamorphic Complex (adapted from Cumming and Jackman, 2018) with key localities indicated.

Recent detrital zircon studies (Mulder et. al. 2020) indicates that the zircon provenance of the Keith Schist is distinctive, and suggests a correlation with the host succession at Savage River, rather than the Oonah Formation.

Victory Springs Formation (including the Keith River Gossan Zone)

This newly defined unit (J. L. Everard, Australian Stratigraphic Units Database, definition card 2019) is herein formally published.

The Victory Springs Formation dominantly consists of mudstone, phyllitic mudstone, siltstone, quartzite, carbonate (dolomite and magnesite), minor quartz-mica schists and rare amphibolite, with intervals of hematite-limonite-pyrite gossan. It crops out as a linear, northeast-southwest oriented partly fault-bounded block ~12km long and up to 900m wide, extending from near Victory Springs (370420mE, 5440685mN) to the middle-upper Lyons River area (~363110mE, 5431100mN). The type section is specified as exposures in the Lyons River between (~366125mE, 5435000mN) and (365940mE, 5435970mN), accessible from the end of Farquhars Road (Figure 3).

The unit is characterised by high-strain, low metamorphic grade and the presence of podiform lenses of dolostone and magnesite-stone. It incorporates thin folded units of hematite-limonite-pyrite gossan, which have been referred to as the Keith River Gossan Zone.

The Victory Springs Formation is juxtaposed against Permo-Carboniferous strata (Inglis Formation) by a northeast-southwest trending fault to the northwest. To the southeast, contacts with the Keith Schist are in part intersected by northwest- and west-southwest trending faults. The unit is concealed beneath Cainozoic basalt to the southeast.

Champion Schist

This stratigraphic unit was introduced informally by Everard (1999), formally defined in 2019 (Australian Stratigraphic Units Database, definition card) and is herein published.

The Champion Schist consists of chloritic schist, with minor pelitic schist, phyllite, dolomite and magnesite, and more-or-less concordant amphibolite bodies. The type section is specified as exposures in the Arthur River, between (367500mE, 5442870mN) and Tiger Bend (368200mE, 5440450mN), on the Folly 1:25 000 map sheet (Everard and Seymour, 1998). The best outcrops on the Keith sheet are in the Lyons River and in an unnamed creek northwest of Pinner Creek

To the northwest, the Champion Schist structurally overlies the Bird Phyllite. It is distinguished from the Bird Phyllite by its schistose fabric, dark green hue (typically weathering to a dark brown soil), the presence of amphibolite bodies and the lack of quartzarenite

beds. The contact with the Bird Phyllite is apparently concordant and is probably conformable or transitional, although a locally faulted contact is possible.

To the southeast, the Champion Schist is faulted against, or unconformably overlain by, Permo-Carboniferous Inglis Siltstone (Lower Parmeener Supergroup). On the Keith sheet, the non-linear trace of the mapped contact, and presence of possible basal conglomerates in the adjacent Inglis Siltstone, suggest a landscape unconformity. For example, a small inlier of chloritic schist and amphibolite crops out in the Lyons River near a bridge on a disused vehicular track (365960mE, 5437755mN) and is surrounded by Inglis Siltstone. A pebble-cobble conglomerate assigned to the Inglis Siltstone crops out on the northern bank of the Arthur River for ~200m below Tiger Bend (368200mE, 5440505mN), with chloritic schist and amphibolite on the opposite (southern) bank. Possible basal conglomerates in the Inglis Siltstone, adjacent to the Champion Schist, were also noted at 366400mE, 5438975mN, and in a creek north of Pinner Creek (~366510mE, 5437655mN; 363880mE, 5436325mN), although alternatively these outcrops may correlate with the Wynyard Tillite. D. B. Seymour (in Everard et al. 1996) inferred a faulted contact between the Champion Schist and Permo-Carboniferous strata north of the Arthur River.

The Champion Schist extends north-eastward to at least the Moorleah area (~384600mE, 5461700mN), and small outcrops in the Inglis River near Wynyard (~390800mE, 5463400mN) are probable correlates. To the southwest it is covered by Cainozoic basalt in the upper Pinner Creek area (~363000mE, 5436200mN). The true stratigraphic thickness of the Champion Schist is difficult to estimate due to deformation. The apparent thickness is approximately 1.5 km on the Keith sheet, increasing northward to about 2.2 km in the type area, and up to 4.5 km in the Flowerdale River area.

Amphibolites intercalated with the Champion Schist are tholeiitic in composition, usually weakly cleaved and mostly consist of albite, epidote, chlorite, actinolite and titanite, an assemblage typical of low-grade (greenschist facies) metamorphism. This may be a retrograde, as sodic amphibole indicative of earlier high pressure (≥ 560 MPa) blueschist facies conditions is preserved in an amphibolite in the Flowerdale River (Everard 1999).

The likely protolith of the Champion Schist was dominantly mafic volcaniclastics intercalated with pelitic mudstone, carbonate and tholeiitic basalt flows, probably deposited in a shallow marine environment. A correlation with similar western Tasmanian Neoproterozoic sequences such as the Kanunnah Subgroup (Togari Group), middle Ahrberg Group and Crimson Creek Formation is likely.

Bird Phyllite

This name was first used informally by Everard (1999), and a formal definition (Australian Stratigraphic Units Database, definition card) is herein published.

The Bird Phyllite dominantly consists of dark grey to grey-green phyllite, with lesser pelitic schist, foliated quartzarenite and well-bedded dolostone. The type section is on the Arthur River, from a point 250m downstream of the site of Hilders Bridge (366500mE, 5445850mN) to a point ~4 km upstream (367500mE, 5442870mN).

To the southeast, the unit has a concordant, probably conformable or transitional contact with the Champion Schist, as described above. To the northwest it overlies the Jacob Quartzite (Rocky Cape Group), probably due to a low angle unconformity. Basal siliciclastic cobble-pebble conglomerate is observed outside the type section (in Eastons Creek around ~364000mE, 5443000mN; and on the Pipeline Road near 359300mE, 5437200mN; Figure 4).

On the Keith map sheet, the Bird Phyllite is largely concealed by Cainozoic basalt cover, with limited outcrops in upper Eastons Creek and upper Pinner Creek. More extensive outcrops occur in Eastons Creek and Wedge Creek to the north on the adjacent Folly map sheet. The unit can be traced north of the Arthur River beneath intermittent basalt cover to the Lapoinya-Moorleah area (~382500mE, 5460900mN).

The presence of basal conglomerates on the Rocky Cape Group, intercalated dolostones and overlying mafic volcaniclastics (Champion Schist) suggests that the unit represents a metamorphosed and deformed correlate of the lower Togari Group, lower Ahrberg Group and Success Creek Formation. This is supported by detrital zircon studies, including a youngest concordant age of 769 ± 5 Ma (Mulder et al. 2020).

Jacob Quartzite

The Jacob Quartzite (Gee 1968, 1971) is the uppermost defined unit of the Rocky Cape Group. Only small tracts of this unit are inferred in the extreme northwest of the Keith map sheet, and no structural data were collected in this area.

In the type area on the north coast, the Jacob Quartzite is a well-bedded, well-sorted pure quartz sandstone with common cross-bedding and ripple marks, about 1.1 km thick (Gee 1971). It can be traced south-southwest from the coast, through the Meunna Hills and across the Arthur River to Blue Peak, immediately north of the Keith map sheet. In Eastons Creek the unit is mostly overturned and dipping steeply west. It consists of massive fine-grained grey quartzite interbedded with phyllitic siltstone.

The Jacob Quartzite thins further to the south-southwest and forms a prominent hill and strike ridges on both flanks of the Savage River Pipeline Road, immediately west of the Keith map sheet. Outcrops are scarce in this area, but platy quartzite, bleached siltstone and phyllite

Figure 4. Probable basal conglomerate of the Bird Phyllite, and correlate of the Forest Conglomerate. Stretched cobbles and small boulders of quartzite in a matrix of fine-grained phyllitic sandstone. The lineation defined by long axes of clasts plunges at about 10° to 195° . Cutting on east side of Savage River Pipeline Road, Beryl map sheet (359280mE, 5437180mN).

are exposed in road and track cuttings. The topography suggests that the unit is folded into a broad, gently south-plunging syncline, the western limb of which can be traced to just north of Roy Creek (357710mE, 5434440mN) where float of fine-grained quartzite was noted. The unit appears to be absent further south in the Rapid River area (~358000mE, 5432000mN).

4.0 Structure of the study area

Form-line maps of bedding, metamorphic foliation (Figure 5), and fold hinges (Figure 6), together with a simplified map showing modal fold hinges of the region (Figures 7 & 8) have been compiled. Modal values of dominant schistosity, bedding, fold plunge and axial surfaces were then used to define the boundary between structural regions. These values are shown in Figure 8 and summarised in Appendix 1. The modal values for each sub region (also referred to as "sub domain") were determined by plotting dominant schistosity, bedding, fold plunge and axial surfaces on a series of individual stereonets. The best fit great circle for the data points was then determined. Modal values for each domain and sub-domain are summarised in Appendix 1, and presented spatially in Figure 7.

4.1 Oonah Formation: Arthur River Region

The least metamorphosed Neoproterozoic sedimentary rocks ascribed to the Oonah Formation occur in the southeast of the mapped area (shown as Arthur River Region in Figure 8). Bedding can be measured, although the younging direction in these units is difficult to interpret. The units are consistently southeast-dipping and the dominant foliation is generally co-planar with bedding. Context with the neighbouring Keith Schist is illustrated through a series of cross-sections (Figure 9). Form-line maps and summary stereonet data for zones within the Oonah Formation are presented in Figure 10. A description of each structural domain, and specific traverses (Arthur River and Halfway Creek; Arthur River south of Junction Road and "Lovely Creek" area) is included below.

4.1.1 Northern Arthur River Region (Sub domain 4.3): Arthur River and Halfway Creek

Alternating quartz-muscovite schist and muscovite schist exhibit sigmoidal to lens-shaped quartz veins entrained within, and parallel to, the dominant foliation in the northern extent of the Oonah Formation (Figure 10; Dm. 4.3; around 373788mE, 5435424mN). West to northwest-trending sheeted chalcedonic white (buck) quartz veins up to 30 cm thick also cross-cut the dominant schistosity and are parallel to the F4 fold axes.

Large areas of alluvium drape the schists and silicified dolostone along Halfway Creek, limiting structural measurements. The dolostones occur as large boudins, enclosed within zones of pale-brown weathered, fine-grained, grey-green phyllite. The dolostone-rich blocks contain quartz veins which do not penetrate into the surrounding lithologies; but terminate at the edges and trend at an acute angle to the elongation direction of the boudins.

Upright, symmetrical, east-plunging and east-west trending F4 folds (indicated as blue arrows in Figures 5-8) and F5 folds (indicated as green arrows in Figures 5-8) were observed along the tributaries which drain into Halfway Creek. Both are fairly steep, and have north and northeast dipping axial surfaces. An earlier F1/F2 fold hinge (indicated as orange arrow in Figures 5-8) plunges to the southwest, with the axial surface dipping to the southeast (observed immediately south of Halfway Creek). Modal bedding measurements in this area are fairly consistent, dipping steeply to the southeast and trending northeast.

4.1.2 Central Arthur River Region (Dm 4.2): Arthur River, south of Junction Road and Pykes Creek

The central zone (Figure 10; Dm. 4.2) around Pykes Creek contains F1/F2 folds which plunge either to the southwest or northeast. Axial surfaces to these folds generally dip to the southeast. North-trending and steeply dipping F3 axial surfaces are also evident around

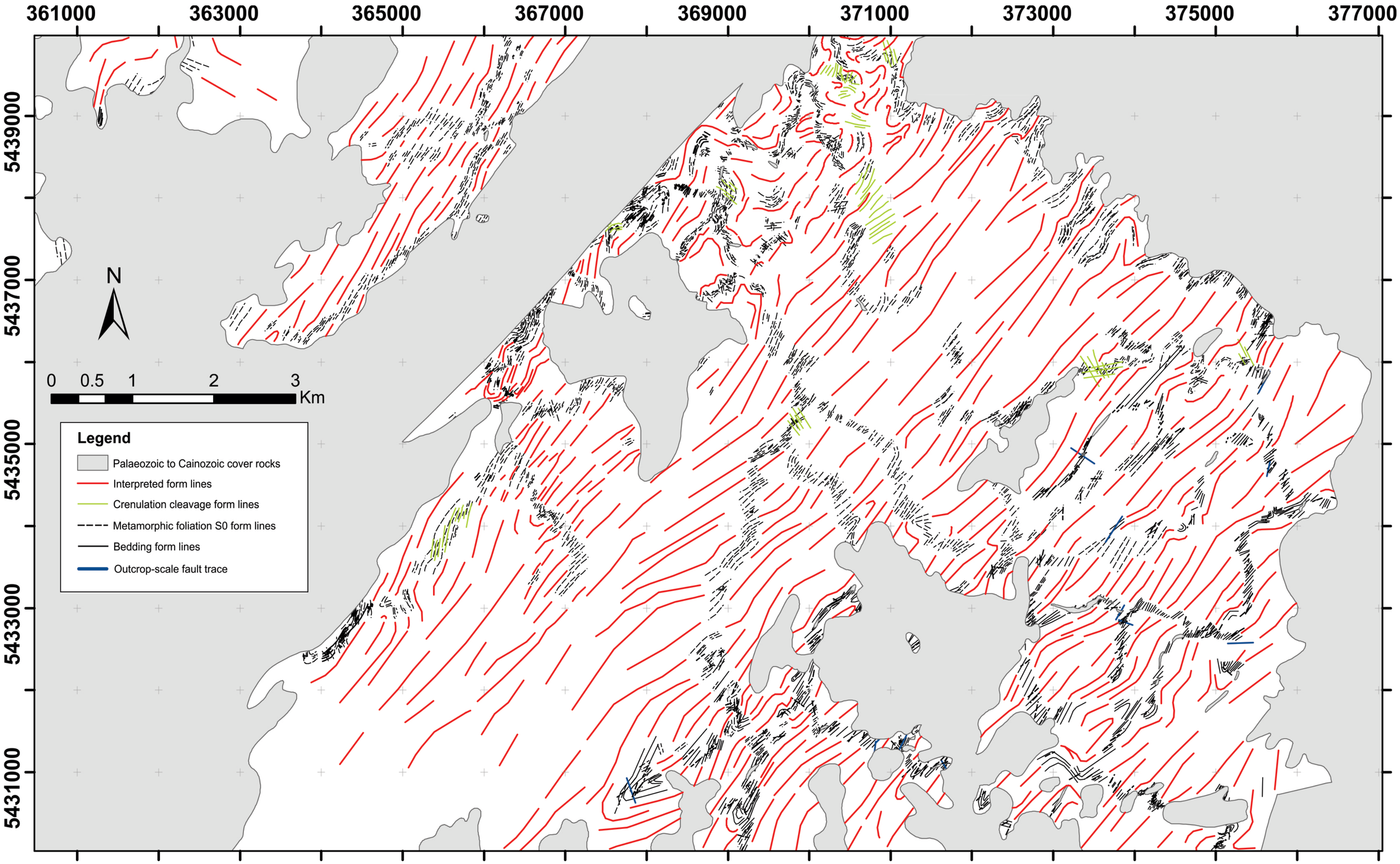


Figure 5. Structural form-line map of the Keith study area.

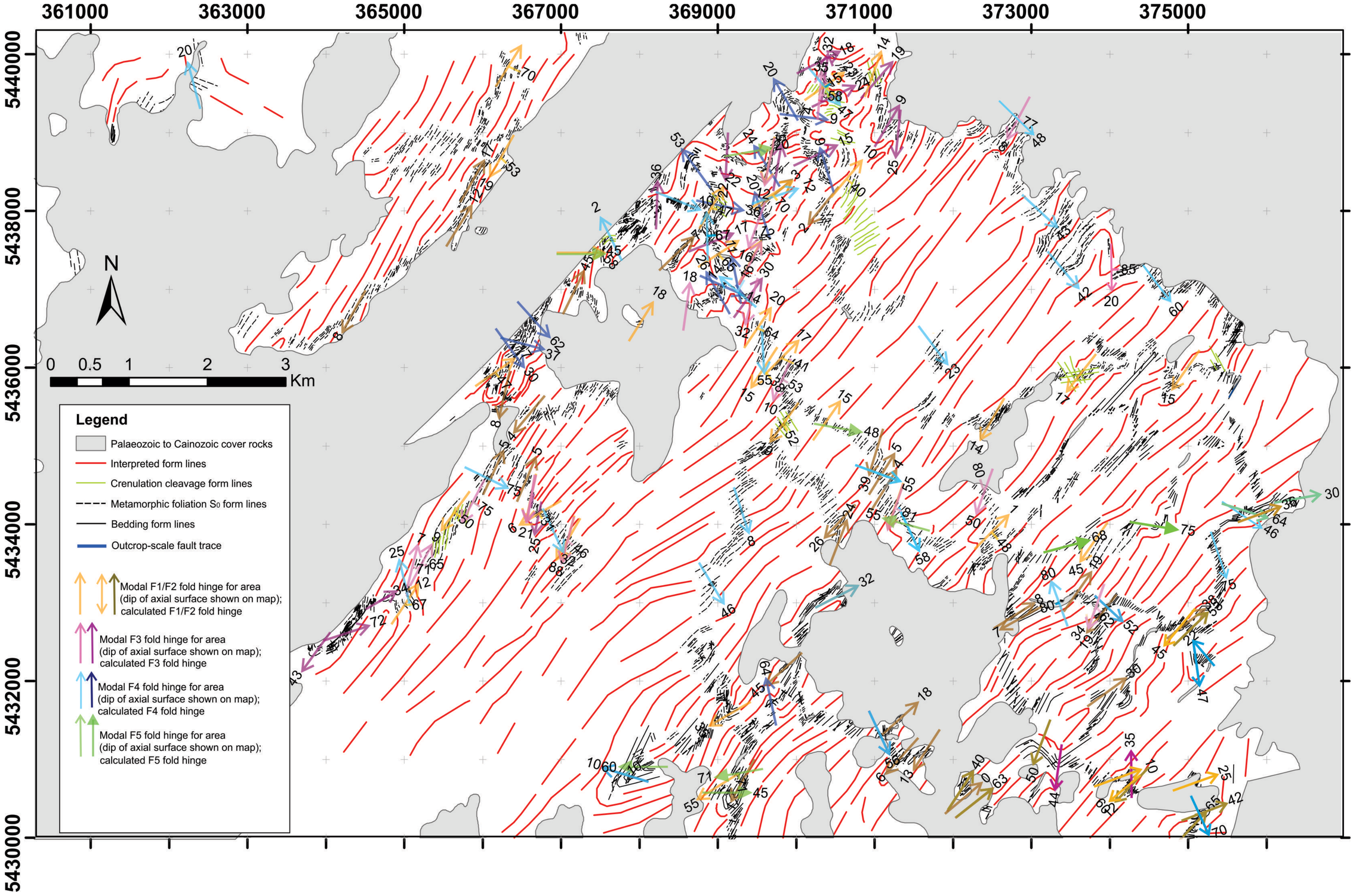


Figure 6. Structural form-line map of the Keith study area with fold hinge-lines and axial surfaces indicated.

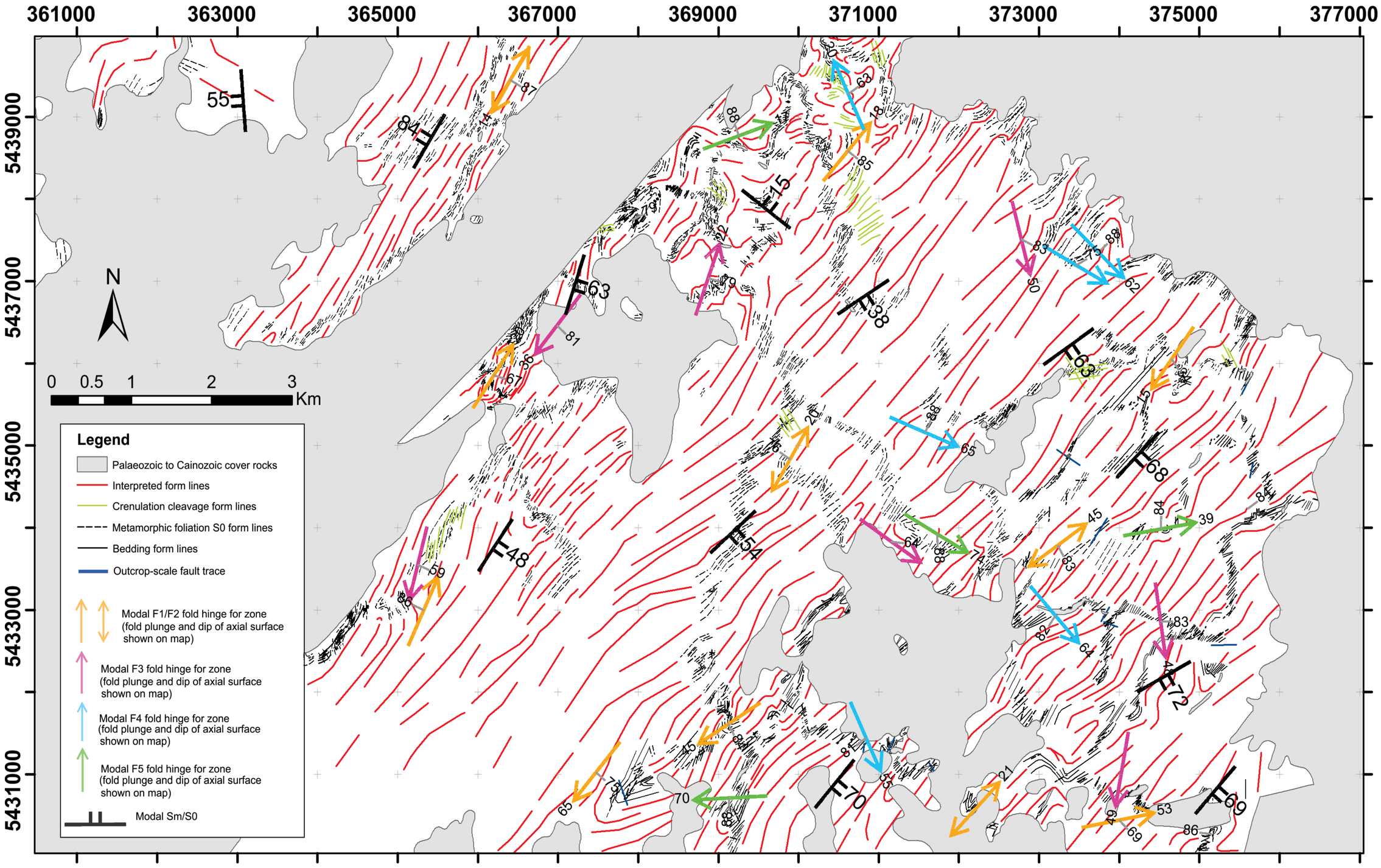


Figure 7. Structural form-line map of the Keith study area with modal fold hinge-lines, axial surfaces and modal values for dominant foliation.

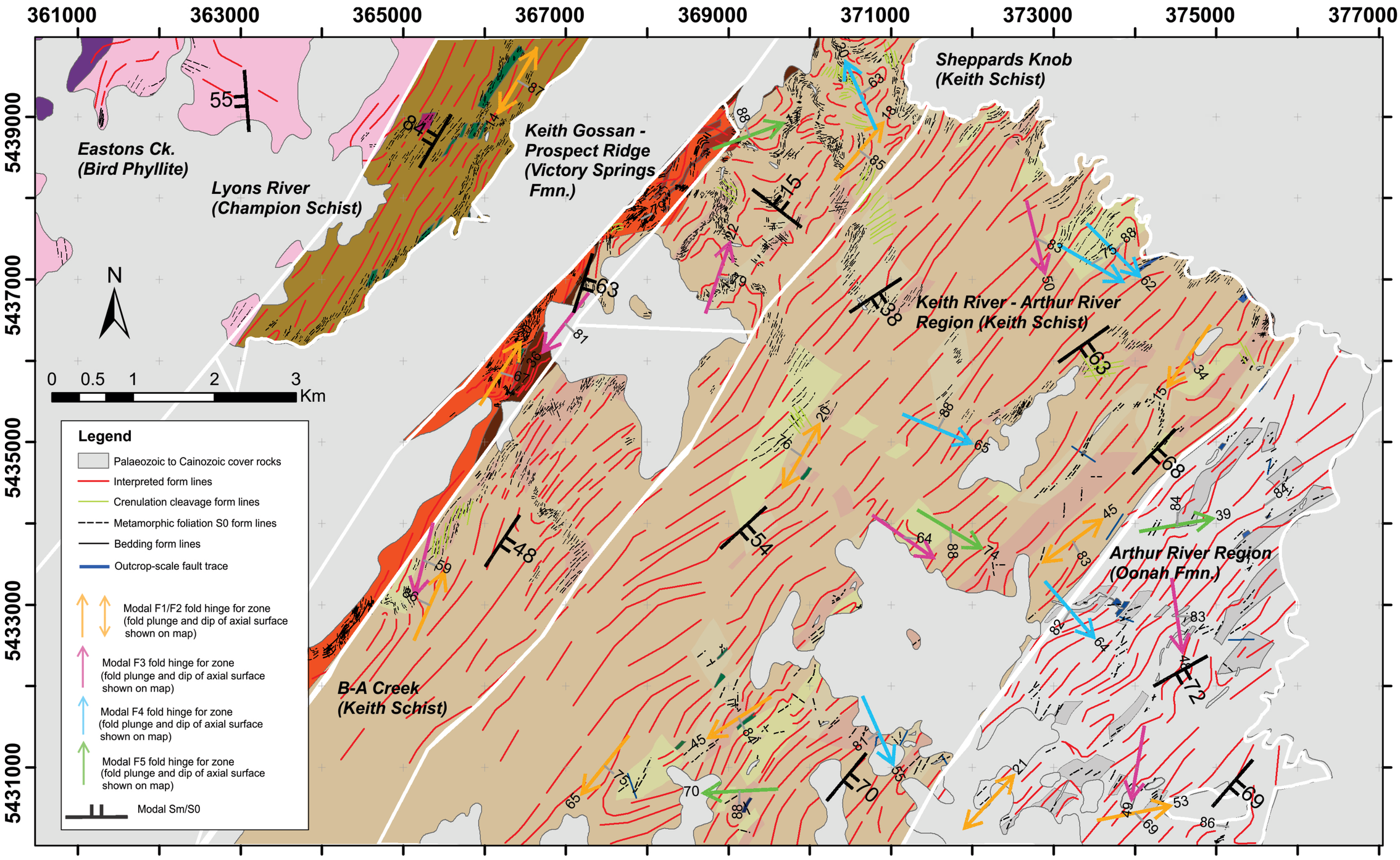


Figure 8. Structural form-line map and simplified geology of the Keith study area with modal fold hinge-lines, axial surfaces and modal values for dominant foliation, and modal bedding as indicated. Refer to Figure 3 for corresponding legend showing geological units.

Pykes Creek. F4 folds are southeast-plunging and have southwest-dipping axial surfaces. East-west (possible F5) folds are also observed in the central part of this area. A simplified representation of the contact between the Oonah Formation and the Keith Schist, along with schematic representation of fold data, is shown in cross-section A'-A" in Figure 9.

The regional structure of the Oonah Formation from Junction Road toward the Arthur River (northern part of Dm. 4.2 in Figure 10) is similar to the north, and dominated by consistent northeast-trending beds. Minor fold hinge orientations vary; southwest trending fold axes are evident south of Pykes Creek and along Junction Road. Interpreted F1/F2 fold hinges plunge to the southwest and axial surfaces dip to the southeast (Figure 10; a). A series of open, south-plunging F3 folds (indicated as pink arrows in Figures 5-8) with steep axial surfaces are also evident along Junction Road.

River exposures south of the confluence of the Hellyer and Arthur Rivers (Figure 10; Dm 4.2) consist of generally east-dipping units which contain south- to east-plunging kink folds, probably related to D4 deformation. Most of the area consists of massive quartz sandstone beds within pelitic intervals. S1 cleavage is manifest in the finer-grained pelitic intervals, and this is generally bedding-parallel, axial-planar or at a low angle to bedding (observed in the area near 375880 mE 5434550 mN) and reflects tight to isoclinal F1/F2 folding.

Asymmetric, outcrop-scale F1/F2 folds were observed halfway along Pykes Creek (Figure 11a and b). These plunge to the southeast or southwest (at 374885mE, 5432673mN). A highly folded zone is traceable for 135 m across several outcrops, but later (F4?) folds plunge to the southeast at 375021mE, 5432690mN, suggesting some refolding of these larger scale folds. Vergence patterns suggest a larger scale fold hinge to the west, as interpreted in cross-section A'-A" in Figure 8.

Bedding dips consistently east to southeast in this area, but in the western part of the Pykes Creek catchment, two large-scale, angular, tight to isoclinal fold hinges with relatively planar limbs are steeply inclined and dip to the northeast and possibly to the southwest (Figures 9 and 11b). This folded zone transitions into faintly banded (1 mm thickness) and fine-grained muscovite-talc schist (Keith Schist) on the ridge along Junction Road. This transition delineates the contact between the Oonah Formation and the Keith Schist and is depicted in a series of cross-sections (cross-section A'- A" in Figure 9).

Symmetrical northwest-trending F4 folds also occur in the upper part of the Pykes Creek catchment near Junction Road (see cross-section A'-A" in Figure 9) and south of Halfway Creek (374606mE, 5434004mN). These may be responsible for the variable plunge directions of the earlier F1/F2 folds in this area.

4.1.3 Southern Arthur River Region (Dm 4.1): "Lovely Creek" Area

The metamorphic intensity increases from east to west along "Lovely Creek" towards its confluence with the Keith River (cross-sections B and C in Figure 9). There is a gradational change from quartzite and phyllite (low to medium-grade Oonah Formation) in the east, to more mica-rich schistose units (Keith Schist), is apparent. Exposures along the eastern stretch of the creek contain abundant tight isoclinal F1/F2 folds that plunge to the southwest and northeast (cross-section B'-B" in Figure 9). Some more open folds occur (see Dm. 4.1; Figure 10) based on form-line interpretations. These areas, however, have been cross-cut by a series of west-dipping faults to the west of, and within, the Keith Schist. East of this faulted area, close to the margin with the Oonah Formation, folds generally plunge to the northeast, possibly due to buckling. Rare instances of F4 folds with southwest-dipping axial surfaces are also observed. Some interpreted F3 folds (indicated as pink arrows in Figures 5 to 8) plunge both to the south and north.

4.2 Keith Schist: Keith River – Arthur River Region

The Keith Schist encompasses a large northeast-trending zone of east-dipping quartzite, phyllite, quartz-muscovite, muscovite, and minor chlorite-muscovite schistose units. Cross-sections extending across the area are summarised in Figures 9 and 12. The area is structurally and lithologically diverse, and has been broken into 6 sub-regions, as depicted in form-line maps (Figures 13 and 14). The contact between more schistose and low-grade metamorphic facies near Arthur River appears gradational, but several outcrop-scale faults have been mapped (shown in cross-sections A'-A" and B'-B" in Figure 9, and C'-C" in Figure 12).

4.2.1 Southern Keith River - Arthur River Region (Dm 2.6, Dm. 2.4 and 2.1): Keith River and "Lovely Creek" Area

Near the confluence of the Keith River and "Lovely Creek", northeast trending schistose units form tight isoclinal F1/F2 folds that plunge steeply south-southwest (Dm. 2.4 and Dm. 2.1 in Figure 13). Much of the complexity in this area is related to structural deformation around the more resistant units (especially carbonate-rich bands, quartz-muscovite schists and amphibolite bodies). The dominant schistosity wraps around resistant units, especially in the chlorite and muscovite schists along the Keith River (368839mE, 5431345mN; Dm. 2.4 in Figure 13, and Figure 15 c). Shear sense can be determined in the chlorite schist and phyllitic units near the confluence of "Lovely Creek" and the Keith River (Figure 15 a; b) where weakly-developed shear bands suggest sinistral shear movement (Figure 15; a). Several folds with steep south-trending

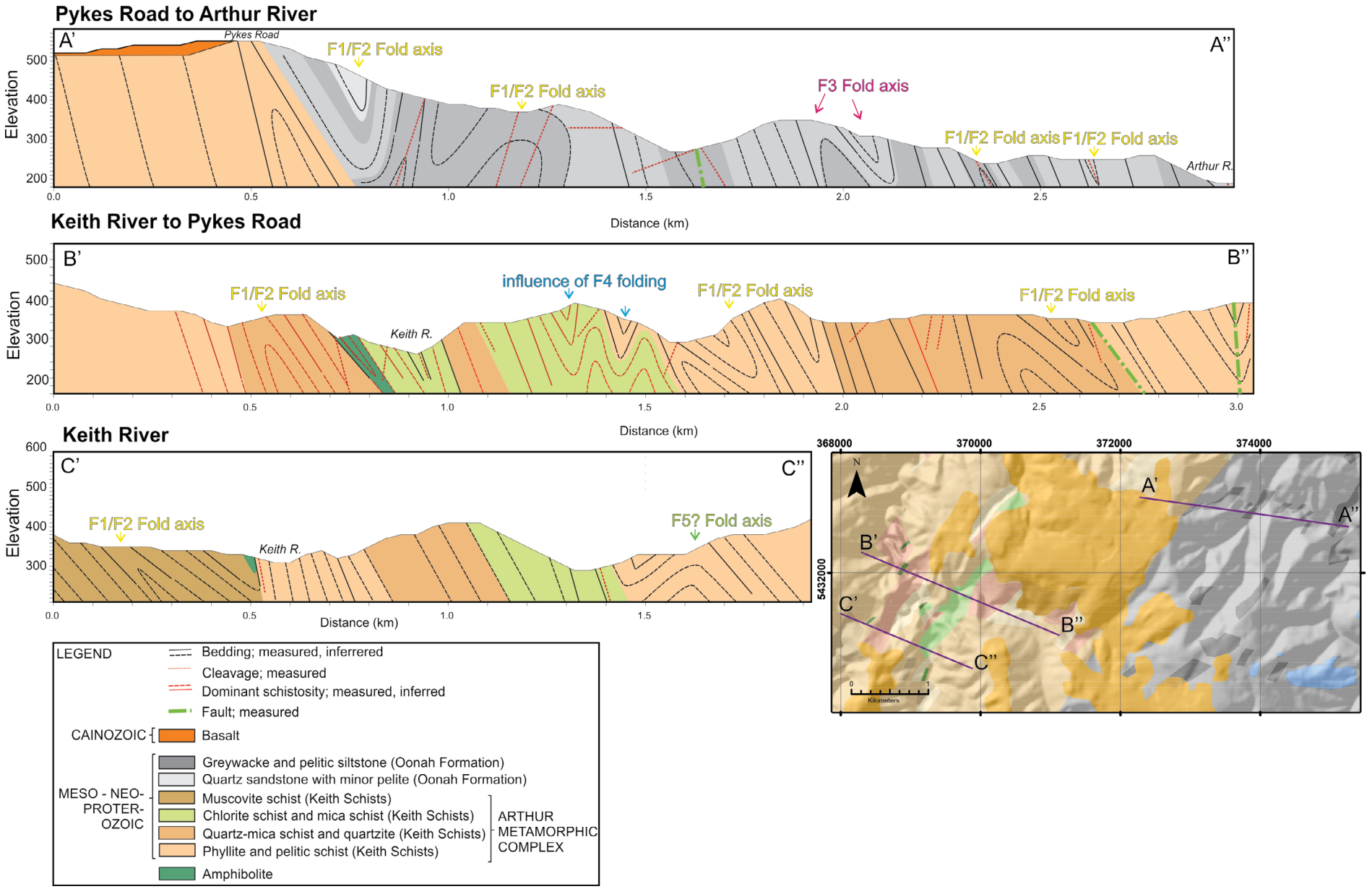
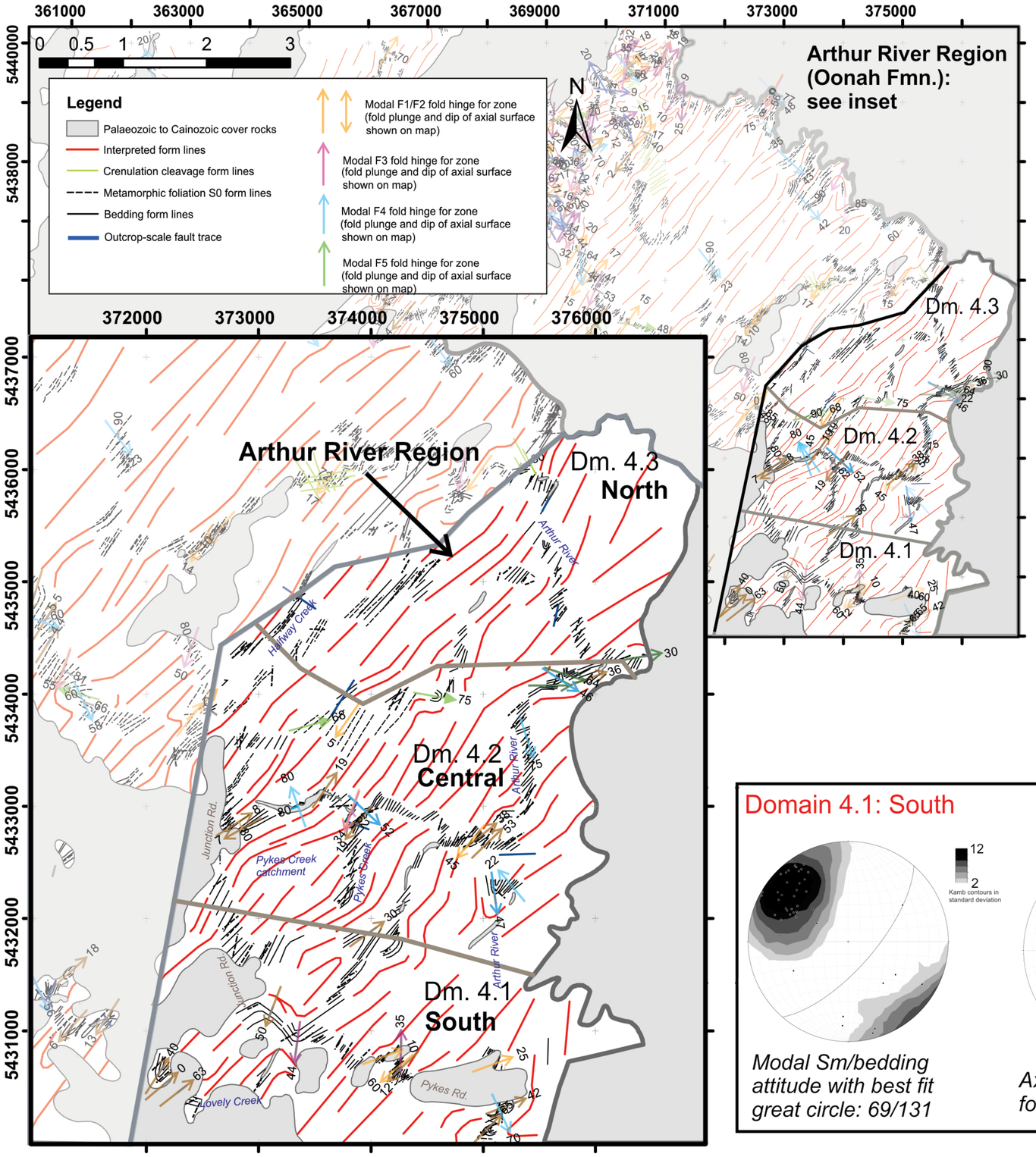
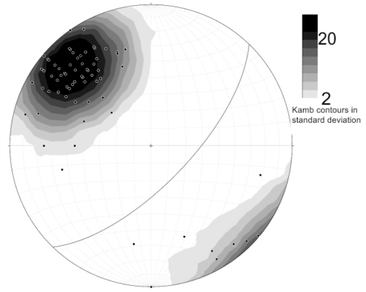


Figure 9. Interpreted cross-sections showing the contact between the Oonah Formation and the Keith Schist (A' to A"), and facies variations and fold-generation distribution in the Keith Schist parallel to "Lovely Creek" (B'-B") and Keith River (C'-C").

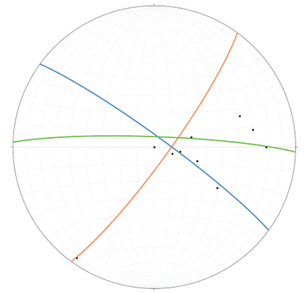


Domain 4.3: North

F1/F2: 82/144
F4: 84/54
F5: 84/001



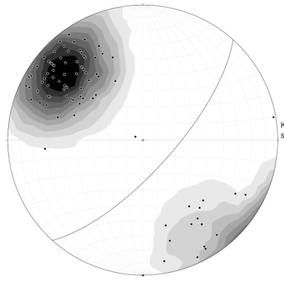
Modal Sm/bedding attitude with best fit great circle: 68/134



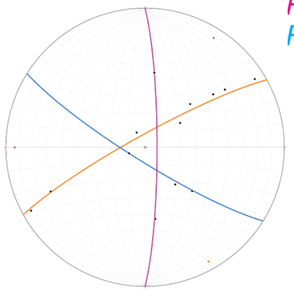
Axial surface "best fit" to fold axis

Domain 4.2: Central

F1/F2: 83/151
F3: 83/90
F4: 82/212



Modal Sm/bedding attitude with best fit great circle: 72/151

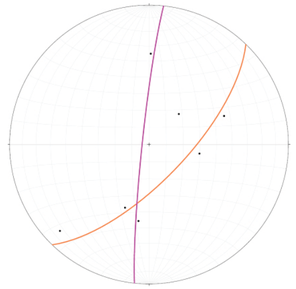


Axial surface "best fit" to fold axis

Domain 4.1: South

F1/F2: 69/136
F3: 86/276

Modal Sm/bedding attitude with best fit great circle: 69/131



Axial surface "best fit" to fold axis

Figure 10. Map of the Oonah Formation (Arthur River region) showing sub-domains, bedding, dominant foliation (Sm) form-lines, corresponding equal area stereonet plots of bedding/Sm attitude and best fit great circle with additional plots showing "best fit" great circles for fold axes.

axial surfaces generally plunge towards the west (Figure 15; d). These folds are assigned tentatively as F5 at this stage, although these may be related to northwest-trending F4 folds observed elsewhere. It is unclear if these overprint or pre-date the F4 folds.

Numerous fold closures have been interpreted based on structural data collected in the field. Small-scale pod-shaped zones can be observed in outcrop (Figure 15c) and at a more regional scale. A 500 m wide, up to 1 km long area comprised of more resistant lithologies was mapped along the Keith River near the southern edge of the map sheet. These resistant lithologies include amphibolite, quartzite and silicified pelitic units bounded by anastomosing high-strain zones. Silicified outcrops of pelitic siltstone preserve the early, bedding-parallel S1 cleavage and an overprinting S2 crenulation cleavage.

4.2.2 Central Keith River - Arthur River Region: Atlas Creek, Last Hope Creek and Keith River Area (Dm. 2.3)

Several traverses in the central part of the Keith River – Arthur River Region (Figure 13; Dm. 2.3) revealed a structurally complex area. The general schistosity dips gently and trends east-northeast. F4 and potentially F5 folds are particularly prevalent in this central zone, where the mode of axial surfaces dips steeply to the northeast. F5 folds plunge to the southeast (and west-northwest) and axial surfaces to these folds dip (mostly) to the south. Axial surfaces to early F1/F2 folds dip steeply towards the northwest, plunging mostly to the north-northeast. Interpreted F3 folds generally plunge to the south with west-dipping axial surfaces. The prevalence of D4 and D5 deformation may account for the change in modal schistosity (Sm) in this area.

The region contains steeply southeast-dipping, northeast-trending units in which the interpreted F1/F2 fold hinges are largely co-planar with the dominant schistosity, and axial surfaces dip steeply to the southeast. In Last Hope and Atlas Creek, units trend ENE and dip west, although less steeply than in neighbouring areas. The area to the north of Lookout Ridge (Dm. 2.2 in Figure 13) consists of gently-dipping units with southeast-plunging fold axes.

4.2.3 Northern Keith River - Arthur River Region: Campbell Rivulet, Searchers Folly and Upper Johnnys Creek (Dm. 2.5)

The northern part of the Keith-Arthur River Region comprises northeast-trending units. Most of this area was mapped during the mid-1990s by Everard et al., 1996 (1:50 000 scale Trowutta map sheet). Some new work was undertaken in the Campbell Rivulet, Johnnys Creek, Shepperds Knob and Searchers Folly areas. The dominant schistosity trends northeast and dips gently to the south-east in this zone. The F1/F2 folds in this region plunge to the southwest with gently southeast-dipping axial surfaces. Minor F3 folds are also present, and rare F4 folds were also observed.

A traverse along Campbell Rivulet and surrounding tributaries revealed a tightly-folded sequence of muscovite schists, phyllite and quartzite. Outcrop-scale F1/F2 folds were interpreted in this area (Figure 9). A weak, possible S3, non-penetrative spaced cleavage was observed in the more micaceous lithologies. This weak (late) cleavage correlates with the interpreted modal F3 fold orientation apparent in the Arthur River and outcrops to the west of Campbell Rivulet. The phyllitic units contain patchy zones with a strongly developed S3 crenulation cleavage. Northwest-trending axial planar cleavage was recorded in outcrop along the Arthur River and is probably due to late-stage F4 folding.

Exposures along Johnnys Creek immediately east of Shepperds Knob and Searchers Folly (Figure 15e) comprise complex folded quartz-mica schists, muscovite schists and phyllites. The dominant schistosity (Sm) in this area is probably an S2 fabric, with bedding and co-planar S1 fabric preserved in fold cores (Figure 15f). The Sm is a penetrative planar fabric and forms an axial planar cleavage to the asymmetric folds. South of 370380mE 5438150mN, the dominant foliation consistently dips gently to the southwest. North of this point, the F3 folds are increasingly evident and have disrupted the dominant foliation, although no associated F3 fold hinges were noted. Along strike, to the north at Arthur River, the interpreted F3 folds plunge gently to the south (discussed further below). Interpreted F4 folds with gentle northwest-plunging fold axes occur along a drill access track to the west of Johnnys Creek.

4.2.4 North-western Keith River - Arthur River Region: Shepperds Knob

The area around Shepperds Knob contains gently-dipping, highly folded units of muscovite schist, quartz-muscovite schist and phyllite (Figure 15 g). The area is complexly folded, and a structural pattern for this region was difficult to define. The modal values for dominant schistosity and bedding indicate that the units generally dip gently (~15°) to the northeast (Figure 8). Modal Sm is parallel to the axial surfaces of the F1/F2 folds. The modal plunge for the major fold in this area has been calculated and it dips gently (18°) to the northeast. F3 folds plunge gently to the north and northeast, with axial surfaces dipping steeply to the east. The generally northwest plunge of the F4 folds in this area contrasts with that of the regions mapped to the east and west. The east-north-east plunge of F5 folds also contrast with the neighbouring areas. Figure 13 shows complexly folded units with multiple fold generations observed at outcrop-scale. The relationships between the various fold generations from an outcrop in the Keith River at 368900mE, 5438010mN are presented in Figure 15g. Most folds plunge to the northeast and both modal bedding and schistosity in this area suggest

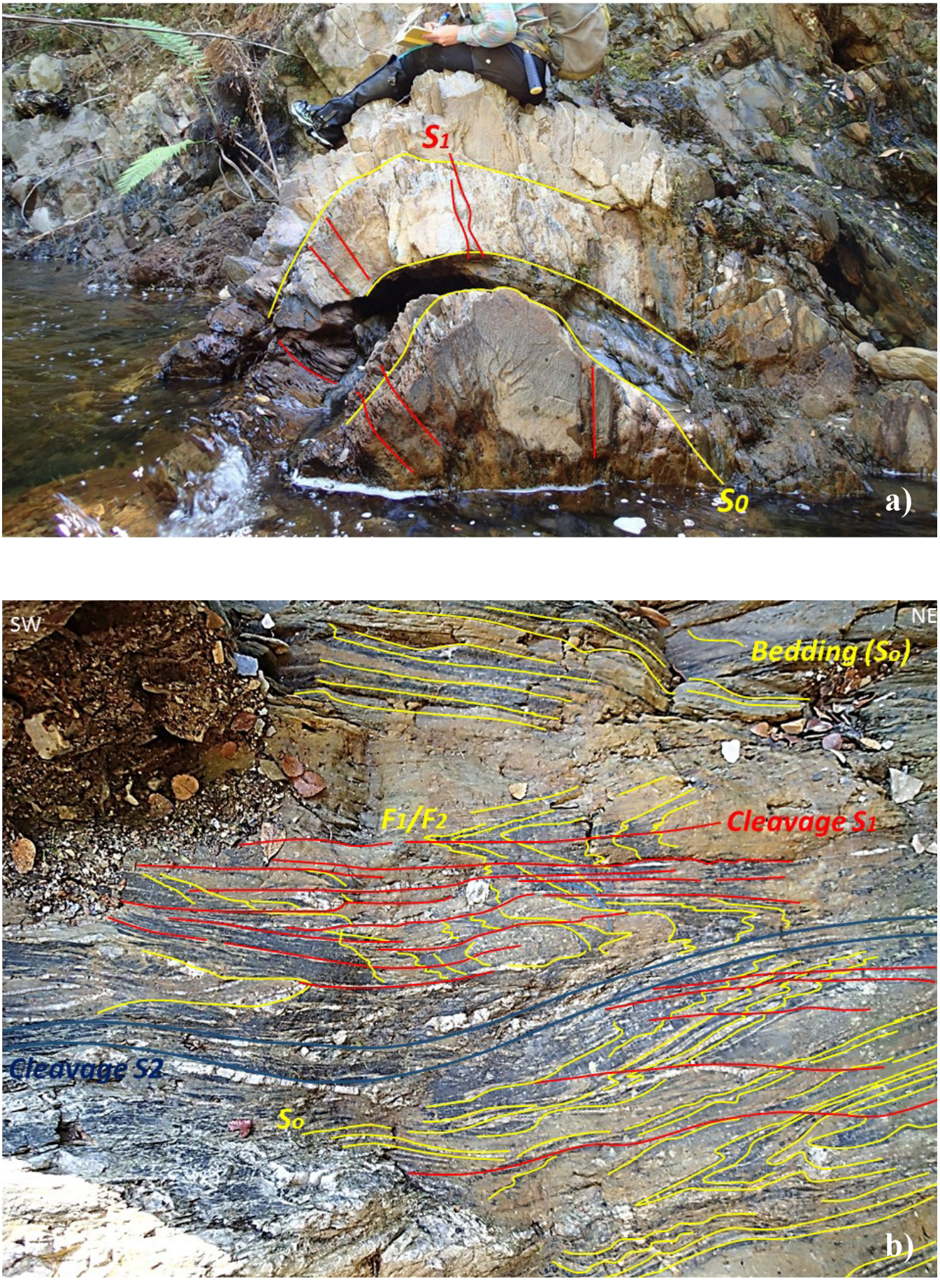


Figure 11. Outcrop-scale structures in the Oonah Formation:
a) Outcrop-scale, slightly asymmetric antiform with southeast-dipping axial surface and axial planar cleavage (indicated by red arrow). b) Isoclinal chevron folds preserve F1/F2 fold hinges along exposures in the upper part of the Pykes Creek catchment. Bedding is indicated in yellow, cleavage in red.

generally dip gently (~15°) to the northeast (Figure 8). Modal Sm is parallel to the axial surfaces of the F1/F2 folds. The modal plunge for the major fold in this area has been calculated and it dips gently (18°) to the northeast. F3 folds plunge gently to the north and northeast, with axial surfaces dipping steeply to the east. The generally northwest plunge of the F4 folds in this area contrasts with that of the regions mapped to the east and west. The east-north-east plunge of F5 folds also contrast with the neighbouring areas. Figure 13 shows complexly folded units with multiple fold generations observed at outcrop-scale. The relationships between the various fold generations from an outcrop in the Keith River at 368900mE, 5438010mN are presented in Figure 15g. Most folds plunge to the northeast and both modal bedding and schistosity in this area suggest the presence of a regional-scale northeast-plunging fold. Alternatively, the area could comprise a large pod of intensely folded units.

4.3 Victory Springs Formation

The narrow, northeast-trending zone encompassing the Victory Springs Formation is described from traverses conducted in the Keith Gossan-Prospect Ridge region, and B A Creek.

4.3.1 Keith River Gossan – Prospect Ridge Region

The Keith River Gossan and Prospect Ridge lies to the immediate west of Shepperds Knob and the B A Creek areas, where a thin northeast-trending zone approximately 500 m wide abuts a major Mesozoic or younger fault structure. The dominant lithologies comprise units of less-deformed phyllite, quartzite and schist, and also carbonate-rich units containing magnesite deposits. Very weakly-metamorphosed sandstones and siltstones with well-preserved primary sedimentary structures are also prominent in this area. These units appear largely conformable with the underlying Keith Schist. Several low to high-angle faults could enclose the less-deformed units. These faults are shown as interpreted structures in cross-sections in Figure 12.

F1/F2 and F3 folds are preserved and may be enclosed by high-strain contacts (similar to those observed along the Keith River and "Lovely Creek" areas). Several cross-sections (Figure 12) show the nature of this contact (Figure 16) and suggest that this zone preserves overturned F1 folds. On section C'-C'', overturned folds are probably obscured by Permian cover. F3 folds have modal plunges that dip to the south and north.

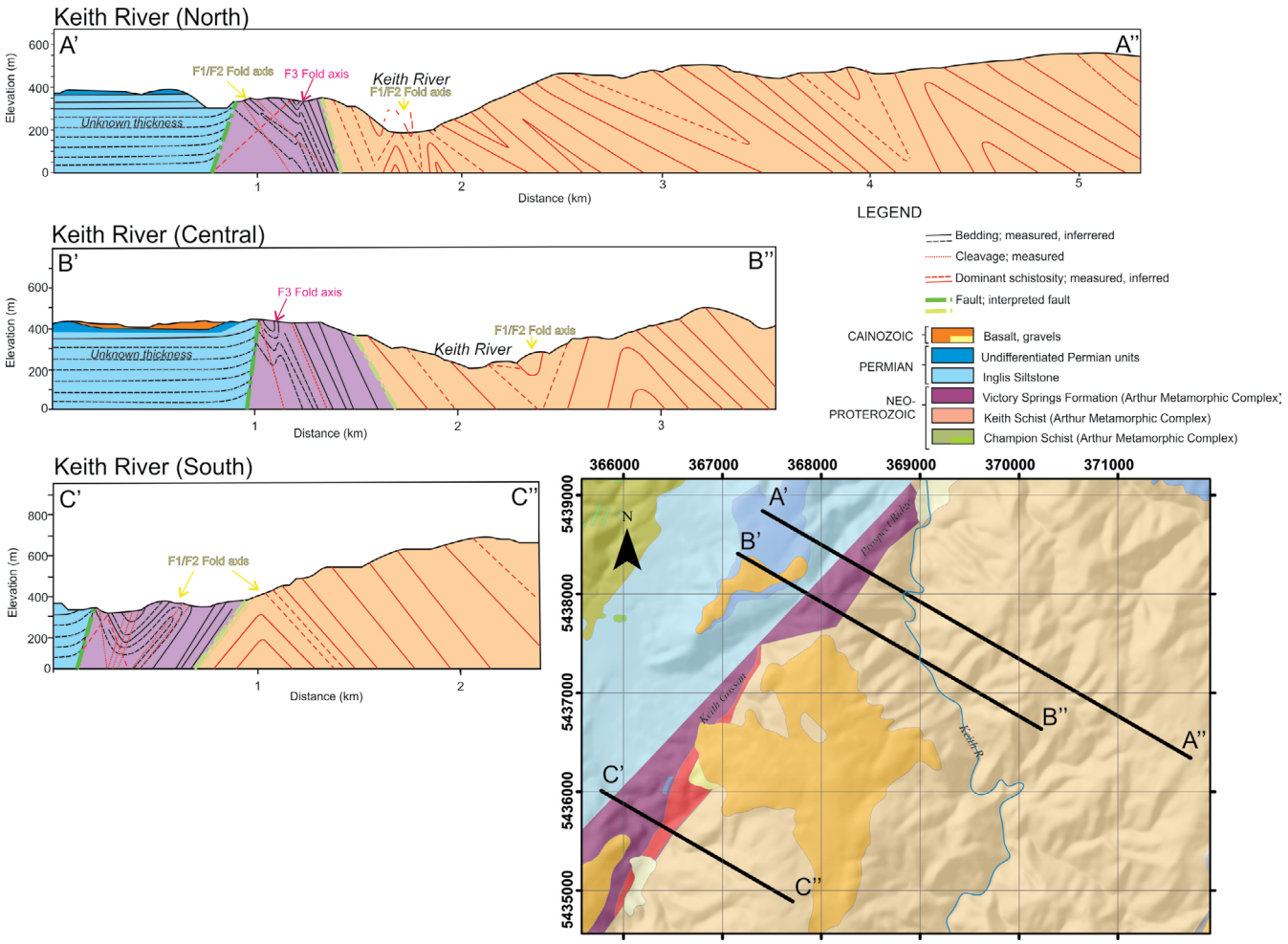


Figure 12. The Keith River Gossan and Prospect Ridge region occur as a linear zone (red and purple areas). The cross-sectional interpretations span from the Permian cover in the west (blue), through the Keith River Gossan zone and terminate in the Keith Schist to the east. A bedding-parallel fault is interpreted to form the eastern contact to the Victory Springs Formation (Bowry Formation correlate). The contact with the Permian unit is interpreted as a younger fault.

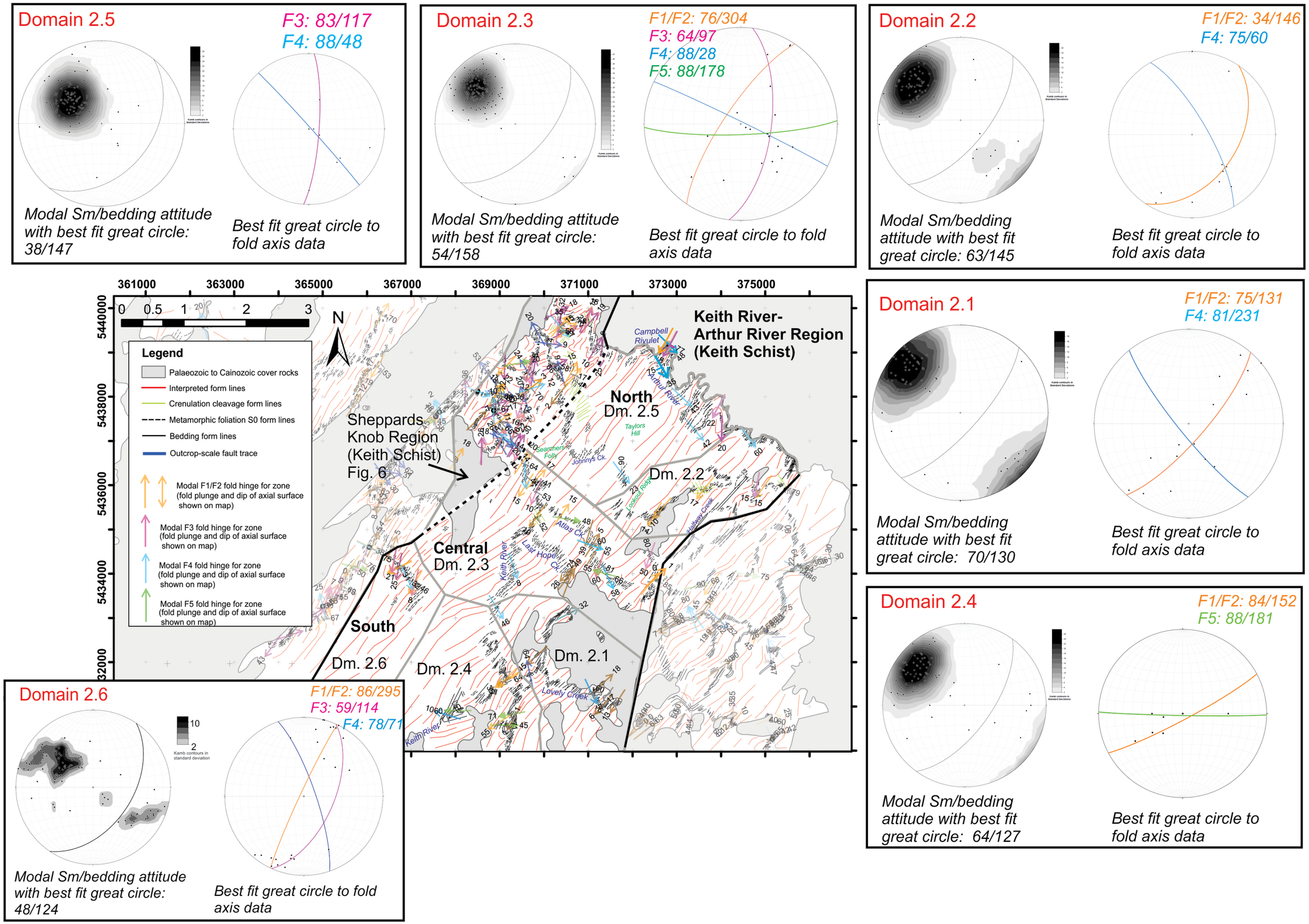


Figure 13. The Keith River-Arthur River region showing sub-domains, bedding and dominant foliation (Sm) form-lines, corresponding equal area stereonet plots of bedding/Sm attitude and best fit great circle with additional plots showing "best fit" great circles for fold axes.

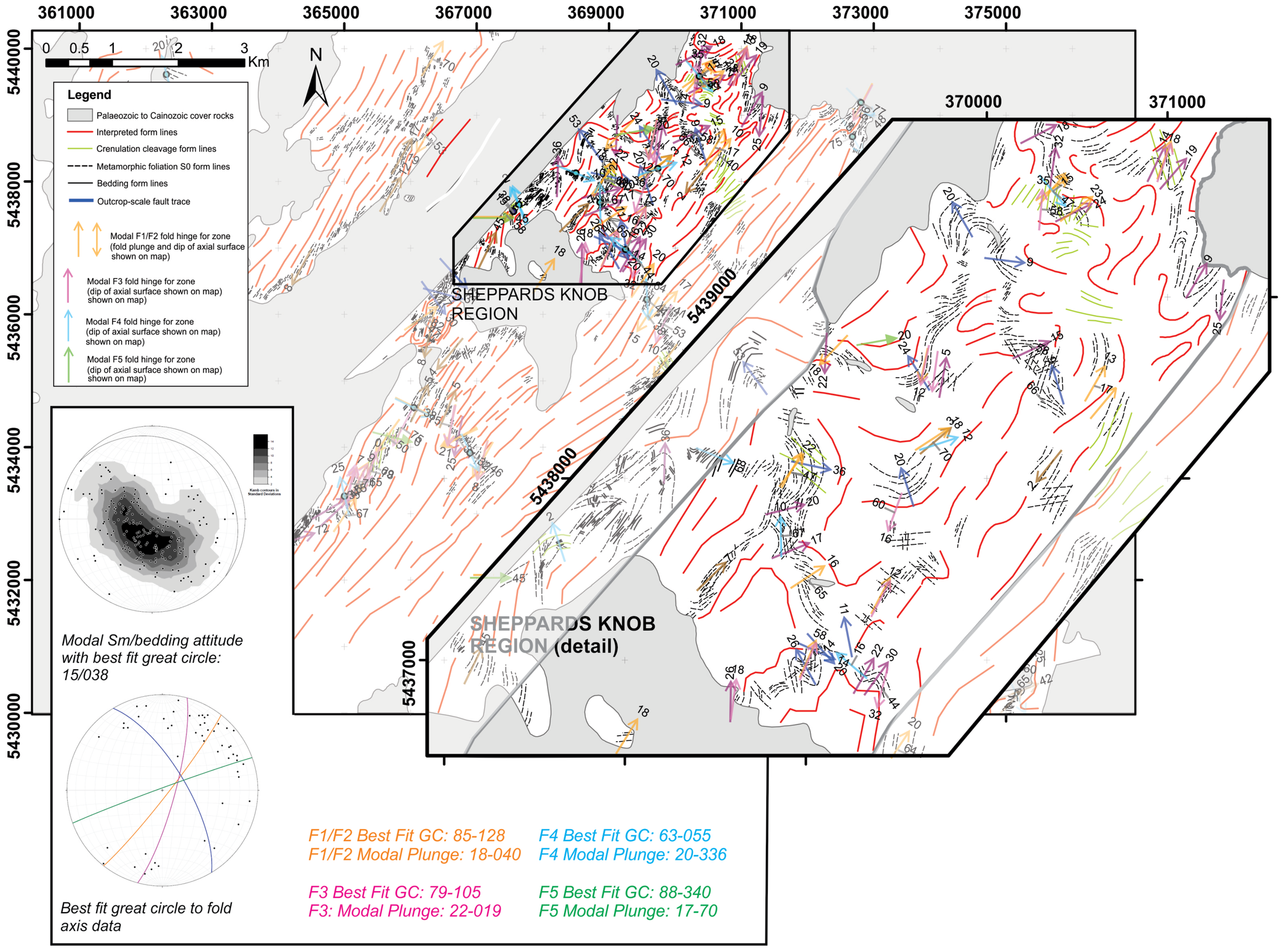


Figure 14. The Shepperds Knob region showing sub-domains, bedding, dominant foliation (Sm) form-lines, corresponding equal area stereonet plots of bedding/Sm attitude and best fit great circle with additional plots showing "best fit" great circles for fold axes.

Figure 15a. Outcrop photograph looking west, showing chloritic schist and phyllite with weakly developed shear bands and sinistral shear sense (white arrows) parallel to S2 foliation. Western block has moved to the south.

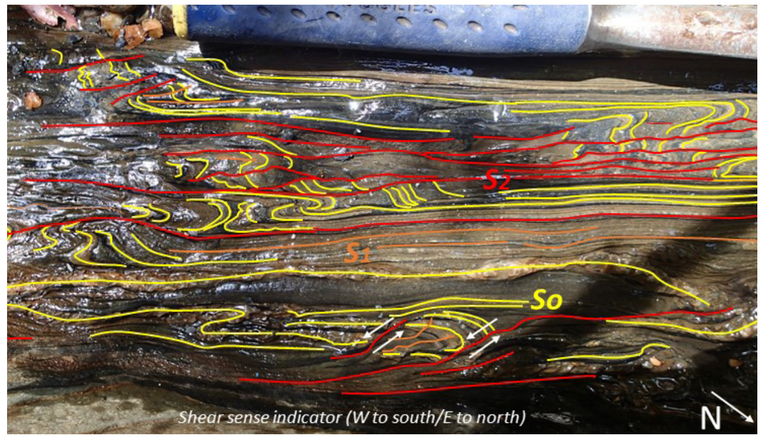


Figure 15b. Detached limb of a micro-fold provides similar sinistral shear sense indicator (west-limb to the south-east and eastern fold hinge to the north-west).

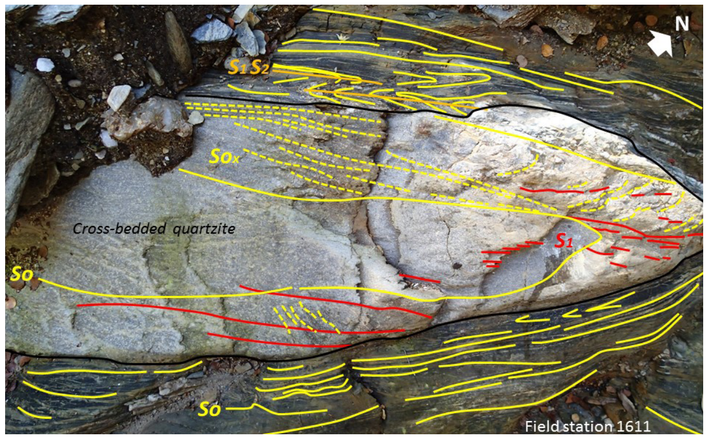


Figure 15c. c. Photograph showing a complex series of pale green/cream thinly-bedded siltstone and black carbonaceous siltstone with recumbent folding (bedding indicated as yellow lines, and axial surfaces of fold hinges as orange lines) with a large resistant lens of cross-bedded? ortho-quartz sandstone. Weak bedding is indicated by yellow lines within the quartzite boudin and suggests a possible fold hinge. The margin of the boudin is indicated as solid black line. Recumbent, isoclinal folds above the upper surface of the boudin have flat fold hinges which dip gently to the north. An additional cleavage (within the lens of quartzite) is indicated in red.

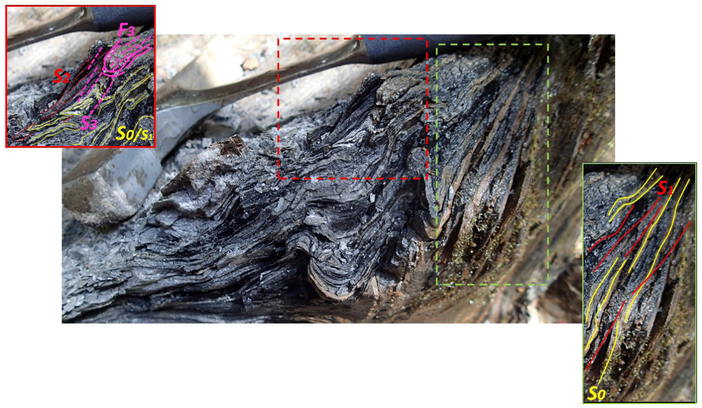


Figure 15d. Outcrop photograph showing the highly complex overprinting relationships between F1 and F2 folds. The pelitic schist shows asymmetric F1/F2 folds (main photograph), which have been disrupted by later F3 folds (pink solid line in the upper left). The spaced penetrative S3 cleavage is patchy around the fold core. Subtle bedding and cleavage relationships can be observed in the limb of the early fold (and right).

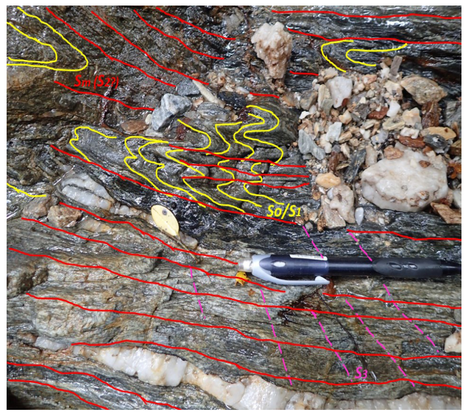


Figure 15e. Outcrop photograph of quartz-mica schist (pale unit) and a darker pelitic mica schist from Johnnys Creek. Folded bedding and a co-planar S1 cleavage (yellow lines) are preserved within the core of a possible shear lozenge. The dominant Sm fabric (red lines) is interpreted as an intense penetrative S2 cleavage that is also axial planar to the central tight folds. This Sm fabric has stretched out the fold limbs, and the morphology of the quartz vein at the bottom of the photograph also suggests extension parallel to the Sm orientation and is suggestive of sinistral shear. A weak fabric, possibly S3 (dashed pink lines), occurs in the quartz-mica schist at a high angle to the Sm fabric.

Figure 15f. Outcrop photograph looking northeast; south draining tributary in the Campbells Rivulet area (372830mE, 5439180mN). Photograph shows quartzite contained within the core of a tight to isoclinal fold (delineated by the yellow lines). A strong to intense Sm (S1/S2) cleavage (red lines) occurs in the more muscovitic schists, and this fabric is axial planar to the folds. A weak possible S3 fabric is evident in the muscovite schists (pink lines) but is non-penetrative into the quartzite core. Late stage quartz veins occupy brittle sinistral faults (white lines).

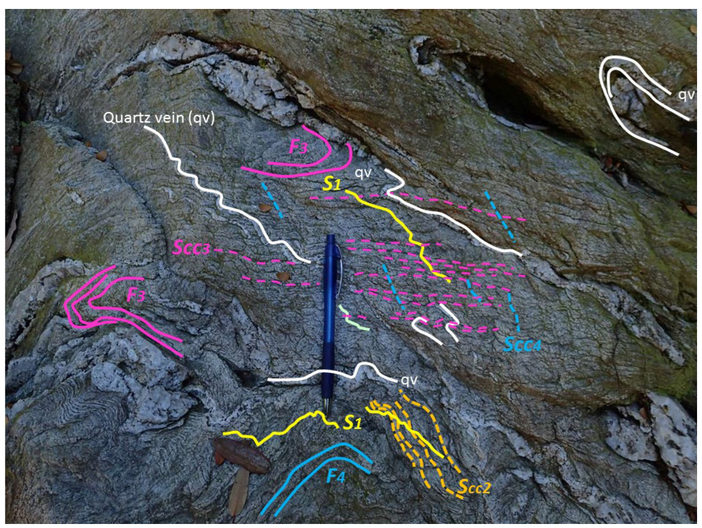


Figure 15g. Outcrop showing the highly complex overprinting relationships between the various deformation events from a quartzite outcrop in the Keith River (Shepperds Knob region).

Figure 15. Outcrop-scale structures in the Keith Schist.

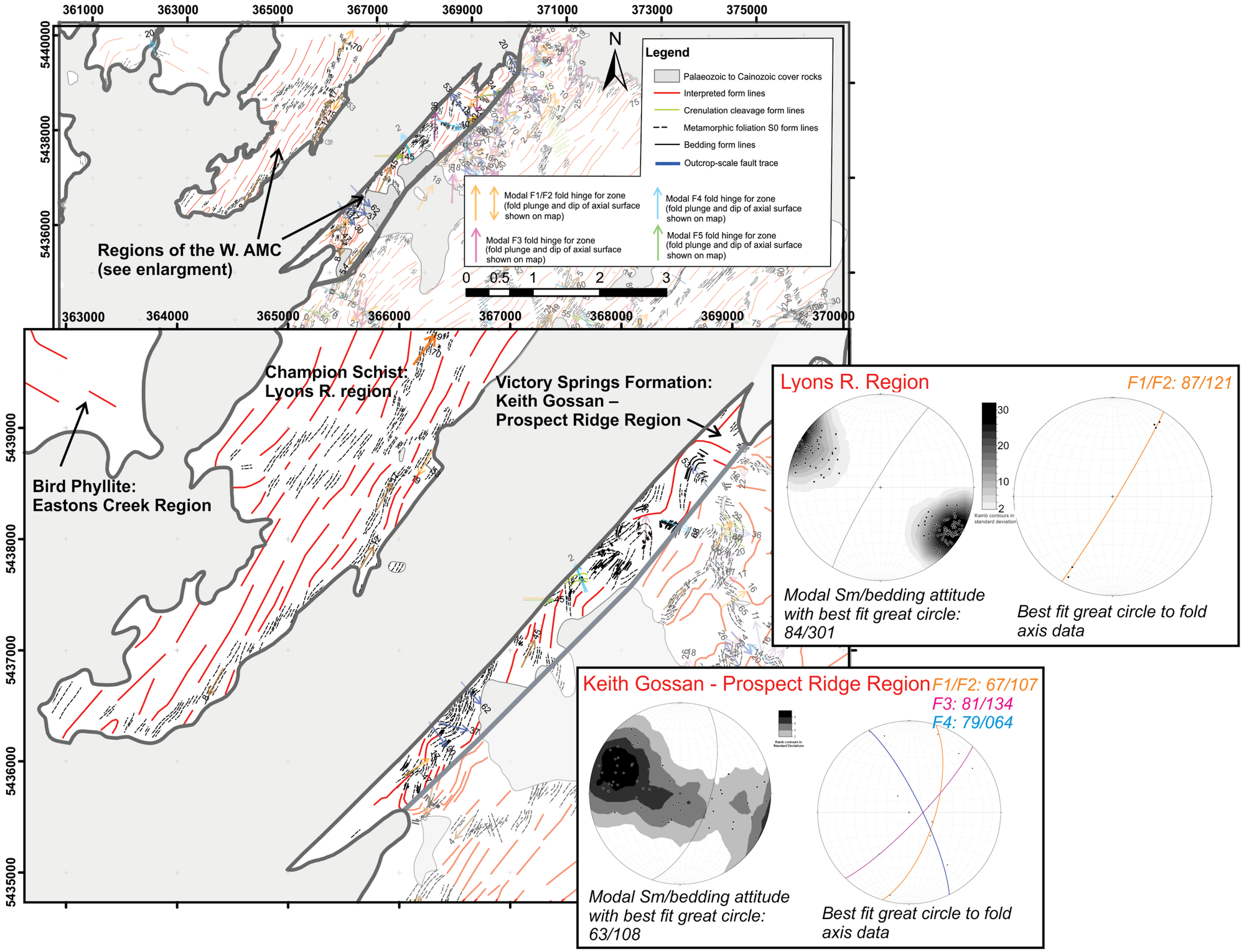


Figure 16. Form-line map of the western AMC showing bedding and dominant foliation (Sm) form-lines and corresponding equal area stereonet plots of bedding/Sm attitude and best fit great circle with additional plots showing "best fit" great circles for fold axes.

This region is interpreted to represent a pod of less-altered and deformed rocks which may preserve earlier F1/F2 and F3 folds. The area to the west of the Keith River Gossan abuts a significant but much younger northeast-trending, west-dipping fault which forms the boundary to Carboniferous - Permian lithologies and obscures the structural trends between this area and the Lyons River region described below.

Consistent, broad-wavelength, southeast-plunging F4 folds are apparent to the south, however several observations suggest that folds may also plunge to the west in the northern part of the block.

4.3.2 Western Keith River - Arthur River Region: B A Creek

B A Creek (Dm. 2.6; Figure 13) is directly southwest of Shepperds Knob and is an area with relatively sparse structural data. The dominant schistosity dips to the southeast but minor F3 folds appear to disrupt the main foliation in the central part of this area (366796mE, 5434167mN) and in the extreme southwest. Fold axes to F1/F2 folds plunge northeast and southwest. These folds are likely to be non-cylindrical and show evidence of later minor northeast-southwest compression otherwise not evident in the disruption of the dominant foliation. The fold axes for these F1/F2 folds are also significantly steeper than the dominant foliation (Sm). F3 folds are also interpreted in this area and plunge towards the northeast and southwest.

4.4 Champion Schist

This unit displays schistose penetrative planar fabric which typically dips steeply to the northwest. A crenulation cleavage is locally present, and tight to isoclinal refolding of the dominant foliation has been noted. Two main fold sets are interpreted as early F1/F2 folds with steep axial surfaces; these plunge gently to the northeast and southwest.

4.5 Bird Phyllite

Few structural measurements were made in the limited tracts of this unit in the far northwest of the Keith map sheet. Based on better exposures to the north on the Folly map sheet, bedding is locally recognisable but a steep north-westerly dipping penetrative cleavage is dominant and commonly crenulated by a later cleavage.

5.0 Summary

Based on cross-cutting relationships at outcrop scale, five deformation events have been identified in the rocks in the Keith area. Throughout the mapping work, outcrops were assessed systematically to categorise fold events and related cleavage development. A summary of all deformation and related structures for each structural region, along with their characteristics, is presented in Appendix 1 (Table 2.1).

5.1 Early isoclinal folding and compression - D1/2

The earliest folding event (D1), is generally difficult to decipher from the overprinting structures. It seems, however, that in the Arthur River area, D1 produced first-order (upright) chevron-style folds. These are generally symmetrical with relatively rounded hinges, but have been tightened and tilted by possibly asymmetrical D2-related folding. It is difficult to unravel D1 from D2 consistently in the historic mapping data, but new mapping indicates that D2 produced both moderately northeast, and southwest-plunging, tight isoclinal folding.

In the west of the AMC in the Champion Schist (Lyons River region), north to northeast and southwest-plunging folds are most prevalent. In this zone the Champion Schist dips steeply to the west-northwest. F1/F2 folds have unimodal plunge directions to the southwest and northeast. No early fold structures were identified in the Bird Phyllite or Jacob Quartzite further to the west.

Cross-section interpretations (section C'-C''; Figure 12) suggest that overturned F1 folds are preserved in the Victory Springs Formation. This unit is probably contained within an early, low-angle thrust-sheet noted elsewhere in the southern part of the AMC (Holm et. al., 2003). This low-angle thrust could not be confirmed during mapping, and the unit could instead be partly conformable with the Keith Schist. The overturned F1 and F2 folds are obscured by Permian cover to the northwest, and have been truncated by several interpreted faults to the southeast (shown in Figure 12; cross-sections A'-A'' and B'-B''). This region is interpreted as a pod of less-altered and less-deformed rocks which preserves earlier F1/F2 and F3 folds.

In the B A Creek region, F1/F2 folds plunge to the northeast. To the north, in both B A Creek and the Shepperds Knob area, modal Sm is almost parallel to the axial surfaces of F1/F2 folds and early folds which plunge gently (18°) to the northeast. This relationship has not been observed elsewhere in the study area and may signify the buckled hinge zone of a large-scale, northeast-plunging fold.

The best preservation of F1/F2 fold closures in the eastern part of the study area was in more resistant zones which appeared to be enclosed by highly sheared zones (eg. "Lovely Creek" area). In this area isoclinal F1/F2 folds plunge steeply to the south-southwest but along Last Hope Creek and Atlas Creek the F2 axial surfaces swing around to dip steeply to the west. Along the Keith River, weakly developed shear bands indicate sinistral shear sense (i.e. west block to the south, east block to the north). These were also observed and interpreted along the Keith River near the southern edge of the map sheet.

5.2 D3 Deformation

The Keith River Gossan/Prospect Ridge area contains F3 folds on the eastern limb of the earlier F1/F2 folds, and these have modal plunges to the south. This region

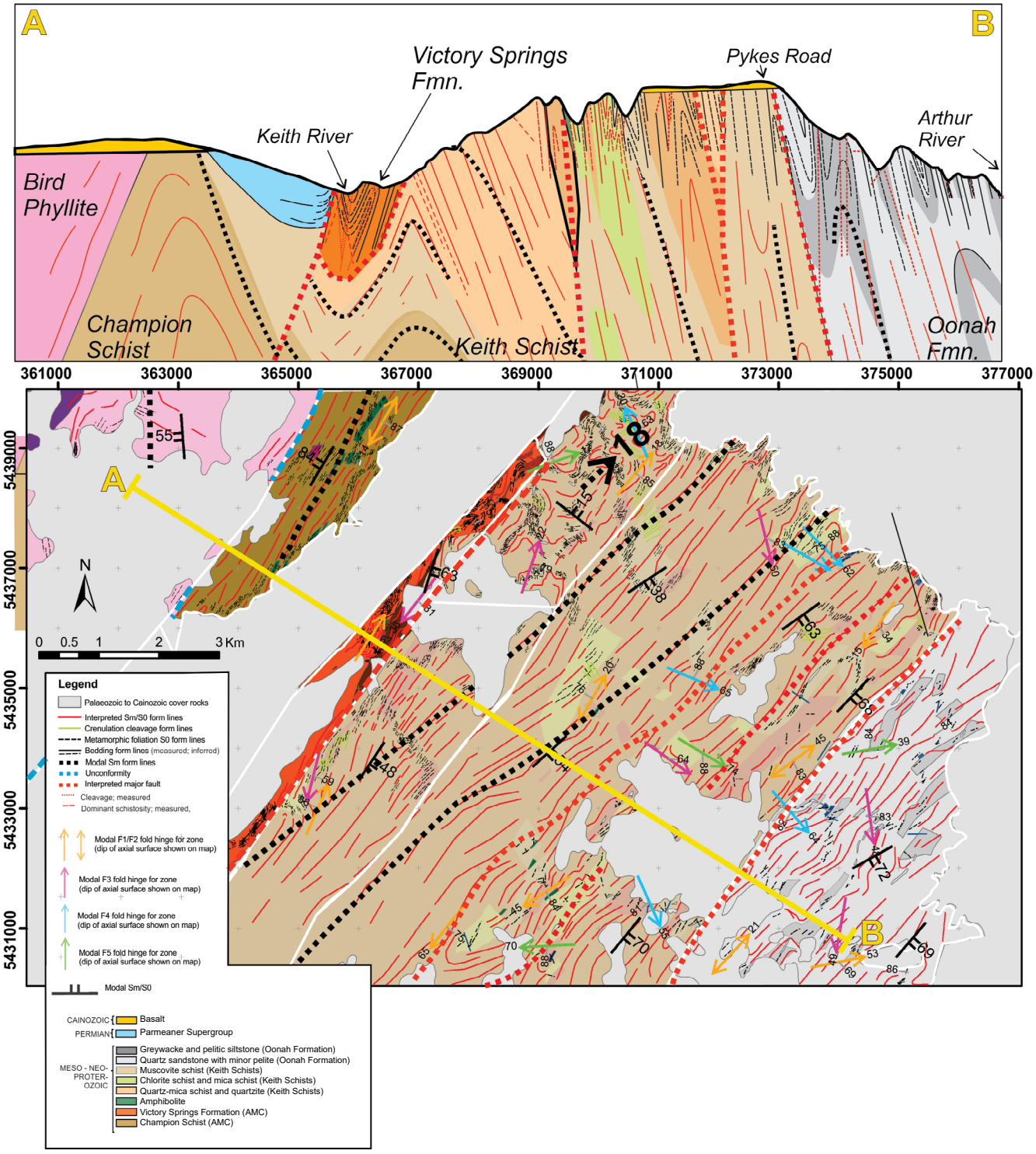


Figure 17. Geological map with modal structural measurements and schematic form-lines with position of A-B profile indicated (below). Schematic geological cross section showing an interpretation of the structural framework of the Keith area. Vertical scale = Horizontal scale.

is interpreted as a segment of less-altered and deformed rocks that likely preserve earlier F1/F2 and F3 folds. The polarity of these F3 folds differs in the Shepperds Knob region where they are north-northeast trending, open, and generally south-plunging. They have east-dipping axial surfaces and a patchy corresponding crenulation cleavage. In the remainder of the area, F3 folds generally plunge consistently south and southeast, with east-dipping axial surfaces. No D3-related deformation was identified west of the Keith River Gossan – Prospect Ridge area in the Champion Schist and Bird Phyllite. A summary of D3-related deformation is shown in Table 2.2 (in Appendix 1).

In the western part of the Keith Schist (B A Creek area), F3 folds appear to disrupt the main S1/S2 foliation and dip gently to the south-southwest. Numerous outcrops of resistant quartzite, dolostone and amphibolite are enclosed within more fissile schistose units. These fissile units are overprinted by S3 foliation. D3-related folding could be the result of mainly north-south compression in the Oonah Formation and the Keith schist. Shear sense indicators suggest that sinistral displacement is likely related to the D3 deformation event, as it overprints the earlier D1/D2 cleavage. D3-related folding is associated with tightly-spaced to planar, relatively strong cleavage

and is also likely related to further rotation and compression during the Cambrian Tyennan Orogeny.

Modal bedding, schistosity and modal plunges for F1-F3 fold hinges in the northwestern part of the Keith Schist (Shepperds Knob area) provide evidence for a northeast plunging, regional-scale fold. North of Atlas Creek, axial surfaces of these folds dip consistently to the northeast.

5.3 D4 and D5 Deformation

D4-related folds are at a high angle to the D2 and D3-related folds. They are evident as generally upright, symmetrical and non-symmetrical, large-amplitude and southeast-plunging outcrop-scale folds with northeast-dipping axial surfaces. These folds are associated with spaced, diffuse cleavage and are probably related to the middle Devonian Tabberabberan Orogeny. The majority of northeast D1 to D3-trending folds (likely Cambrian) were disrupted by this deformation and probably further tightened during this event. Open, high amplitude, east-southeast plunging folds, probably related to Devonian compression, have further rotated the earlier fold closures. Southeast-plunging kink folds relating to the F4 and F5 folding event(s) are consistently recorded throughout the Keith Schist and Oonah Formation, but these folds also show opposing polarity in the Shepperds Knob region.

Another fold event (termed D5) is suggested by east- and west-plunging folds, but the relationship between D4- and D5-related folding is largely unclear. A spread of east and southeast-plunging folds were also measured and these may relate to a later, possible D5 folding event.

The F4 folds appear to switch polarity in the western AMC, close to the hinge of the interpreted regional scale fold hinge (Figure 17). The significance of this is not fully understood, and as D5-related folds (described here as D4) also plunge northeast, so it is plausible that this late-stage regional folding event is responsible (at least in part) for the regional-scale folding and tilting of units to the northeast along the core of the AMC.

Another possible explanation for the apparent change in polarity of the F1/F2, F3 and F4 fold axes at Shepperds Knob (as defined in Fig. 14) may be that this area represents a large, 5 km wide, tilted or fault-bound block which has preserved earlier fold orientations. However, there is no evidence for any change in facies, or any rheology contrast (resistant vs. non-resistant units) across the area with contrasting structure. Furthermore, there is no evidence to suggest this zone is entrained by a higher-strain zone (as observed in outcrop scale elsewhere; Figures 9 and 10).

6.0 Discussion

The Keith-Lyons River region includes lithological units which have been subject to increasing strain towards the core of the AMC. The units share both gradational, and probably low-angle, faulted contacts. In the east, the Oonah Formation and most of the Keith Schist have similar structural patterns and are mostly separated by a gradational metamorphic contact, although this is not clear everywhere. In this area, the imprint of Early Cambrian (D1/D2) deformation reveals compression and tilting from north to south, resulting in consistently southwest plunging F1/F2 folds. Both units dip gently to the east, and northwest-directed D3-related compression appears to have disrupted the earlier folds. Shear sense indicators, although sparse, indicate sinistral movement in the Keith Schist and Oonah Formation.

The units in the core of the AMC (the remainder of the Keith Schist and Victory Springs Formation) show markedly different structural patterns, and indicate a larger-scale, gently-dipping, north-plunging antiform. The antiform encloses a less-deformed earlier F1/F2 synform in the hinge of this larger-scale fold. The fold is confirmed by patterns in schistosity, which are axial planar to the plunge of F1/F2 folds. The area north of Shepperds Knob may represent the hinge of this inferred regional-scale synform. The feature has tilted early D1/D2-related structures, and appears to have further folded gently-plunging D3-related folds, which also plunge northeast.

The contact relationship between the Keith Schist and the weakly metamorphosed sediments and carbonates (Victory Springs Formation) to the far west, is still largely unclear. Analysis of cross-sections from this area indicates the presence of overturned folds. These northeast trending blocks contain mixed carbonate, sediments and mafic rocks (in the Keith River Gossan and Prospect Ridge regions) and are probably bound by local, thin, high-strain, low-angle shears. The shears have essentially helped to preserve the earlier (Cambrian) structural history and metamorphic facies at the hinge of the regional-scale fold. The Victory Springs Formation is interpreted to represent a correlate of the Bowry Formation. To the west, the Champion Schist and Bird Phyllite are likely correlates of the Western Ahrberg and Togari Group based on lithological similarities and recent detrital zircon geochronology (Mulder et. al., 2020). Although the contact relationships between the Champion Schist and Bird Phyllite have not been adequately defined due to poor outcrop, these units dip consistently to the northwest, and may, if relatively conformable, also support the presence of a large-scale, northeast-plunging fold which has folded all of the fault-bound units in the AMC corridor. The idea of a regional-scale fold supports the structural reconstruction of Holm and Berry (2002), who proposed that a broad, regional-scale fold structure developed as a result of Late Cambrian D3-related folding and thrusting. This event folded and tightened the stacked lithostratigraphic units and created the linear geometry of the Arthur Metamorphic Complex observed to the south.

Holm and Berry (2002) suggest that the Oonah Formation, Keith Schist and Timbs Group (or "Eastern Ahrberg" Group and Bowry Formation) were emplaced as sub-horizontal slices (or nappes) during the Early Cambrian. Turner and Bottrill (2001) suggested that the Bowry Formation represents a subducted, ductile wedge of continental mafic rocks buried to approximately 20 km in a west-dipping subduction zone between 514 Ma and 510 Ma. This was then rapidly exhumed back to the surface by east-directed thrusting and emplaced as sub-horizontal nappes (Berry, 2014). Sinistral shear bands within the Keith Schist indicate north-over-south shear sense during the Early (D1/D2) deformation. These nappes may have been subsequently disrupted by south-directed and/or west-directed thrusting episodes as noted in Holm and Berry (2002).

The Arthur Metamorphic Complex has been a zone of structural weakness for much of the Phanerozoic. Not only was it again an area of high strain during the Devonian Tabberabberan Orogeny, but in the Carboniferous, glacial activity may have carved out a long (~40 km) NNE/SSW-trending deep, narrow fjord-like valley in the relatively soft schists of the AMC. The valley was subsequently filled with Late Carboniferous and Permian glaciomarine sediments. In the Mesozoic or early Cainozoic, this palaeogeographic feature was a locus for faulting (e.g. of the Permo-Carboniferous strata against the Victory Springs Formation). The resultant half-graben extends along the core of the AMC, from the near the modern Savage River Mine to the Arthur River, and broadens northward towards Wynyard.

6.0 Conclusions

The Keith region contains early isoclinal (D1-D2) folds that have been tightened and re-folded (D3) to form non-cylindrical, asymmetric folds, which were later subject to northwest-directed compression (D4-5) and tilting.

Lithological units in the Keith area share transitional metamorphic boundaries and interpreted low-angle faulted contacts which, at a regional-scale, imply the presence of a late-stage north-plunging fold along the highest strain zone of the northern AMC.

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APPENDIX I

Tables

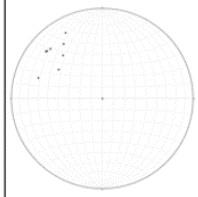
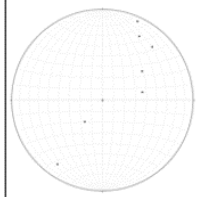
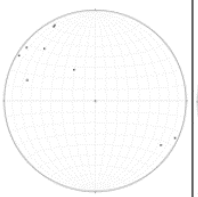
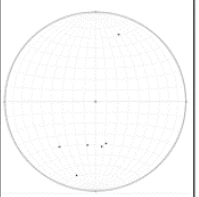
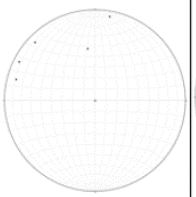
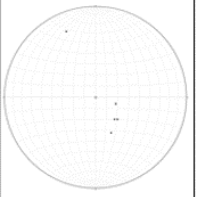
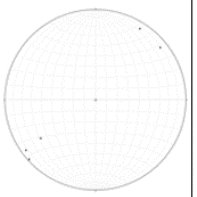
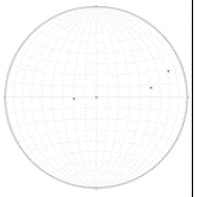
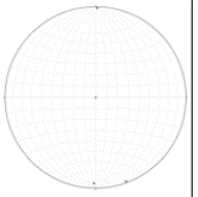
		Modal Sm		*F1-F2 Fold Plunge*		*F1/F2 Axial Surface*		*F3 Fold Plunge*		*F3 Axial Surface*		*F4 Fold Plunge*		*F4 Axial Surface*		*F5 Fold Plunge*		*F5 Axial Surface*	
Region	**Sub-domain**	**Dip**	**Dip direction**	**Dip**	**Plunge**	**Dip**	**Dip direction**	**Dip**	**Plunge**	**Dip**	**Dip direction**	**Dip**	**Plunge**	**Dip**	**Dip direction**	**Dip**	**Plunge**	**Dip**	**Dip direction**
Arthur River	Arthur River - South	69	131	53	79	69	136	49	190	48	172	64	139	82	212	39	80	84	1
	Arthur River - North	72	151	45	54	83	151	48	172	83	90	71	108	84	54	-	-	-	-
Keith River – Arthur River	Keith River – Arthur River South	70	130	21	43	-	-	-	-	-	-	55	156	81	231	70	267	88	181
	Keith River – Arthur River West	54	138	65	219	84	152	-	-	-	-	-	-	-	-	-	-	-	-
	Keith River – Arthur River Northeast	68	134	15	215	34	146	50	166	83	117	-	-	-	-	-	-	-	-
	Keith River – Arthur River Northwest	63	145	20	30	76	304	-	-	-	-	62	135	88	48	-	-	-	-
Western Area	Sheppherds Knob	15	38	18	40	85	128	22	19	79	105	22	336	63	55	17	70	88	340
	B A Creek	48	124	6	24	86	295	16	194	-	-	-	-	-	-	-	-	-	-
	Keith Gossan – Prospect Ridge	63	108	6	24	67	107	36	218	81	134	-	-	-	-	-	-	-	-
	Lyons River	84	301	16	32	87	121	-	-	-	-	-	-	-	-	-	-	-	-
	Eastons Creek	55	266	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
																			

Table 1. Summary of modal schistosity/bedding (Sm) and fold information for each structural region referred to in the text.

		Modal Sm		*F1-F2 Fold Plunge*		*F1/F2 Axial Surface*		*Fold Characteristics*	*Metamorphic Fabric*
Region	**Sub-region**	**Dip**	**Dip Direction**	**Dip**	**Plunge**	**Dip**	**Dip Direction**		
Arthur River	Arthur River - South	69	131	53	79	69	136	Tight to isoclinal, moderately east-plunging upright folds with moderate to steep south-dipping axial surfaces. Minor asymmetric outcrop-scale F2 folds.	Planar foliation and compositional layering with spaced and fine continuous cleavage network. Slaty cleavage.
	Arthur River - North	72	151	45	54	83	151	Tight to moderately east, southwest and northeast plunging upright folds with steep southeast dipping axial surfaces.	Bedding-parallel, axial planar S1 cleavage. Commonly slaty cleavage.
Keith River – Arthur River	Keith River – Arthur River South	70	130	21	43	80	170	Tight isoclinal F1/F2 folds plunge steeply to the south-southwest	S1 penetrative slaty fabric with alignment of micas. Rare discrete D2 related crenulation cleavage
	Keith River – Arthur River West	54	138	65	219	84	152	Axial surfaces to early F1/F2 folds dip steeply towards the northwest, plunging mostly to the north.	Penetrative bedding-parallel cleavage.
	Keith River – Arthur River Northeast	68	134	15	215	34	146	Tight isoclinal and chevron folds, shallowly south-plunging.	Penetrative bedding-parallel cleavage.
	Keith River – Arthur River Northwest	63	145	20	30	76	304		Penetrative bedding-parallel cleavage.
Western Area	Sheppherds Knob	15	38	18	40	85	128	Tight, symmetrical, shallowly northeast-plunging folds.	The dominant schistosity (Sm) is likely an S2 fabric with bedding and co-planar S1 fabric preserved in fold cores. The Sm is a penetrative axial planar cleavage to asymmetric folds.
	B A Creek	48	124	6	24	86	295	Non-cylindrical fold hinges to F1/F2 folds plunge northeast and southwest	Penetrative planar fabric
	Keith Gossan – Prospect Ridge	63	108	6	24	67	107	Potentially overturned F1 folds. Less deformed rocks preserve earlier F1/F2 fabrics	Penetrative planar fabric
	Lyons River	84	301	16	32	87	121	Two main fold hinges in this area plunging shallowly to the northeast and southwest	Penetrative planar fabric
	Eastons Creek	55	266	-	-	-	-		Penetrative planar fabric

Table 2.1 Summary of D1/D2 deformation in each structural domain in the Keith region.

		Modal Sm		*F3 Fold Plunge*		*F3 Axial Surface*		*Fold Characteristics*	*Metamorphic Fabric*
Region	**Sub-region**	**Dip**	**Dip Direction**	**Dip**	**Plunge**	**Dip**	**Dip Direction**		
Arthur River	Arthur River - South	69	131	49	190	48	172		
	Arthur River - North	72	151	48	172	83	90	Open, south-plunging F3 folds with steep axial surfaces	
Keith River – Arthur River	Keith River – Arthur River South	70	130	-	-	-	-		
	Keith River – Arthur River West	54	138	58	138	-	-	Non-cylindrical, steeply to moderately plunging folds with moderate to steep east dipping axial surfaces.	Spaced weak crenulation cleavage.
	Keith River – Arthur River Northeast	68	134	50	166	83	117	Steeply to moderately plunging folds with steep east dipping axial surface.	Spaced weak crenulation cleavage.
	Keith River – Arthur River Northwest	63	145	-	-	-	-		
Western Area	Sheppherds Knob	15	38	22	19	79	105	Symmetrical, shallowly north-plunging open folds with steep east-dipping axial surfaces.	Non-penetrative S3 spaced cleavage. Phyllitic units contain patchy zones with a strongly developed crenulation cleavage
	B A Creek	48	124	16	194	-	-	Tight, south-southwest shallowly plunging folds with moderate to steep east-dipping axial surfaces.	
	Keith Gossan – Prospect Ridge	63	108	36	218	81	134	Tight, south-southwest shallowly plunging folds with steep east-dipping axial surfaces.	Non-penetrative spaced cleavage
	Lyons River	84	301	-	-	-	-		
	Eastons Creek	55	266	-	-	-	-		

Table 2.2 Summary of D3 deformation in each structural domain in the Keith region.

		Modal Sm		*F4 Fold Plunge*		*F4 Axial Surface*		*Fold Characteristics*	*Metamorphic Fabric*
Region	**Sub-region**	**Dip**	**Dip Direction**	**Dip**	**Plunge**	**Dip**	**Dip Direction**		
Arthur River	Arthur River - South	69	131	64	139	82	212	Steep southeast plunging kink folds with steep southwest-dipping axial surfaces	Patchy northwest-trending axial planar cleavage related to F4 folds
	Arthur River - North	72	151	71	108	84	54	Steeply dipping generally symmetrical east-plunging F4 folds with steep north dipping axial surfaces.	Patchy axial planar cleavage related to F4 folds
Keith River – Arthur River	Keith River – Arthur River South	70	130	55	156	81	231	Open moderately to steeply dipping folds with steep south-trending axial surfaces.	Patchy northwest-trending axial planar cleavage related to F4 folds
	Keith River – Arthur River West	54	138	-	-	-	-		
	Keith River – Arthur River Northeast	68	134	-	-	-	-		
	Keith River – Arthur River Northwest	63	145	62	135	88	48	Open moderately to steeply plunging kink folds with steep north-trending axial surfaces.	Patchy northwest-trending axial planar cleavage related to F4 folds
Western Area	Sheppherds Knob	15	38	22	336	63	55	Open shallowly north-west plunging folds with north-east dipping axial surfaces.	Patchy northwest-trending axial planar cleavage related to F4 folds
	B A Creek	48	124	-	-	-	-		
	Keith Gossan – Prospect Ridge	63	108	-	-	-	-		
	Lyons River	84	301	-	-	-	-		
	Eastons Creek								

Table 2.3 Summary of D4 deformation in each structural domain in the Keith region.

		Modal Sm		*F4 Fold Plunge*		*F4 Axial Surface*		*Fold Characteristics*	*Metamorphic Fabric*
Region	**Sub-region**	**Dip**	**Dip Direction**	**Dip**	**Plunge**	**Dip**	**Dip Direction**		
Arthur River	Arthur River - South	69	131	39	80	84	1	Open, moderately plunging, relatively upright, symmetrical outcrop-scale folds with steep axial surfaces.	Patchy diffuse cleavage.
	Arthur River - North	72	151	-	-	-	-		
Keith River – Arthur River	Keith River – Arthur River South	70	130	70	267	88	181	Southeast, steeply plunging, moderately reclined folds.	Patchy diffuse and spaced cleavage.
	Keith River – Arthur River West	54	138	-	-	-	-		
	Keith River – Arthur River Northeast	68	134	-	-	-	-		
	Keith River – Arthur River Northwest	63	145	-	-	-	-		
Western Area	Sheppherds Knob	15	38	17	70	88	340	Symmetrical shallowly northeast plunging folds with steep north-west dipping axial surfaces.	Patchy diffuse and spaced cleavage.
	B A Creek	48	124	-	-	-	-		
	Keith Gossan – Prospect Ridge	63	108	-	-	-	-		
	Lyons River	84	301	-	-	-	-		
	Eastons Creek	55	266	-	-	-	-		

Table 2.4 Summary of D5 deformation in each structural domain in the Keith region.

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