



# Geological Survey Paper 16: Structural Geology of northern Tasmania An Overview and Structural Synthesis

## PART 1: The Forth Metamorphic Sheet

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High-grade (H-G) schistosity at the Camp Clayton beach outcrops adjacent to the Forth Valley High Strain Zone (HSZ). The HSZ is a shear interface within the composite Forth Metamorphic Sheet. The outcrop is intensely foliated, schistose pelite containing disrupted, rootless, isoclinally folded quartz veins. The isocline hinges show markedly variable plunge within the dominant schistosity  $S_m$ . The H-G schistosity in the outcrop shows a low-T/low strain rate ( $\dot{\epsilon}$ ) dissolution creep overprint, as part of the final stages of sheet stacking within the Forth Sheet and amalgamation with the Ulverstone Sheet.



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## ***Abstract***

*The Forth Metamorphic Sheet is the lowest sheet in a Cambrian "thrust"-stack made up of lithotectonic units of different metamorphic grade. They include the high-grade (H-G) amphibolite facies Forth Metamorphic Sheet of Proterozoic protolith, overlain by the low-grade (L-G) greenschist facies Ulverstone Oonah Sheet of Neoproterozoic protolith, overlain by the low-grade (sub-greenschist facies) Oonah sheet of Neoproterozoic protolith, overlain by the Early Cambrian chert-basalt sequence of the obducted Penguin-Luina Sheet at the highest structural level. The sheets are separated by high strain shear zone interfaces commonly reactivated in the Devonian as brittle faults.*

*The Forth Metamorphic Sheet itself is an allochthonous composite sheet, made up of a collage of structurally interlayered, isoclinally folded and shear zone-bounded quartzite, amphibolite and schist. The structurally intercalated quartzite, micaceous quartzite, quartz-mica schist and garnet-mica schist enclose Sm parallel belts of amphibolite and minor serpentinite.*

*The Sheet shows 1) a gradient in metamorphism, and 2) a change in the morphology of the foliation from the structurally highest western part to the structurally lowest eastern part. Peak metamorphic conditions reached approximately 700°C and 1.3 GPa in the eastern part with kyanite-garnet-biotite assemblages, and lower peak temperatures (600°C) in the western part with staurolite-chloritoid assemblages. This is accompanied by a change in foliation character from a spaced crenulation cleavage with microlithons in phyllitic pelites in the west, to a prominent schistosity/metamorphic segregation in the east. Fabric microstructure indicates two phases of fabric formation in the high-grade schists: an initial high P-T metamorphic fabric followed by low-T/low strain rate deformation of this fabric at higher crustal levels during sheet amalgamation. U-Th-Pb dating of monazite yielded ages around 509±7 Ma with Ar-Ar muscovite ages of 508 Ma and 522 Ma. The significance of older 522 Ma ages is uncertain.*

*The Forth Metamorphic Sheet has undergone a complex deformational history. It has been affected by six different fault systems including 1) a Cambrian subduction/exhumation "thrust" system that created the lithotectonic sheet stacking, 2) Middle-Cambrian extensional fault system that created the Dundas-Fossey graben including a Cambrian volcano-sedimentary rift sequence and massive sulphide exhalation, 3) a Late Cambrian brittle obduction thrust system involving southwards sheet transport, 4) a Devonian reverse fault system developed along the western limb of the Devonian Forth Anticline, and 5) a post-Permian extensional fault system that created the Mersey Graben. As a consequence, the complexly deformed Forth Metamorphic Sheet now exists as a relict Middle Cambrian extensional horst modified by Devonian thrusting and the post-Permian normal faulting.*

*The Forth-Ulverstone map geology displays curved outcrop trends in lithological layering due to broad folding of the metamorphic thrust sheets by two younger Devonian folds. They are the south-plunging, north-south trending Forth Anticline and the companion southwest plunging and southwest-trending Abbotsham Anticline. These two folds in map pattern have a compound form with a pseudo, box-like geometry defined by variably plunging hinges.*

*The younger Devonian folds refold a large-scale, 1st order, southeast-closing, isoclinal fold nappe within the structurally lowest part of the Forth H-G Sheet. This macro-fold is disrupted and offset by two major mylonitic, high-strain zones (the Buttons Creek HSZ and Forth Valley HSZ). The interpreted macro-fold has a reclined geometry with the hinge zone marked by a series of interdigitating, second- and third-order, isoclinal folds hinges typical of a large-scale mullion structure. There is a distinct variation in Lm across interpreted macro-fold hinge, where the upper western limb has a west- or northwest- plunge, the hinge proper has a southwest-plunge and the lower or eastern limb has an east-plunge.*

*Mesoscopic isoclinal folds within quartzite and thin-bedded quartzite pelite sequences are common and exhibit specific geometries. The folds are typically asymmetric with long planar limbs and angular, chevron "arrow-head" hinges. They dominate in thin-bedded quartzite layers and tend to have gentle plunges within the dominant foliation. In zones of significantly higher strain marked by ductile deformation, mylonitic quartzites and intensely foliated garnet schist these folds tend to have steeper plunges within the dominant foliation.*

*The emplacement sense of the Forth Metamorphic Sheet is debated with evidence suggesting south-directed emplacement. Limited shear sense data from the Forth Sheet restricts the analysis to Lm/Sm data, where movement planes (MP1) derived from lineation Lm and dominant foliation plane (Sm) indicate a dominant north-northeast to south-southwest trend with a south-directed sense. Geometrical tests were also applied to match documented relationships for 1) fold attitude and lineation attitudes, and 2) shear band attitudes and senses, given expected patterns for different shear senses. The results indicate that the Forth Sheet was emplaced with a north-over-south shear sense.*

*Devonian deformation has significantly impacted the Forth Metamorphic Complex with 1) reactivation of older thrust and extensional faults, 2) development of the antiformal character, where the Forth Anticline may have formed as a ramp anticline above a subsurface thrust ramp, and 3) crustal scale, thrust imbrication playing a significant role in the crustal architecture of northern Tasmania.*

## Structural Geology of northern Tasmania— An Overview and Structural Synthesis

### PART 1: THE FORTH METAMORPHIC SHEET

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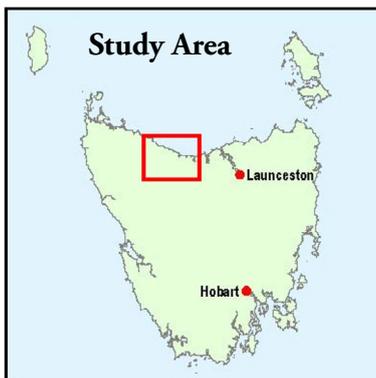
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#### 1.0 INTRODUCTION

Northern Tasmania, particularly the almost continuous coastal exposures along the north coast, provides a unique window into the structural relationships between deeply subducted, high-grade (H-G) metamorphic rocks (Forth Metamorphic Complex/Sheet) and overlying, allochthonous, low-grade (L-G) Neoproterozoic-Early Cambrian sequences (Figure 1). The L-G sequences occur as a series of fault/shear zone bounded sheets, including the greenschist facies Ulverstone Sheet (Neoproterozoic protolith), the sub-greenschist facies Oonah Sheet (Neoproterozoic protolith) and the obducted Early Cambrian oceanic (chert-basalt) Luina Sheet (Figures 1 and 2). The exposures provide the most accessible exposure of the contact between the External and Internal Zones of Berry (2014).

All of these sheets represent different parts of, and/or slices from different levels of a Cambrian margin subduction and exhumation system (see Berry, 2014; Mulder et al., 2018; Gray et al., 2023). Each sheet has distinct and different structural geometry and fabrics. There is a marked contrast in strain, metamorphic grade and style of deformation across the main contacts, as well as a reactivation of the earlier subduction-exhumation thrusts overprinted by younger, east-directed thrust-reverse faults.

The Tasmanian north coast structural-tectonic elements (Figure 1) include the Rocky Cape autochthon ("basement" relict of the Tasmanian micro-continent), the Arthur Structural-Metamorphic Zone (exposed edge of the allochthon), inliers of the allochthonous Neoproterozoic Oonah Formation (including the Burnie, Ulverstone and Badger Head inliers), inliers of Early Cambrian mélangé (Luina Group) and the H-G Forth Metamorphic sheet (subducted and exhumed slice of the Tasmanian micro-continent margin). The Proterozoic age units are part of continental margin deposits that were subducted to depths of ~20 to 60 km beneath an advancing ophiolite sheet during a Cambrian arc-continent collision along the eastern margin of Gondwana (see Berry and Crawford, 1988; Berry, 2014, fig. 4.10; Gray et al., 2023).

This publication is the first in a series of MRT Geological Survey papers dealing with the structural character and inter-relationships of the major lithotectonic elements of northern Tasmania. These include:

1. H-G Forth Metamorphic Sheet (this Paper)
2. L-G Ulverstone Metamorphic Sheet
3. L-G Burnie-Oonah Sheet
4. Penguin-Luina Sheet
5. Arthur Structural and Metamorphic Zone

The H-G Forth Metamorphic Sheet (Figures 1 and 2) is the focus of this paper. It has a litho-tectonic sequence of Proterozoic high-grade garnet schists (Burns, 1963a, 1964; Lewis, 1991) structurally overlain by Neoproterozoic low-grade quartzite ± phyllite (originally designated the Ulverstone Metamorphics (Burns, 1963a, 1964) and low-grade Neoproterozoic turbidites of the Oonah Formation (Berry & Gray, 2001; Mulder et al., 2018). In map projection the Forth Metamorphic Sheet has arcuate form folded about the south-plunging, north-trending Devonian Forth Anticline (Figure 1b). It has a ~16 km length and ~16 km width, including the outer carapace of the structurally concordant, low-greenschist facies Ulverstone

Metamorphic sheet (Figure 2). The H-G metamorphic rocks are predominantly exposed along the western limb and core of the younger anticline. The eastern limb is truncated by a post-Permian extensional fault system of the Mersey Graben.

It was originally designated as the Forth Block and/or a Precambrian massif (Turner, 1989) and was subdivided into a lower metamorphic grade, greenschist facies part (Ulverstone Metamorphic Complex) and a structurally concordant higher-grade part (Forth Metamorphic Complex) (Burns, 1964; Turner, 1989, p.30-32).

Limited detrital zircon data suggests that the Ulverstone Metamorphic Sheet is Neoproterozoic in age and correlative of the low-metamorphic grade Oonah Formation (Black et al., 1997; Mulder et al., 2018, p. 2019). This suggests a tripartite definition of the former Forth-Ulverstone Metamorphic Complex into three separate and distinct metamorphic sheets including 1) a L-G, sub-greenschist, facies Neoproterozoic Oonah Formation (unit 3, Figure 2a), 2) a greenschist facies, higher strain Ulverstone slice/sheet of the Oonah Formation (unit 2, Figure 2a), and 3) the Proterozoic Forth Metamorphic Complex (unit 1, Figure 2a).

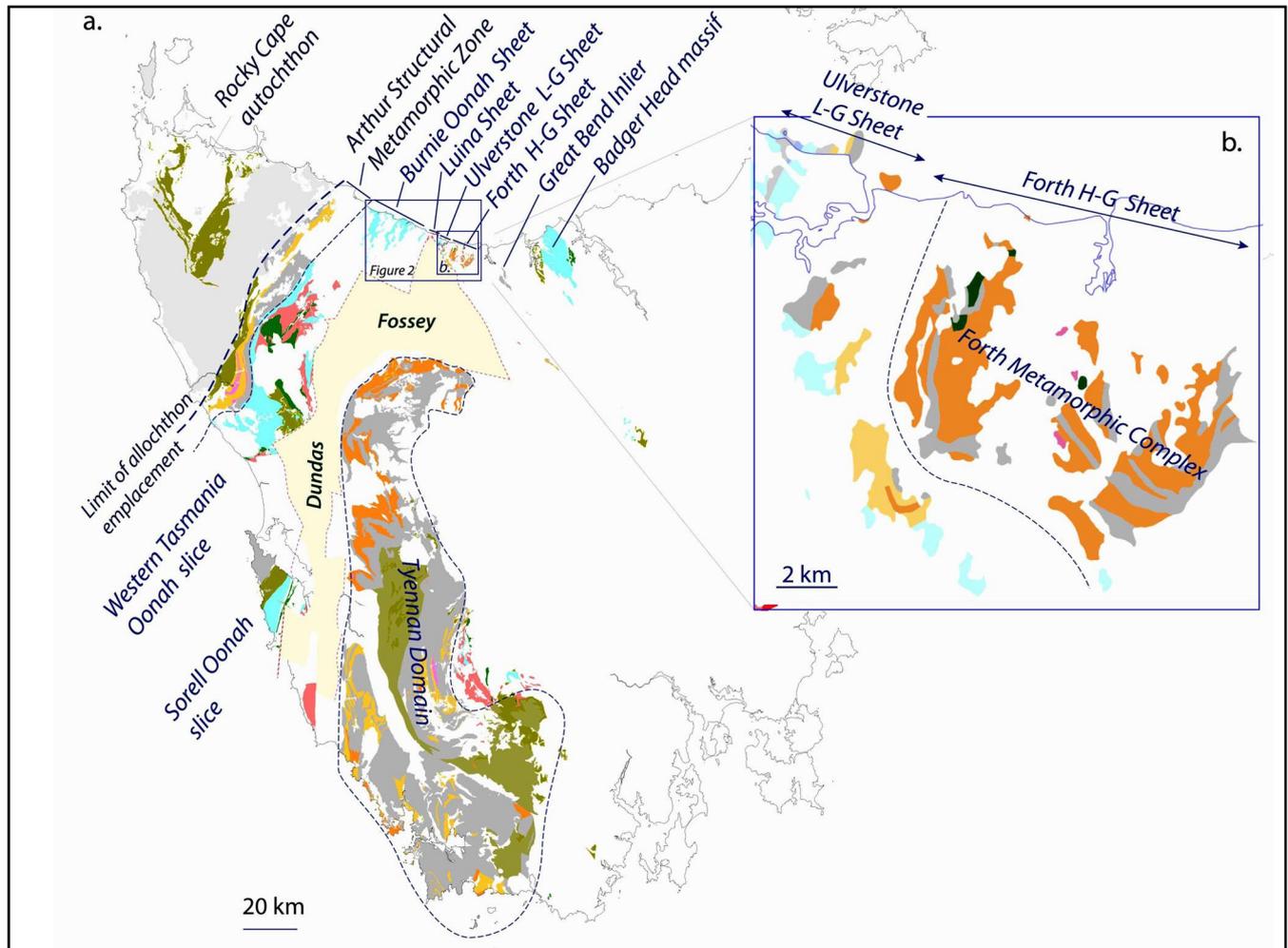


Figure 1. The Proterozoic regions of western Tasmania shown in a). Map base is Mineral Resources Tasmania 1:25,000 and 1:250,000 digital geological atlas. b) Enlarged map with the location of the Ulverstone-Forth Metamorphic Complex. The approximate Ulverstone-Forth Metamorphic Complex map sheet polygon boundaries are 5448000 mS (northern boundary), 5430500 mS (southern boundary), 425000 mE (western boundary) and 444200 mE (eastern boundary).

The Forth Metamorphic Sheet represents the northernmost outcrops of metamorphosed and polydeformed Proterozoic rocks separated from equivalent rocks of the Tyennan Domain by the Middle Cambrian Mt Read Volcanic succession of the Dundas-Fossey graben system (Figure 1). It is now an outlier of H-G rocks isolated and

preserved within a mid-Cambrian horst block. The horst block is a fault-bounded remnant along the eastern and northern flanks of the combined Dundas-Fossey graben system (Figure 1). This horst block has been modified by Devonian thrusting and post-Permian extensional faulting of the Mersey Graben (Figure 2b).

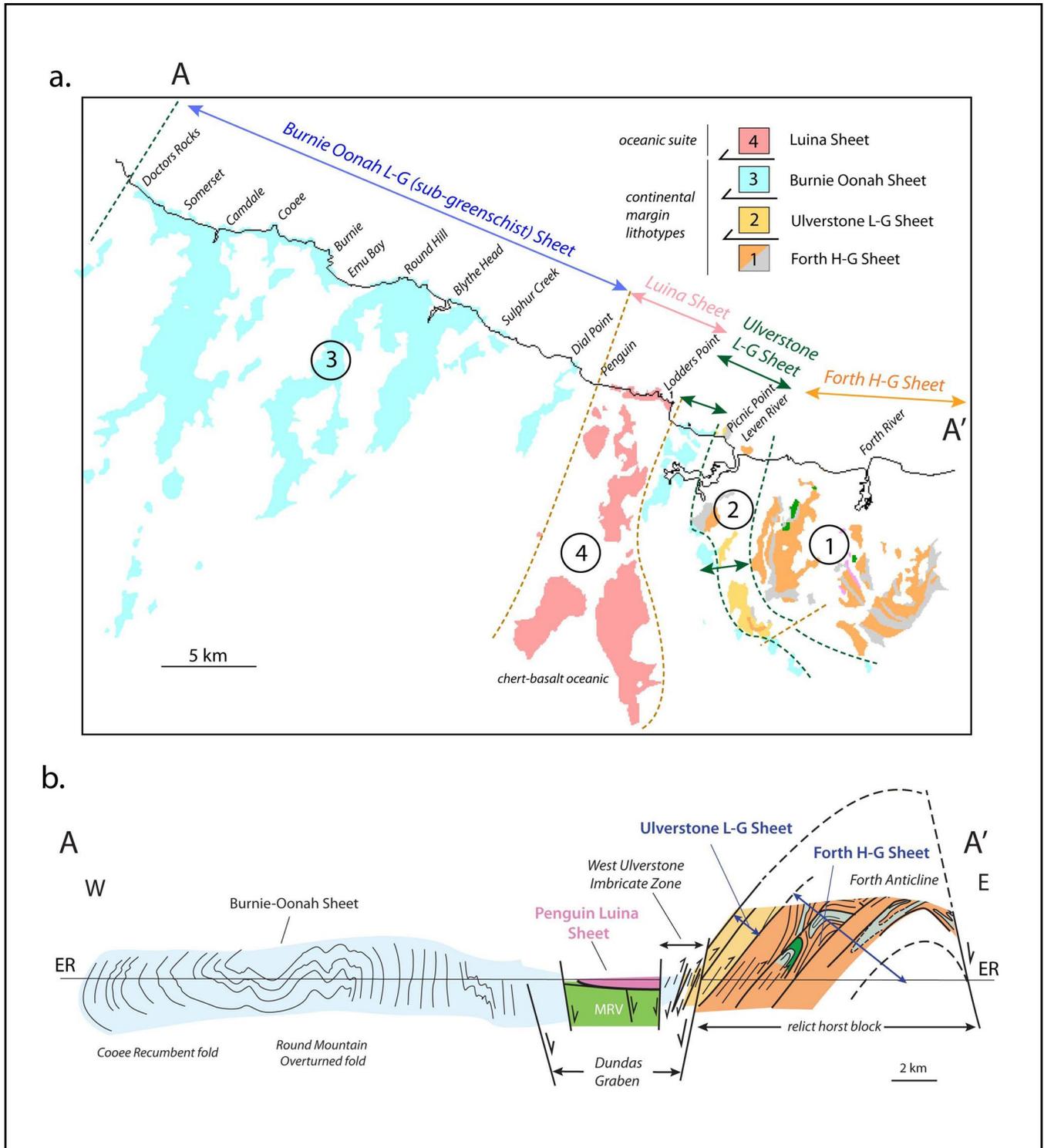


Figure 2. Simplified geological map of the north coast Proterozoic and Cambrian lithotectonic units (see Figure 1a for location). The north coast geology consists of stacked, subducted and exhumed continental margin segments including the Forth H-G Metamorphic Sheet, the greenschist facies L-G Ulverstone Metamorphic Sheet and the sub-greenschist facies Burnie Oonah Sheet. The uppermost sheet is an oceanic chert-basalt suite (Luina Sheet). b) Composite structural profile A-A' along the north coast from Wynard to Leith (see (a) for location). The profile includes the Gee (1977, fig. 3) Burnie structural profile on the west and an up-plunge projection of the Forth and Ulverstone Metamorphic sheets from the MRT 1:25,000 digital atlas on the east.

## 1.1 Contentious/Problematical Issues

1. Emplacement sense and direction of the H-G Forth Metamorphic sheet, the greenschist facies Ulverstone-Oonah Metamorphic Sheet, the L-G sub-greenschist facies Oonah Sheet and ultramafic slices.
2. Relationships of the Forth Metamorphic Sheet to the Tyennan Domain
  - separated and isolated by the Dundas-Fossey Graben system
  - different transport direction to the Tyennan Domain
3. Origin of the ultramafic slices within the Forth Metamorphic Sheet and their emplacement sense and direction.
4. Origin of Togari Group correlate blocks within the interface zones between the sub-greenschist Oonah Sheet and the low-greenschist Ulverstone Metamorphic Sheet.
5. Devonian or Cambrian age for the north-trending, open to tight, upright folds in the Ulverstone Metamorphic Sheet previously attributed to the Devonian deformation.

## 2.0 BACKGROUND

### 2.1 Geographic Elements

The area of the Forth Metamorphic Complex is a generally low-lying (<300 m elevation) compound coastal landform with old terraces dissected by north-flowing rivers and creeks, and bounded on the north by Bass Strait (Figures

3a, b and c). Major drainages include the Leven, Gawler, Forth and Mersey Rivers with rivulets including Clayton and Little Clayton rivulets. The area consists of rolling, low-lying hills with elevations up to ~300 m. The region is now mostly farmland over the rich basaltic soils, with forested areas occupied by the quartzite-dominated parts of the Metamorphic Complex (Figure 3b).

### 2.2 Geological Elements

Tertiary tholeiitic basalt covers most of the area (orange unit, Figure 4a) with erosion and dissection of this basaltic flow by the Leven, Gawler, Forth and Mersey rivers. The drainages provide windows into the underlying collage of low-grade, massive and flaggy quartzite, muscovite-chlorite schist and subordinate conglomerate of the Ulverstone Metamorphics, and the high-grade garnet schists, mica-quartz schists (Ltpg) and massive to schistose, micaceous quartzites (Lts) of the Forth Metamorphics (buff and brown units, Figures 4a and 4b). The Forth region is bounded on the east by Permian glaciomarine sequences and coal measures (Pu) within the post-Permian Mersey graben (blue units, Figure 4a) and on the west by klippen of Early Cambrian chert (Ccw) and tholeiitic basaltic lava of the Luina Group (Ccw) overlying Middle Cambrian volcano-sedimentary sequences (Cds) of the Fossey Graben (lime green units, Figure 4a). All these units are unconformably overlain by Late Cambrian-Ordovician sandstones and conglomerates (Owen Group equivalents and Moina sandstone) of the Dial Range and Porcupine Hill area south of Forth.

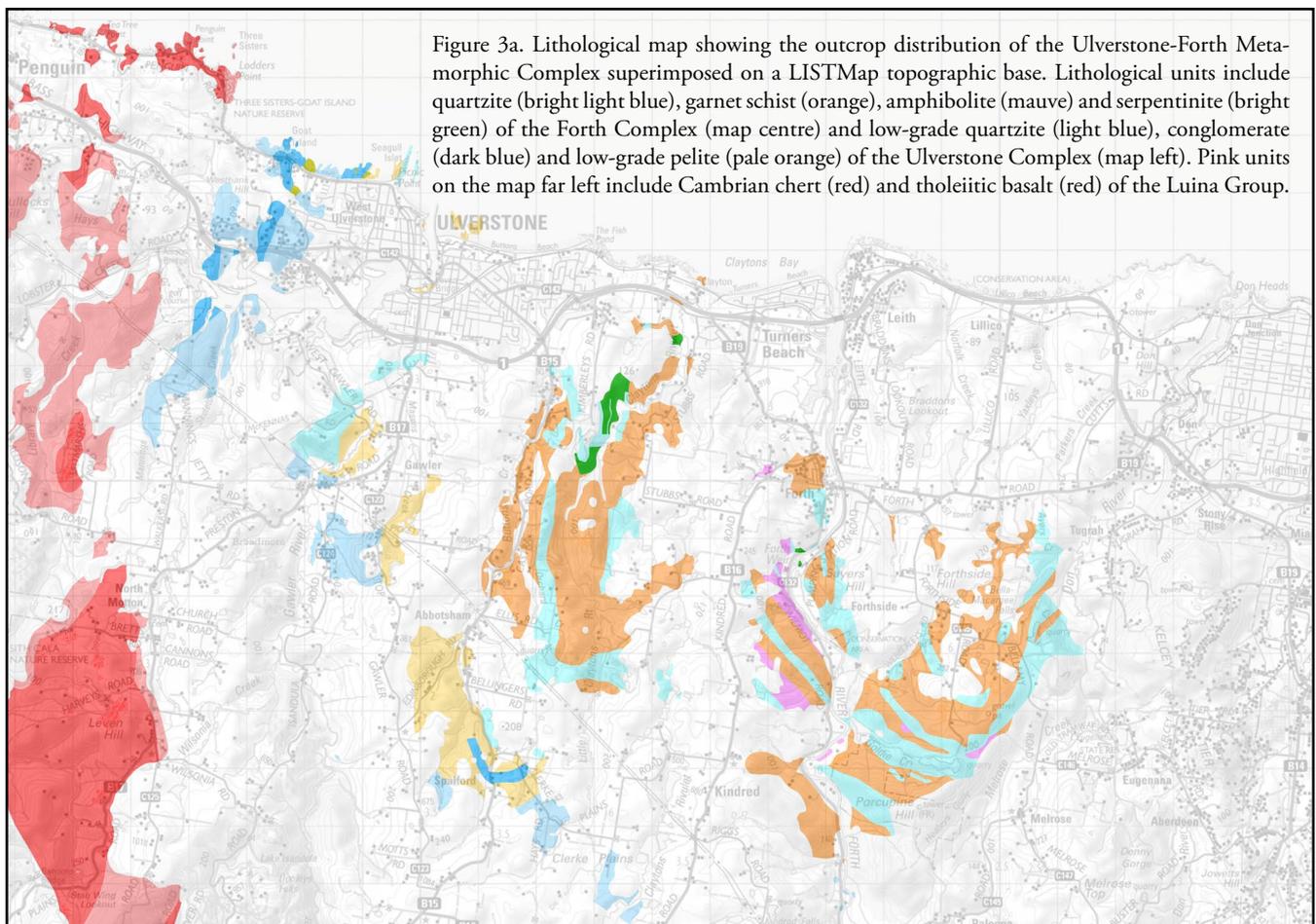




Figure 3b. LISTMap stitched air photo base with outlines of the outcropping quartzites and schists of the Ulverstone-Forth Metamorphic Complex. The farmed areas in between the Proterozoic outcrops utilise the rich, fertile soils developed on the Tertiary basalt (see orange area Figure 3).

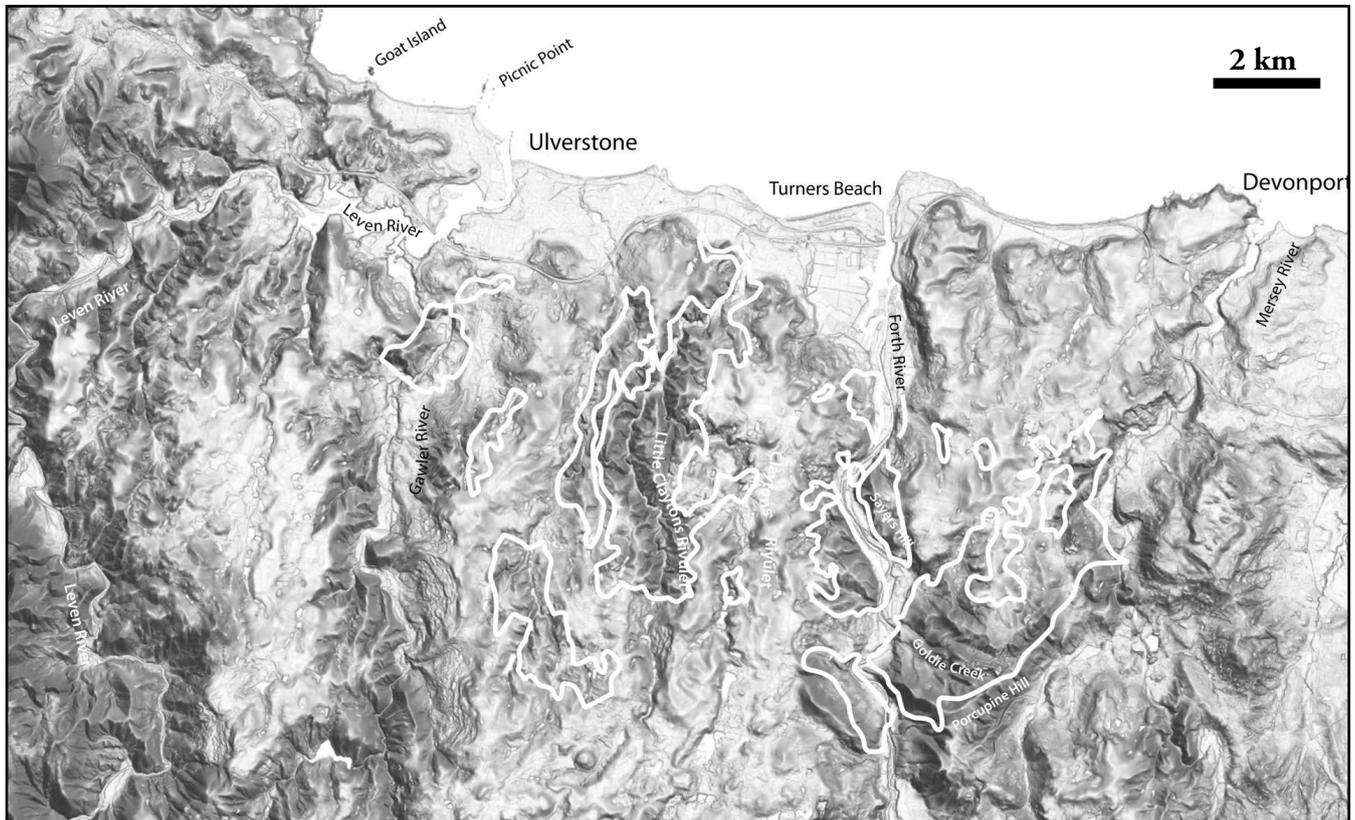


Figure 3c. LISTMap digital elevation model showing outcrop boundaries of the Ulverstone-Forth Metamorphic Complex (white line traces) and a dissected coastal terrace(s) and basalt plain bounded by Bass Strait in the north and cut by north flowing rivers, rivulets and creeks. Major rivers include the Leven (mouth at Ulverstone), the Forth (mouth at Turners Beach) and the Mersey (mouth at Devonport).

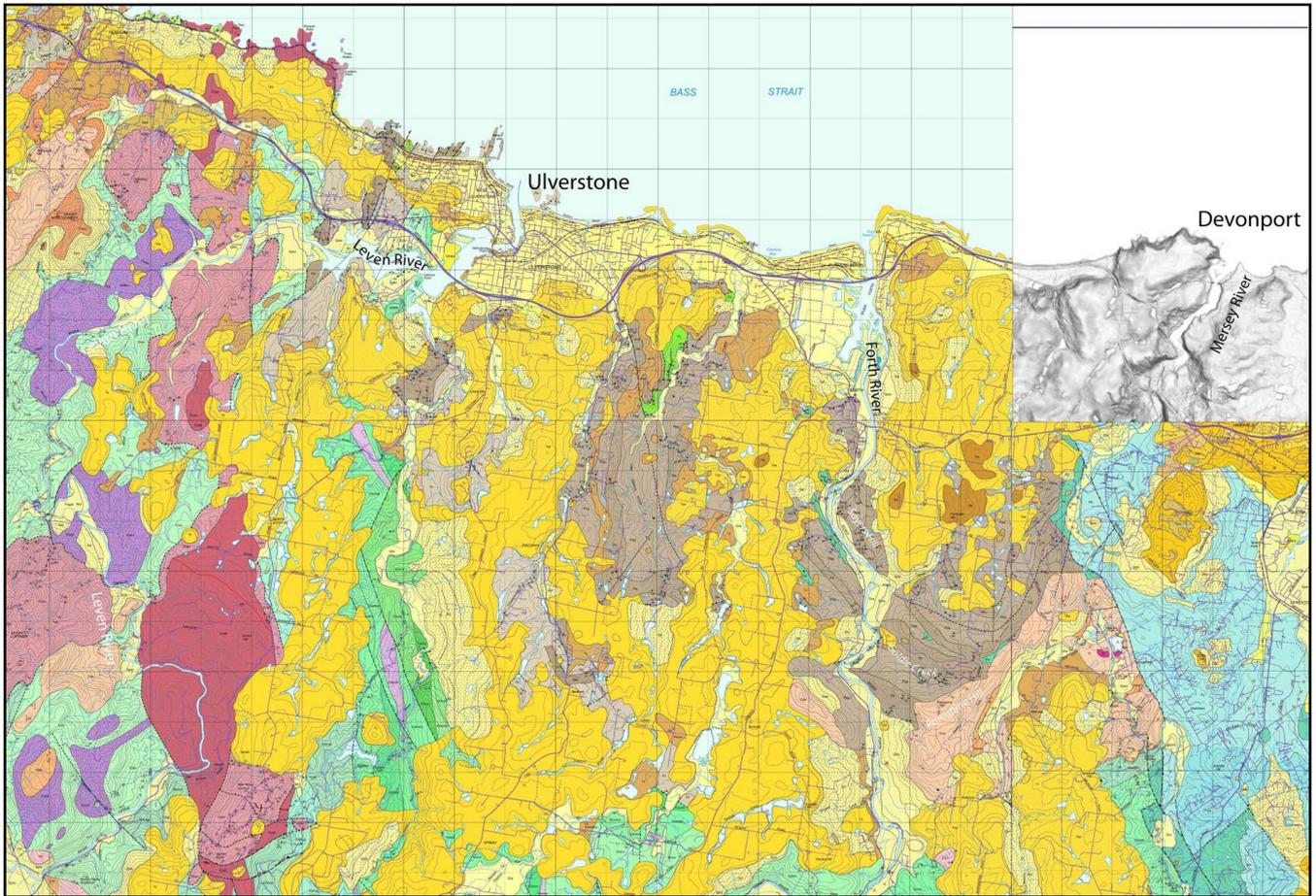


Figure 4a. Geological map of the Ulverstone-Forth area based on the Mineral Resources Tasmania 1:25,000 digital atlas.

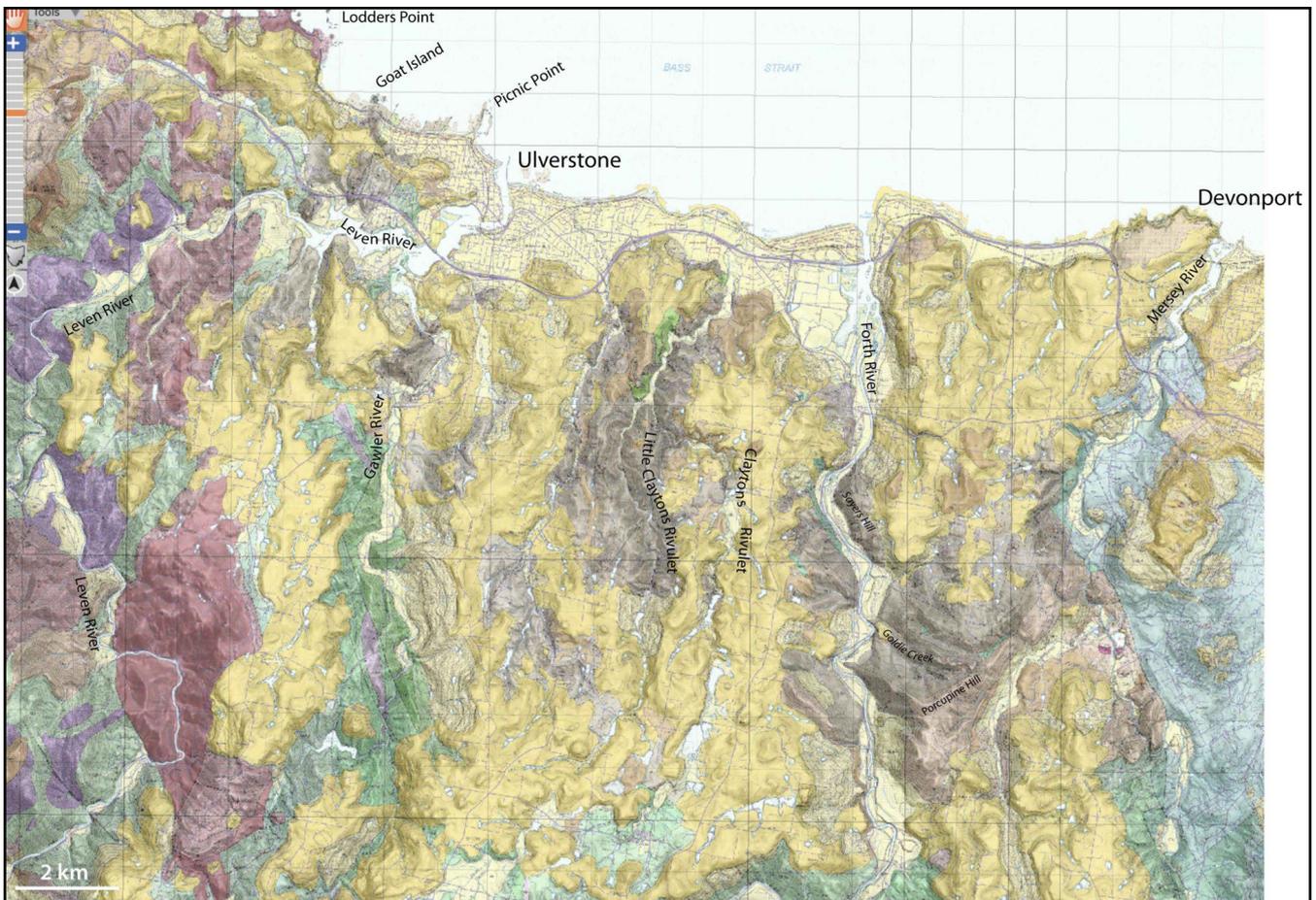


Figure 4b. LISTMap digital elevation model with drape of the 1:25,000 geological map from the Mineral Resources digital atlas. The image highlights the dissection of the Tertiary basaltic plateau and outcrop-control by the major north-flowing rivers.

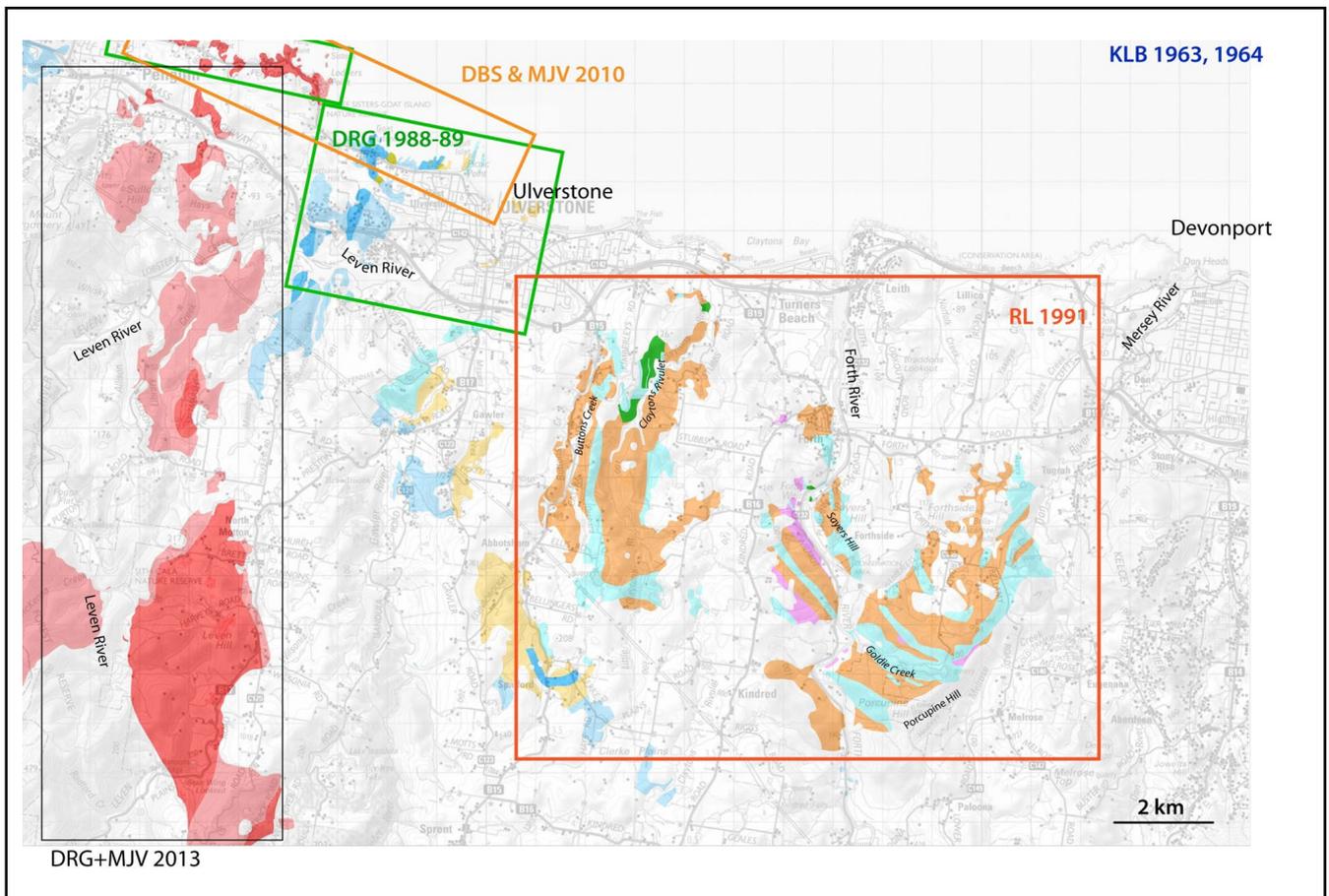


Figure 5. Mapping contributions to the Forth region are shown on a lithological map draped on a ListMap topographic base. Kerry Burns (KLB 1963b, 1964) mapped the area of the outer blue rectangle. Rob Lewis (RL 1991) mapped the Forth Metamorphic complex (red rectangle). David Gray (DRG1988-1989) mapped the coastal area between Penguin and East Ulverstone (green rectangles). David Seymour and Michael Vicary (DBS & MJV 2010) mapped the coastal fault and mega-breccia zones between Penguin and Picnic Point, West Ulverstone (orange rectangle). David Gray and Michael Vicary examined selective Luina Group chert-basalt outcrops in the Penguin-Leven River area in 2013.

### 2.3 Previous Mapping

An index map for mapping and structural data sources for the Ulverstone-Forth region is shown in Figure 5. Kerry Burns undertook mapping in the Dial Range in the early 1960's as part of a PhD at the University of Tasmania (Burns, 1963a) while on staff at the Department of Mines. The mapping led to publication of the Devonport 1:63,360 Quadrangle (Burns, 1963b) and the Devonport Explanatory Report (Burns, 1964). It also led to a strain study on the deformed pebble shapes (Burns and Spry, 1969), discussion on the origin of the deformed conglomerate (Spry and Burns, 1967), and petrofabric work on the quartz fabrics in the deformed conglomerates at Goat Island (Spry and Burns, 1972).

Australian Research Council (ARC) supported University research by David Gray in the period 1988-1989 enabled further detailed mapping of the coastal strip between Penguin and Leith and led to field guides (Berry et al., 1990; Berry & Gray, 2001). This mapping was also utilised in a subsequent Ar-Ar study by David Foster, David Gray and Catherine Spaggiari on the Forth Metamorphics (Foster et al., 2005).

The Forth Metamorphic Complex was further mapped and the structure and metamorphism defined as part of UTas BSc Honours project in 1991 by Rob Lewis (Lewis, 1991).

Geological Survey Mapping was also undertaken by 1) David Seymour across the region as part of the MRT 1:25,000 mapping update, 2) David Seymour and Michael Vicary on the fault and broken formation zones from Penguin to Picnic Point as part of the TasExplore Project (Seymour & Vicary, 2010), and David Gray and Michael Vicary in 2013 as part of the Central North 3D Model Project.

Field observations collected by David Gray between 1976 and 2025 in the Ulverstone to Forth River area are presented in Gray (2025).

### 2.4 Previous Structural Interpretations

Major definition of the structure of the Forth Metamorphic Complex was first provided by Burns (1963a, 1964) and then Lewis (1991). Their results are summarised below.

### 1. Burns (1963a, 1964): UTas PhD thesis

- recognised juxtaposed belts of structurally concordant low-grade greenschist facies Ulverstone Metamorphics and the high-grade amphibolite facies Forth Metamorphics (Figure 6).
- recognised the dominant fabric as an S2 crenulation cleavage with almost complete transposition and overprinting of the S1 fabric, but argued about the "hazards of identifying the latest dominant foliation as S2 everywhere" (Burns, 1964, p.171).
- recognised polyphase deformation with multiple crenulation cleavage fabrics (Scc), overprinting foliations and refolding.
- realised the complexity of multiple fabrics at low angles with parallelism of different fabric types and the concordance with So/Sm.
- recognised two types of lithologically-dependent fold axis/linear structures:
  - ◇ in quartzite a near horizontal lineation in S2 associated with isoclinal folds and mullion structure (Porcupine Hill style).
  - ◇ in belts of schist and amphibolite a steeply pitching lineation in S2 associated with isoclinal folds (Goldie Creek style) (Figure 7).
- recognised a change in foliation character from a spaced crenulation cleavage with microlithons in the west to an intense foliation in the east where earlier fabrics are obliterated by recrystallisation of muscovite and biotite (Burns, 1963a, p.8)
- introduced the concept of tectonic "fish" for isolated pods enveloped by the dominant foliation Sm.

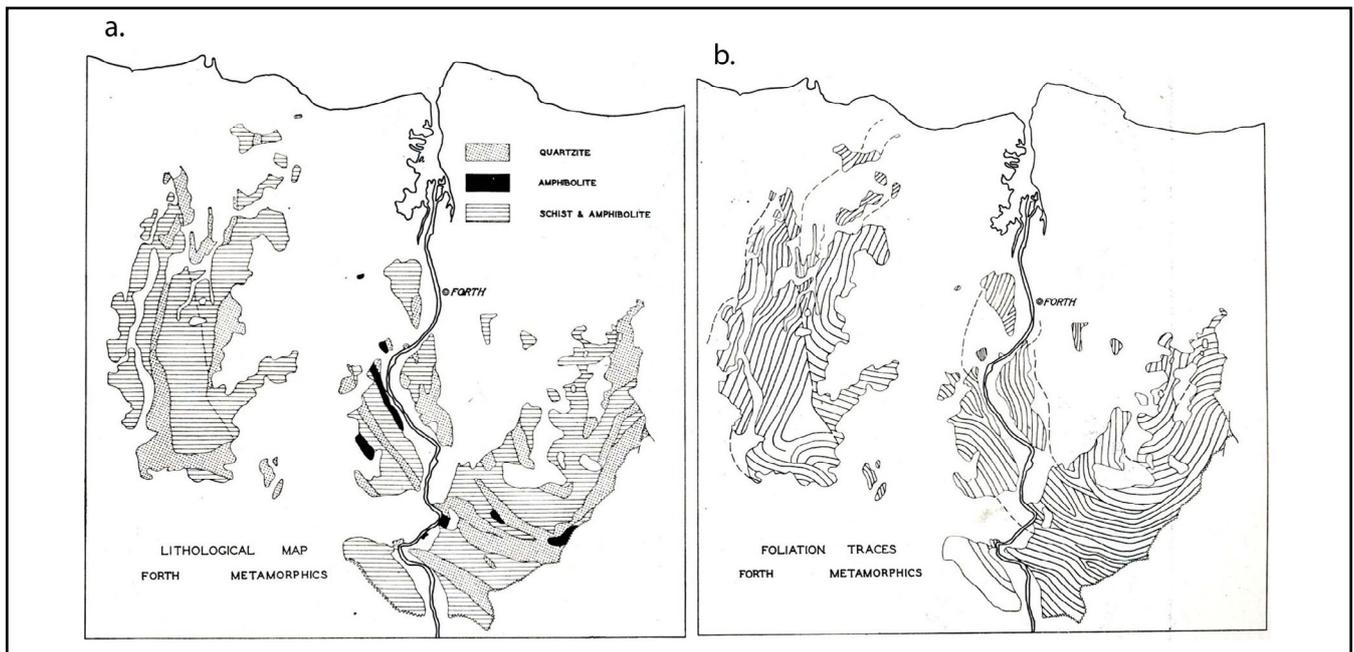


Figure 6. Forth Metamorphic Complex maps from Burns (1964). a) Lithological map. b) Foliation trace form line map (modified from Fig. 25, Burns, 1964).

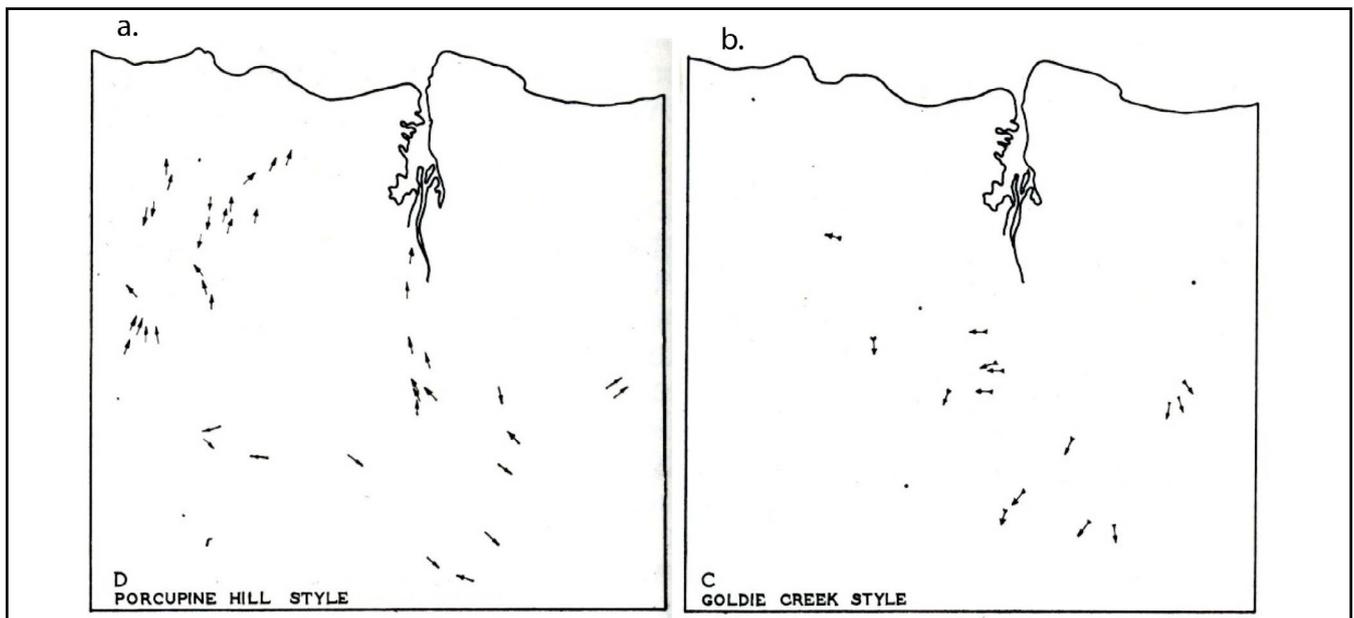


Figure 7. Fold axis maps from Burns (1964). a) Gently plunging "Porcupine Hill" style folds. b) Moderately to steeply plunging "Goldie Creek" style folds (modified from Fig. 24, Burns, 1964).

## 2. Lewis (1991): UTas BSc Hons thesis

Lewis (1991) defined the Forth Metamorphic Complex as a zoned metamorphic complex made up of banded garnetiferous schist and quartzite, interlayered with sub-ordinate ortho-amphibolites of tholeiitic MORB-type affinity (Figure 8). The alternating quartzite and schist lithologies define a compositional banding sub-parallel to the dominant foliation Sm (S2), whereas the amphibolites show a mineralogical banding due to alternating light coloured plagioclase-quartz and dark garnet or hornblende/clino-pyroxene/zoisite domains parallel to Sm as a metamorphic segregation (Lewis, 1991, p.23).

The structural observations of Lewis (1991) include:

- Early isoclinal fold phase (D1) produced a penetrative muscovite foliation largely overprinted by the S2 schistosity.
- No F1 folds present east of Claytons Rivulet. S1 is only present as microstructure in S2 microlithons and inclusions in garnet
- High-T, relatively low strain quartz mylonites developed in narrow zones during west-directed transport, separated by zones of west-vergent, isoclinal F2 folds.
- 2 lineation types based on orientation and style:
  - ◊ L12 intersection lineation gently plunging defined by coarse muscovite.
  - ◊ LS tectonite fabric with down dip mineral lineation associated with mylonitic grain fabrics. These occur east of Claytons Rivulet
- Quartz mylonites, common in the Forth Valley, occur as tough, fine to medium grained quartzite with a penetrative quartz-muscovite foliation and a muscovite, quartz ± tourmaline stretching lineation
- quartz mylonites give consistent west-directed tectonic transport based on deformation lamellae.
- Structurally concordant serpentinite bodies within the metamorphic complex show S-C fabrics consistent with early west-directed emplacement and overprinting by younger east-directed Devonian thrusting.

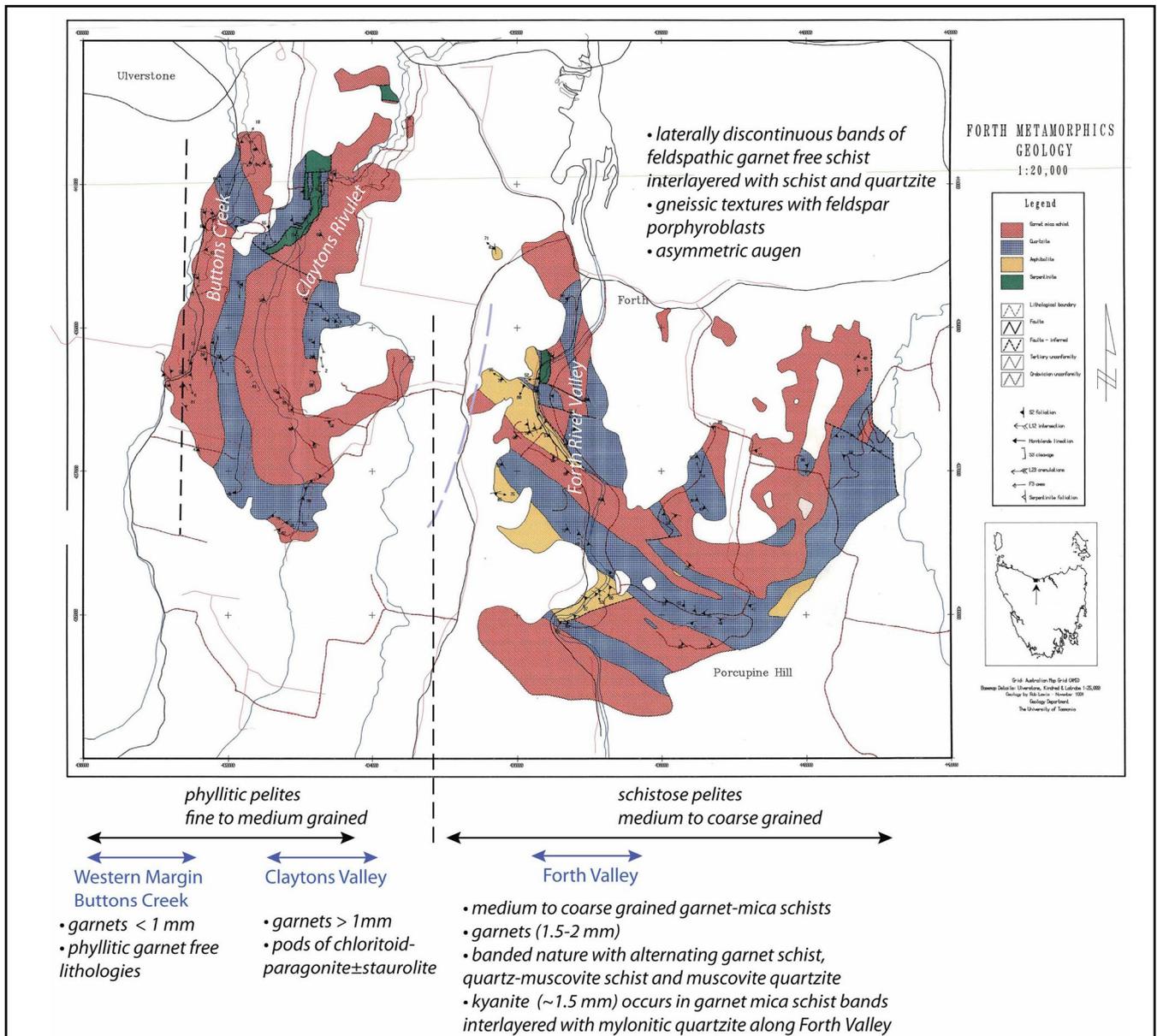


Figure 8. Forth Metamorphic Complex lithological map from Lewis (1991, fig. 2.1). Additional to the map are Lewis (1991) descriptions and summaries of the structural character, metamorphic petrology and lithology across the Complex. Note there is an apparent metamorphic grade increase from west to east.

## 2.5 Metamorphism of the Forth Metamorphic Complex

Lewis (1991) documented a complex metamorphic history coupled with significant P-T zonation involving mineralogic domains of kyanite-garnet-biotite schists in the eastern part of the Complex (Forth Valley) and staurolite-chloritoid schists in the western half of the Complex (Figure 8).

### East (structurally lowest part)

- thermobarometry on kyanite-garnet-biotite schists (Forth valley) give peak conditions of  $700^{\circ}\pm 50^{\circ}\text{C}$  and  $13\text{ kb}\pm 2\text{ kb}$
- garnet-clinopyroxene-albite assemblages give  $660^{\circ}\text{C}$  and  $11\text{ kb}$  during garnet core growth.
- semi-quantitative P-T modelling of calcite-altered garnet-clinopyroxene-zoisite interbands developed locally in a poor H<sub>2</sub>O during compression suggest heating from  $675^{\circ}\text{C}$  and  $9\text{-}11\text{ kb}$  to peak conditions of  $740^{\circ}\text{C}$  and  $13\text{-}15\text{ kb}$ .

- late D2 K-metasomatism along a local high strain zone between garnet-amphibolite schist and pelitic schists.

### West (structurally highest part)

- staurolite-chloritoid schists in the western half of the area suggest peak temperatures  $100^{\circ}\text{C}$  lower than the peak  $700^{\circ}\text{C}$ .
- paragonite and chloritoid textures consistent with breakdown of glaucophane may indicate an early high P-low T history.
- Late sphene and possibly albite developed during decompression.
- Preservation of substantially unretrogressed high-grade assemblages indicates rapid late-D2 uplift and cooling.

Chmielowski (2009) and Chmielowski and Berry (2012) undertook geothermobarimetric work on two Forth Valley garnet-mica schists (samples 75596 and 75637 of Lewis, 1991) obtaining a thermocalc average pressure/temperature estimates of  $670^{\circ}\text{C}$  and  $1.61\text{ - }1.77\text{ GPa}$ .

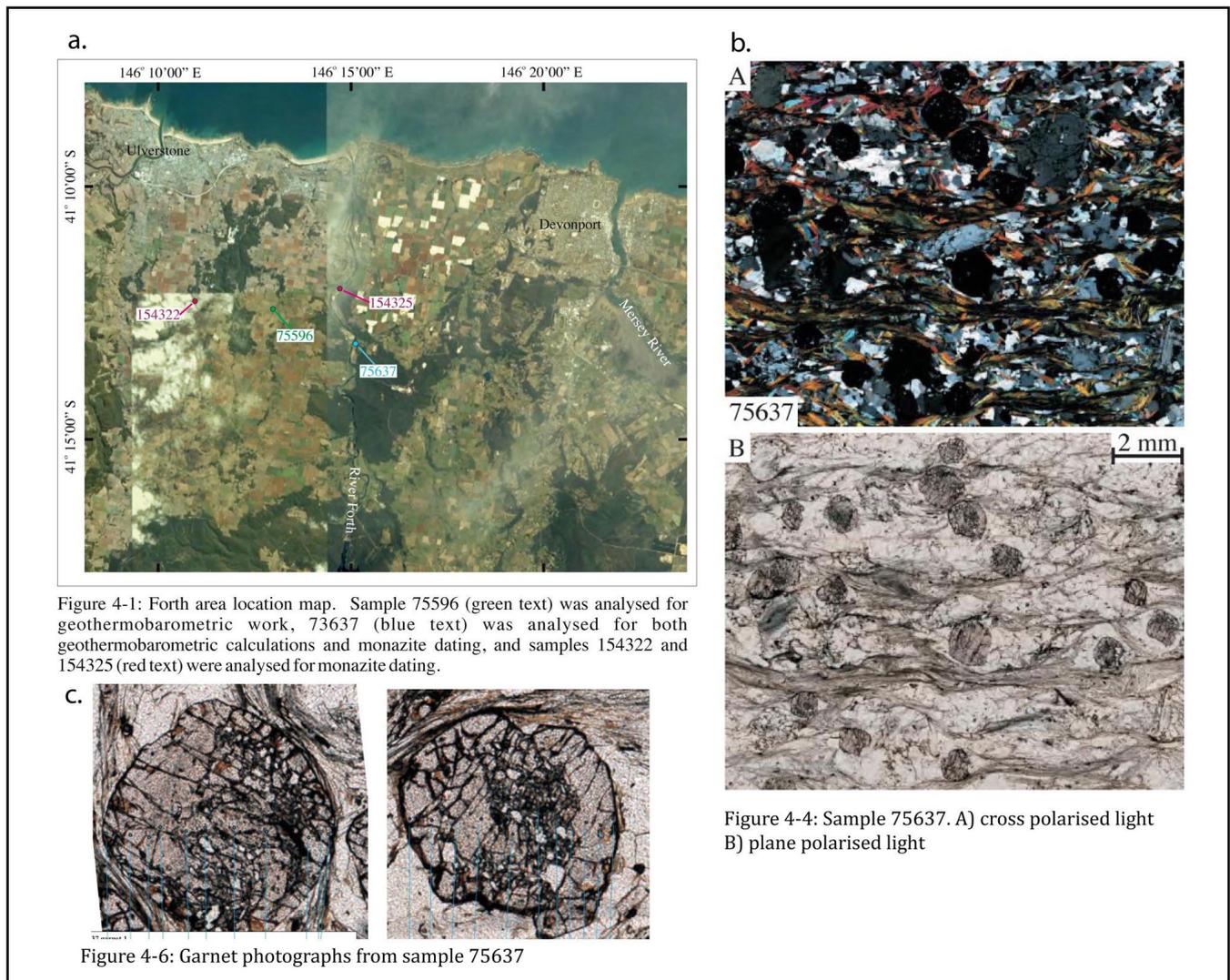


Figure 9. Locations and microstructural relationships of the Forth Metamorphic Complex samples analysed by Chmielowski (2009). The diagram is a composite made up of diagrams from Chmielowski (2009) with the original figure numbers and captions included. a) Sample locations superimposed on satellite imagery of the Forth-Ulverstone area. b) Fabric relationships within Sample 75637 in both cross-nicols (labelled A) and plane polarised light (labelled B). c) Enlarged views of garnets also from Sample 75637.

## 2.6 Geochronology of the Forth Metamorphic Complex

1. Chmielowski (2009) as part of a PhD thesis on the Cambrian metamorphism of Tasmania undertook U-Th- Pb dating of in situ monazite grains in 3 samples from the Forth Metamorphic Complex (Figure 9). A single generation of monazite provided a combined weighted mean age of  $509 \pm 7$  Ma (Chmielowski, 2009).
2. A garnet amphibolite from this complex has yielded zircons with an age of  $514 \pm 4$  Ma (Black et al., 1997).
3. Ar-Ar geochronology of the Ulverstone-Forth Metamorphic Complex (Figure 10). Ar/Ar white mica measurements from this area cluster at 508 Ma (five samples) and 522 Ma (2 samples) (Foster et al., 2005).

## 2.7 Nature of the Layering, Foliations and Lineations

Burns (1964) established the nature and chronology of the foliations. The main and/or dominant foliation was defined as the second foliation (S2). It varies from a crenulation cleavage in L-G, lower strain rocks, with cleavage foliae defined by oriented grains of syntectonic mica, to a penetrative schistosity in the H-G rocks defined by coarse recrystallised muscovite and biotite.

The first foliation is difficult to see in the field and is best observed in the cores of isoclinal F1/F2 folds. In thin-section. S1 is a penetrative foliation sub-parallel to compositional banding that is preserved within S2 microlithons (Lewis, 1991).

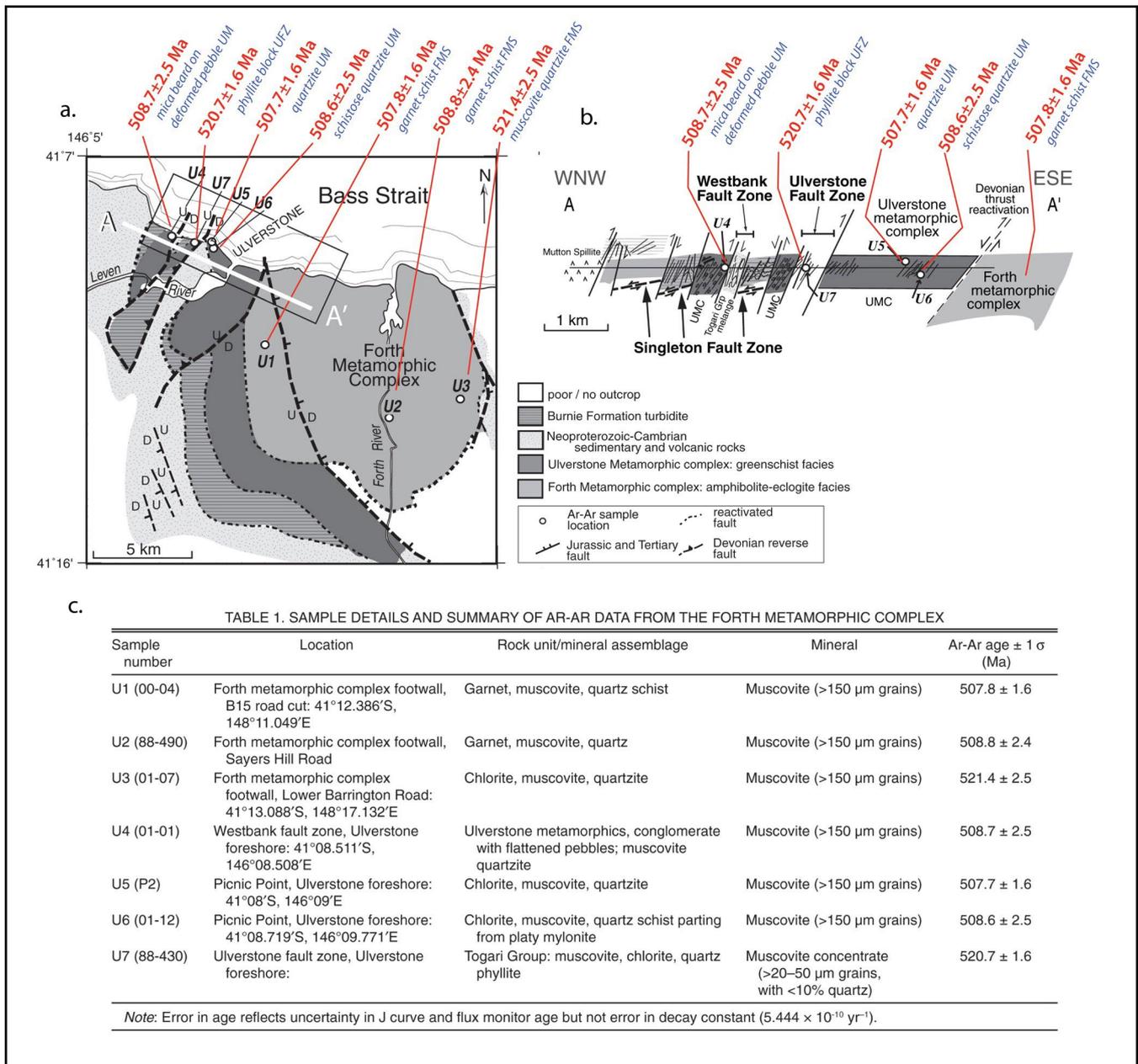


Figure 10. Ar-Ar geochronology of the Ulverstone-Forth Metamorphic Complex presented as a composite figure incorporating diagrams from Foster et al. (2005). a) Sample location map of the Complex on a simplified geology base (fig.3, Foster et al., 2005). b) Detailed sample map of the West Ulverstone coastline between Goat Island and the Forth River (fig.4, Foster et al., 2005). c) Schematic structural profile showing sample locations in the exposed coastal section (fig.4, Foster et al., 2005). d) Ar-Ar data table with sample location, sample mineralogy and Ar-Ar age (Table 1, Foster et al., 2005).

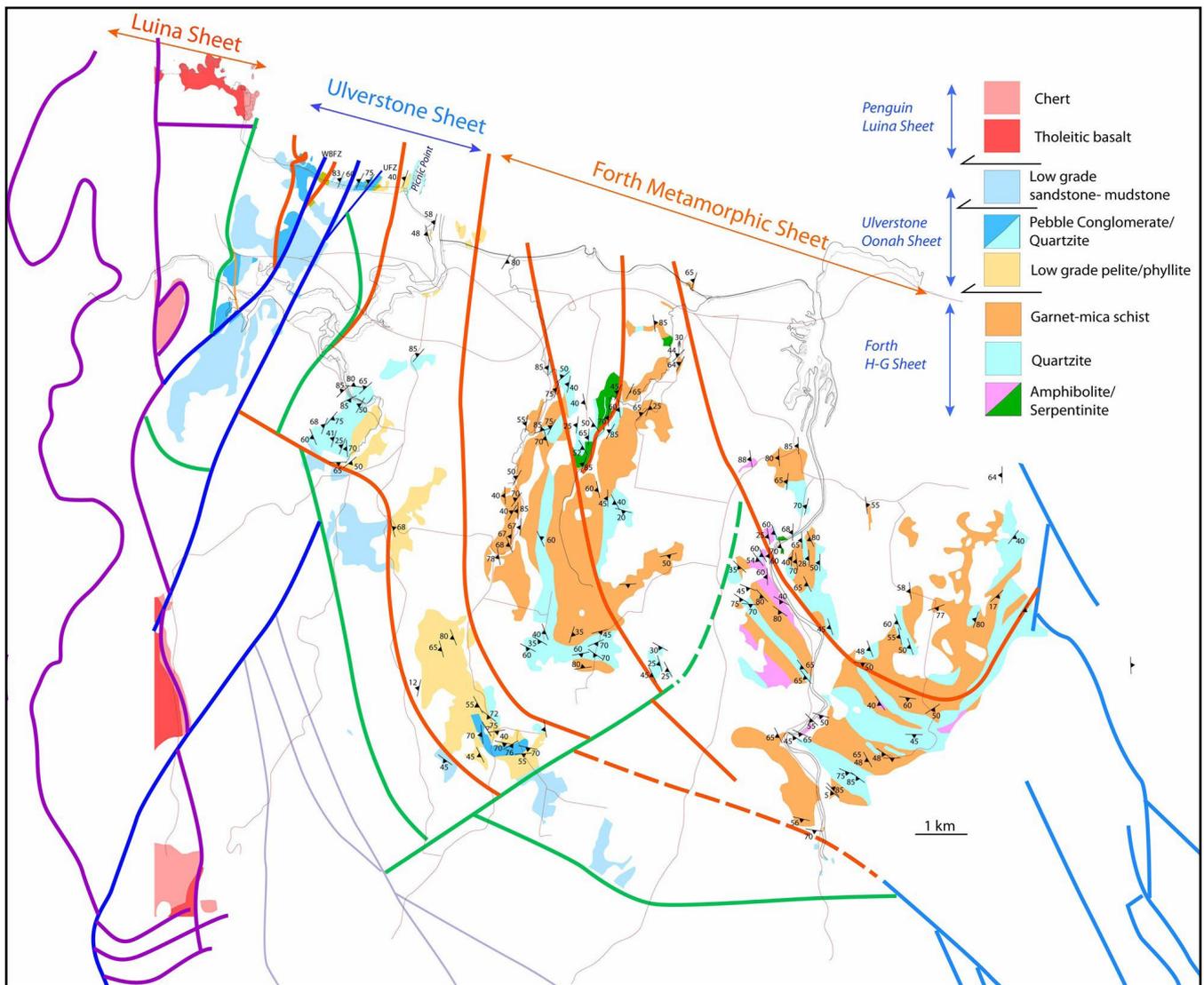


Figure 11. Forth-Ulverstone area geological map showing the three main thrust sheets, the main lithological units, major faults and shear zones (coloured line traces), outcrop traces (thin black line traces) and the attitudes of the dominant foliation  $S_m$ . The base map is from the Mineral Resources Tasmania 1:25,000 digital atlas.

### 3.0 GEOLOGY SUMMARY/OVERVIEW OF THE FORTH METAMORPHIC SHEET

The Forth Metamorphic Sheet is an allochthonous composite sheet, made up of a collage of structurally interlayered, isoclinally folded and shear zone-bounded quartzite, amphibolite and schist (Burns, 1964; Lewis, 1991; Berry and Gray, 2001; Meffre et al., 2000 and Meffre et al., 2001). The structurally intercalated quartzite, micaceous quartzite, quartz-mica schist and garnet mica schist enclose  $S_m$  parallel belts of amphibolite and minor serpentinite (Figure 11).

The amphibolites occur as two 500 m wide belts in the Forth Valley and as discontinuous bands along the western margin of the Claytons serpentinite (Lewis, 1991). Some of the quartzite occurs as pods or tectonic fish (Burns, 1963a).

#### 3.1 Major Structural Elements

##### 3.1.1 Lithotectonic Sheets

The major, regional scale structural elements of the Ulverstone-Forth map area (Figure 12) include:

- a stacked series of metamorphic sheets (Units 1 and 2, Figure 12) including the high-grade Forth metamorphic sheet of Proterozoic protoliths (pink coloured Unit 1, Figure 12) overlain by the low-grade Oonah sheet of Neoproterozoic protoliths (brown coloured Unit 2, Figure 12) separated by higher strain shear zone interfaces.
- extensional faults bounding Middle Cambrian Dundas Fossey pull apart basin or graben (green coloured Unit 3, Figure 12),
- a Late Cambrian oceanic thrust sheet (salmon pink unit 4, Figure 12) that consists of a basalt-chert-sedimentary olistostrome sequence, with a basal fault shown by the heavy pink barbed line.
- a major Devonian anticline-syncline pair of the Abbotsham/Forth Anticline and Eugena Syncline (Figure 13).
- a series of north-trending, west-dipping reverse faults along the western flank of the Devonian Forth Anticline (Figure 12).
- northwest-trending post-Permian extensional faults bounding the Mersey pull-apart basin or graben.

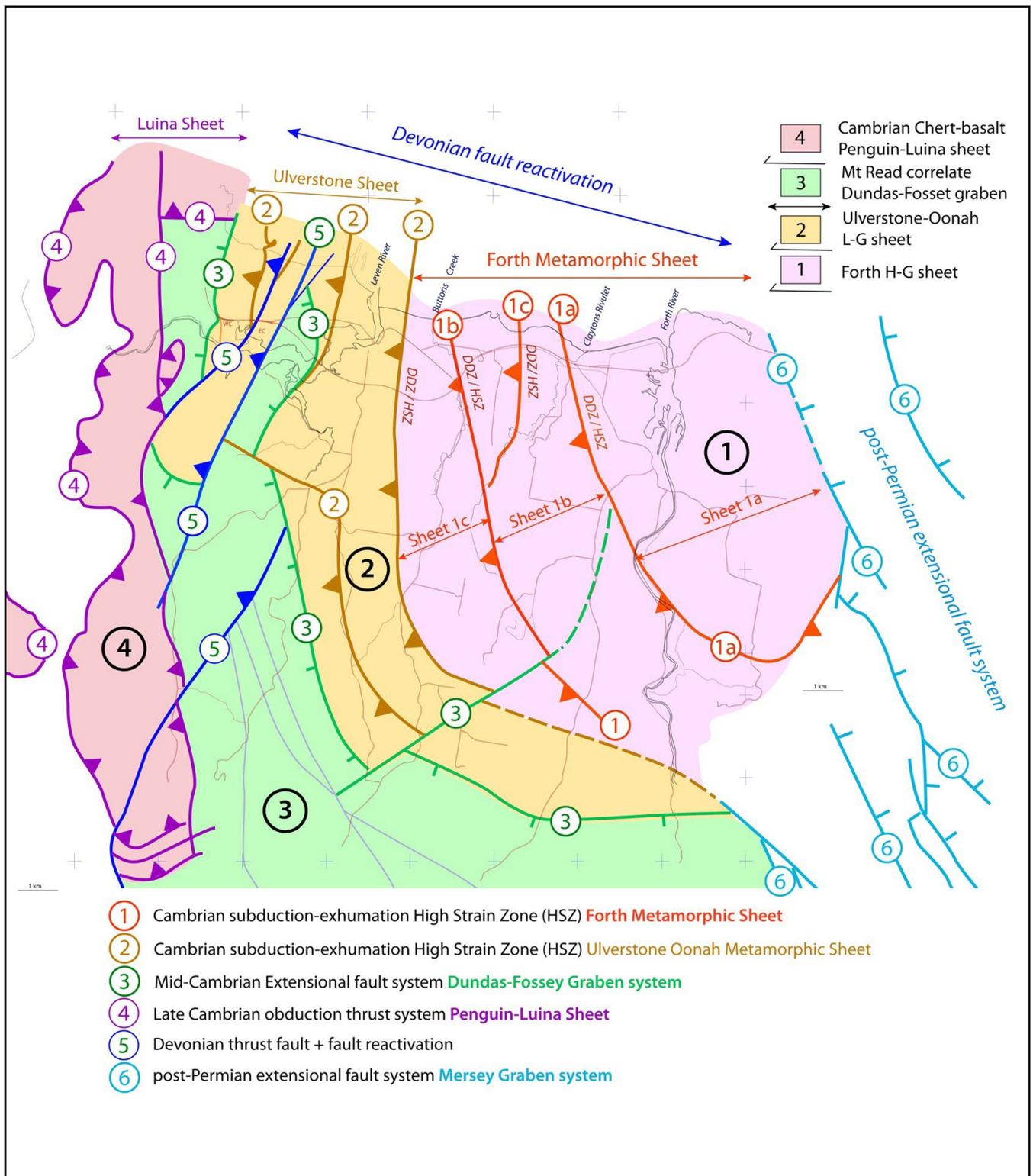


Figure 12. Lithotectonic sheet map showing the four major lithotectonic units (black circled numbers) and the associated complex fault network (coloured circled numbers). The lithotectonic units include the structurally lowest, H-G Forth Metamorphic Sheet (pink sheet/Unit 1), the overlying L-G Ulverstone Oonah Sheet (orange sheet/ Unit 2), the Cambrian volcano-sedimentary rift sequence of the Dundas-Fossey Graben (pale green/ Unit 3) and the structurally highest Cambrian chert-basalt sequence of the obducted Penguin-Luina sheet. The complex fault history from the oldest Cambrian subduction-exhumation high strain zones (HSZ) (red circled 1 faults) to the post-Permian extensional fault system (blue circled 6 faults) is tabulated at the base of the figure.

Red circled 1a: Forth Valley HSZ

Red circled 1b: Buttons Creek HSZ

Red circled 1c: Clayton Rivulet HSZ

### 3.1.2 Fault Systems

The map represents an interaction of six different fault systems (coloured circled numbers, Figure 12) including:

1. Cambrian obduction "thrust" system made up of:
  - internal shear zones within the isoclinally folded high-grade stack (Forth Metamorphic complex Unit 1) (red line traces and circled 1 HSZ, Figure 12), and
  - a composite slip interface along the base of the low-grade Oonah-correlate sheet (Unit 2) with emplacement over the Forth sheet (brown line traces and circled 2, Figure 12). This fault has varying morphological variants including:
    - ◊ basal, greenschist facies high strain zone (Ulverstone Metamorphic equivalents), and
    - ◊ block-in-mud-matrix mélange incorporating fragments of Oonah correlate off the fault hanging wall and "rip-up" Togari Group fragments off the footwall (Rocky Cape autochthon).
2. Mid-Cambrian extensional fault system (green line traces and circled 3, Figure 12) related to Dundas-Fossey graben development, rift-volcanism and massive sulphide exhalation.
3. Late Cambrian brittle thrust system shown by the (thick purple barbed line traces circled
4. Devonian reverse fault system (dark blue line traces and circled 5, Figure 12) developed along the western limb of the Devonian Forth Anticline. These faults are superimposed on and cause reactivation of parts of the earlier obduction "thrust" systems.
5. Post-Permian extensional fault system (light blue line traces and circled 3, Figure 12) related to Mersey Graben development.

### 3.1.3 Major Folds

The Forth-Ulverstone map geology displays curved outcrop trends in lithological layering due to broad folding of the metamorphic thrust sheets by two younger Devonian folds (Figure 13). These are the south-plunging, north-south trending Forth Anticline (green circled 1, Figure 13) and the companion southwest plunging and trending Abbotsham Anticline (green circled 2, Figure 13).

The respective hinges are cut and appear offset by the high-strain shear zones (HSZ/DDZ shown by the thick pink lines, Figure 13), that are both internal to, and bounding the Forth Metamorphic Sheet. The two major anticlinal folds are further truncated and offset by a reactivated, northeast-trending Cambrian transfer fault within the Cambrian Dundas-Fossey Graben system (Figures 12 and 13).

This overall map pattern exhibits a compound form with box-like geometry defined by the two variably plunging hinges (Figures 13 and 14). The Forth Anticline also has a truncated geometry due to 1) by onlap of the Cambro-Ordovician fluviatile sandstone/conglomerate sequence (Moina Sandstone) in the southeast, 2) fault truncation on the east by the post-Permian extensional fault system of the Mersey Graben and 3) imbrication and truncation on the western limb of the Anticline by a series of younger Devonian west-dipping, east-directed reverse faults that reactivate or splay off the Cambrian extensional faults.

The Forth Metamorphic Sheet also contains a series of isoclinal macro-folds highlighted by pinchouts/closures within the structurally intercalated garnet schist and quartzite lithological layering. These macro-isoclines are folded by the Devonian Anticlines and now have reclined geometry (see isocline plunges shown by the red arrows relative to the fold hinges in Figure 13).

### 3.2 Mesoscopic Structural Relationships

Mesoscopic structural elements include the foliation  $S_m$ , the mineral/stretching lineation  $L_m$ , early isoclinal fold axes and shear bands  $S_b$ . The patterns and relationships across the Forth and Ulverstone Metamorphic Sheets are shown in a series of maps.

#### 3.2.1 Foliation $S_m$ Pattern

Form lines based on the foliation  $S_m$  attitudes define the compound, south-plunging fold form of the younger Devonian, regional Abbotsham and Forth Anticlinal folds (Figure 16). The form lines are overall sub-parallel to the lithological contacts, but cut across the contacts, particularly in the interpreted macro-isoclinal fold noses, or lithology pinch-outs, where they are sub-parallel to the fold axial surfaces. Form lines are also truncated by the associated HSZ and younger faults (Figure 16).

#### 3.2.2 Lineation $L_m$ Pattern

Lineations in the Forth and Ulverstone Sheets record different components of the deformation. These include:

1. Lint, Lrod and Lmullion (red arrows, Figure 17) that are sub-parallel to, or define, the early isoclinal fold hinge lines. These match the mesoscopic fold axis patterns shown in Figure 19.
2. Lhornblende (green arrows, Figure 17) that define the lineation pattern within the strongly deformed lenses and pods of amphibolite. These are commonly steeply plunging within an intense foliation  $S_m$  marking high strain zones.
3.  $L_m$  (black arrows, Figure 17) that mark the mineral elongation or stretching within the foliation  $S_m$ . These are commonly moderately to steeply plunging within the dominant foliation, typical of the fabric relationships with high strain zones of the Forth Metamorphic Sheet (Lewis, 1991).

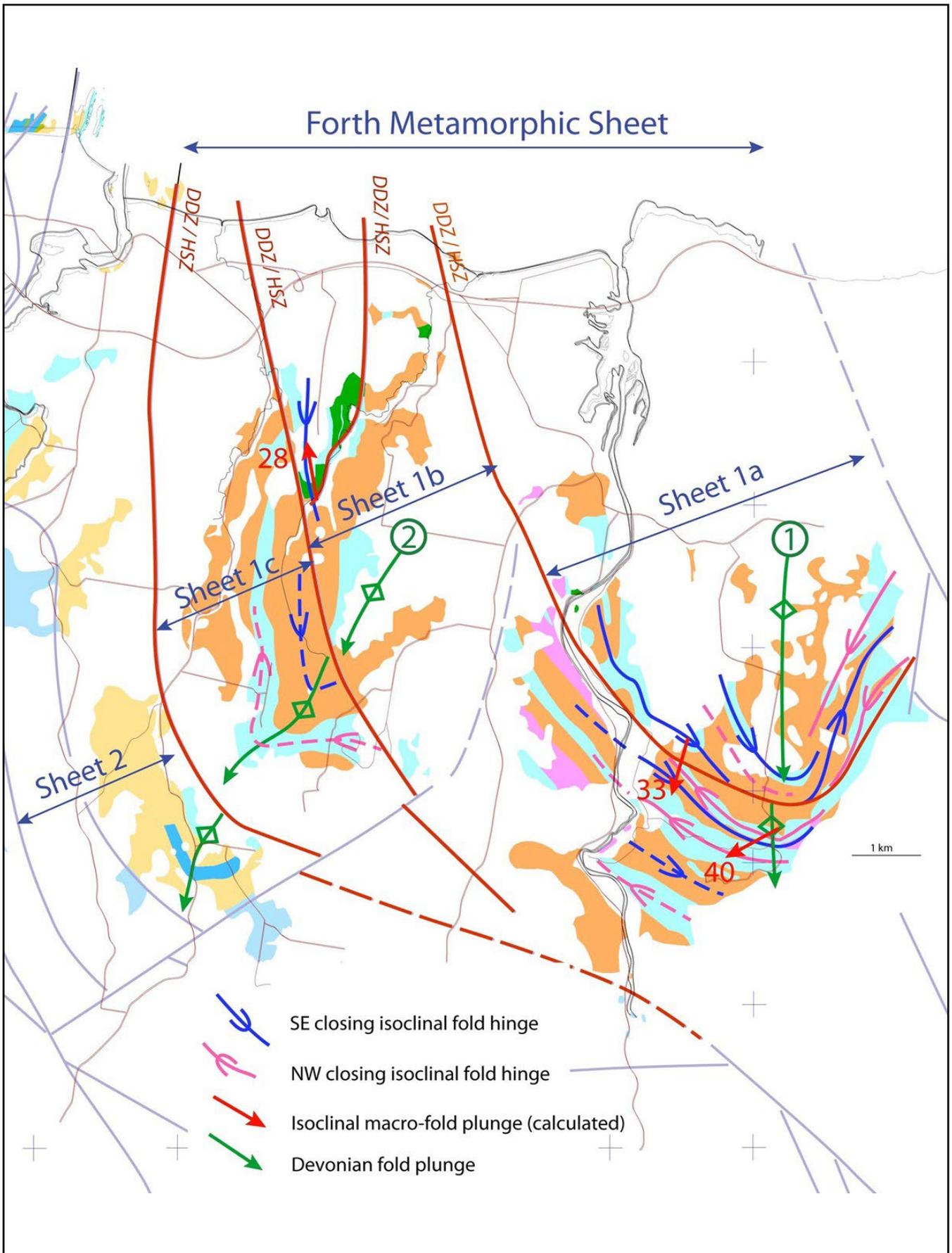


Figure 13. Fold axial surface trace map for the Forth Metamorphic Sheet showing early, isoclinal macro-fold axial surface traces (blue and pink line traces), early isoclinal macro-fold plunges (red arrows) and younger Devonian fold axial surface traces and plunges (green lines and green arrows). Green circled 1 trace= Forth Anticline and green circled 2 trace = Abbotsham Anticline. The early isoclinal macro-fold axes were calculated as stereonet  $\beta$  points from foliation attitudes defining the macro-fold hinges on the 1:25,000 maps.

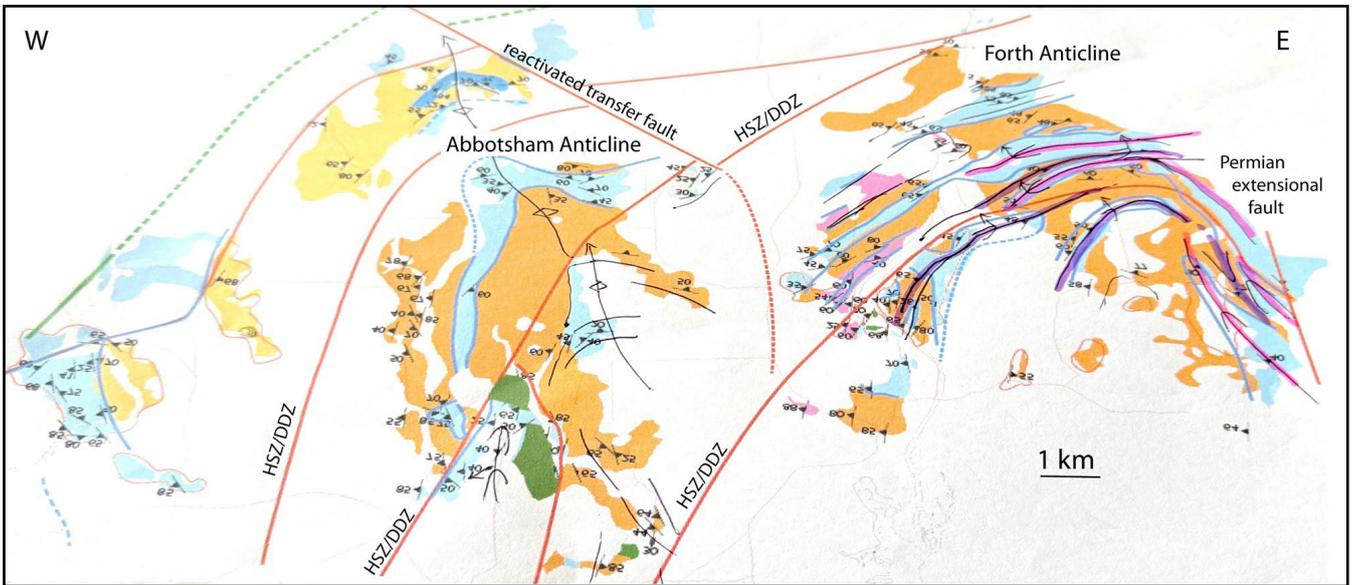


Figure 14. Up-plunge map projection to give a structural profile across the Forth and Abbotsham Anticlines (see Figure 15 for construction diagram). The folds have an apparent box-like geometry but are separated by a reactivated Cambrian extensional-transfer fault formed during Dundas-Fossey Graben development. Reactivation occurred in the Devonian. The base of the projection plane is located at the position of the present coastline (see Figure 13).

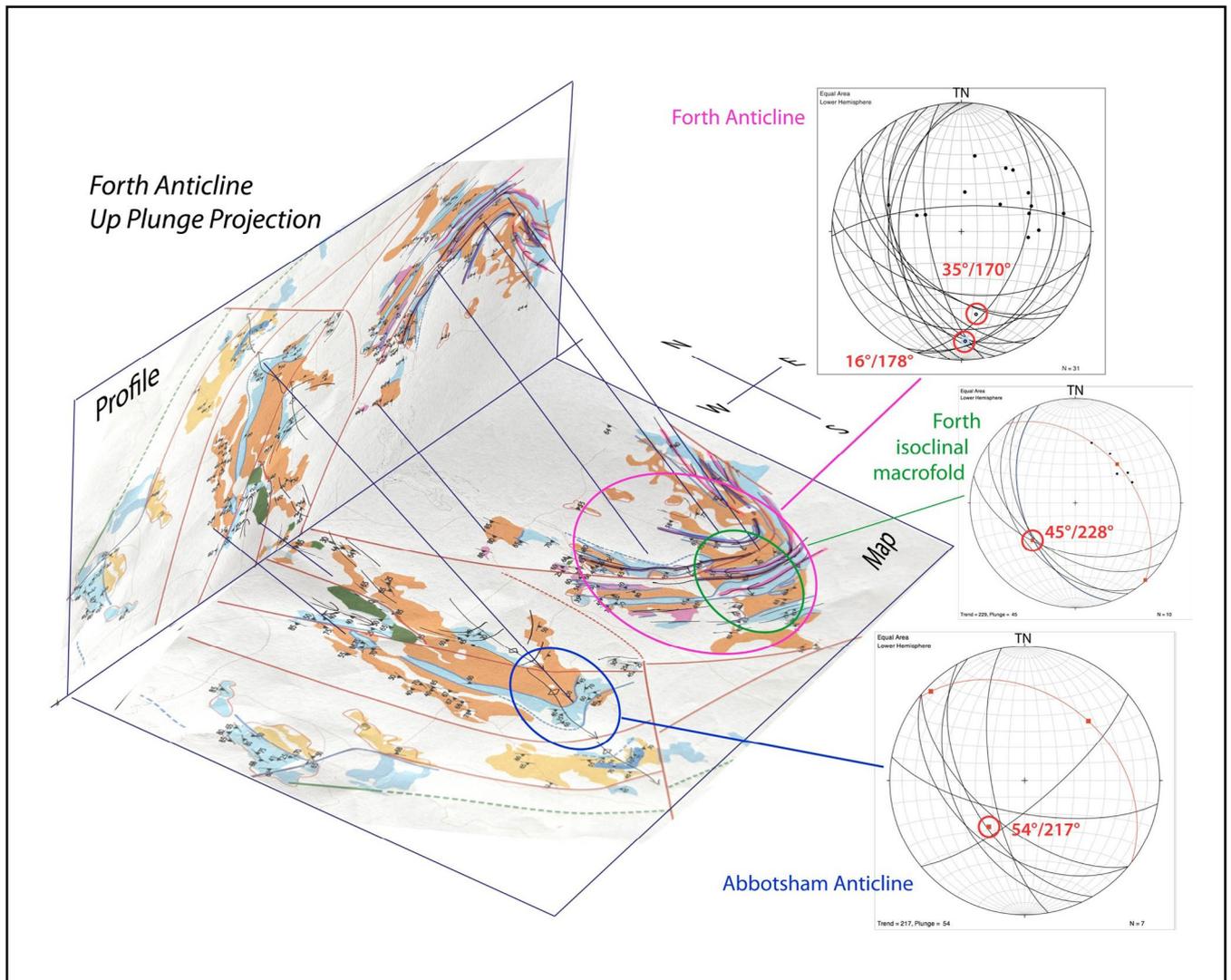


Figure 15. Up-plunge projection construction diagram for the Forth and Abbotsham Anticlines where the map view is projected up the fold plunges. The up-plunge profile is shown in Figure 14. The base line of the projection plane is located at the present coastline (i.e. top of the map). The stereonets are great circle plots of  $S_0/S_m$  and  $S_m$  for the Forth Anticline (top right) and the Abbotsham Anticline (bottom right), with the inferred southeast-closing, isoclinal macrofold stereonet (middle right). The red circles define the  $\beta$  intersection points or equivalent fold axes for the respective folds. The stereonets suggest a polyclinal form for the Anticlines with non-cylindrical hinge lines (compare with Figure 13).



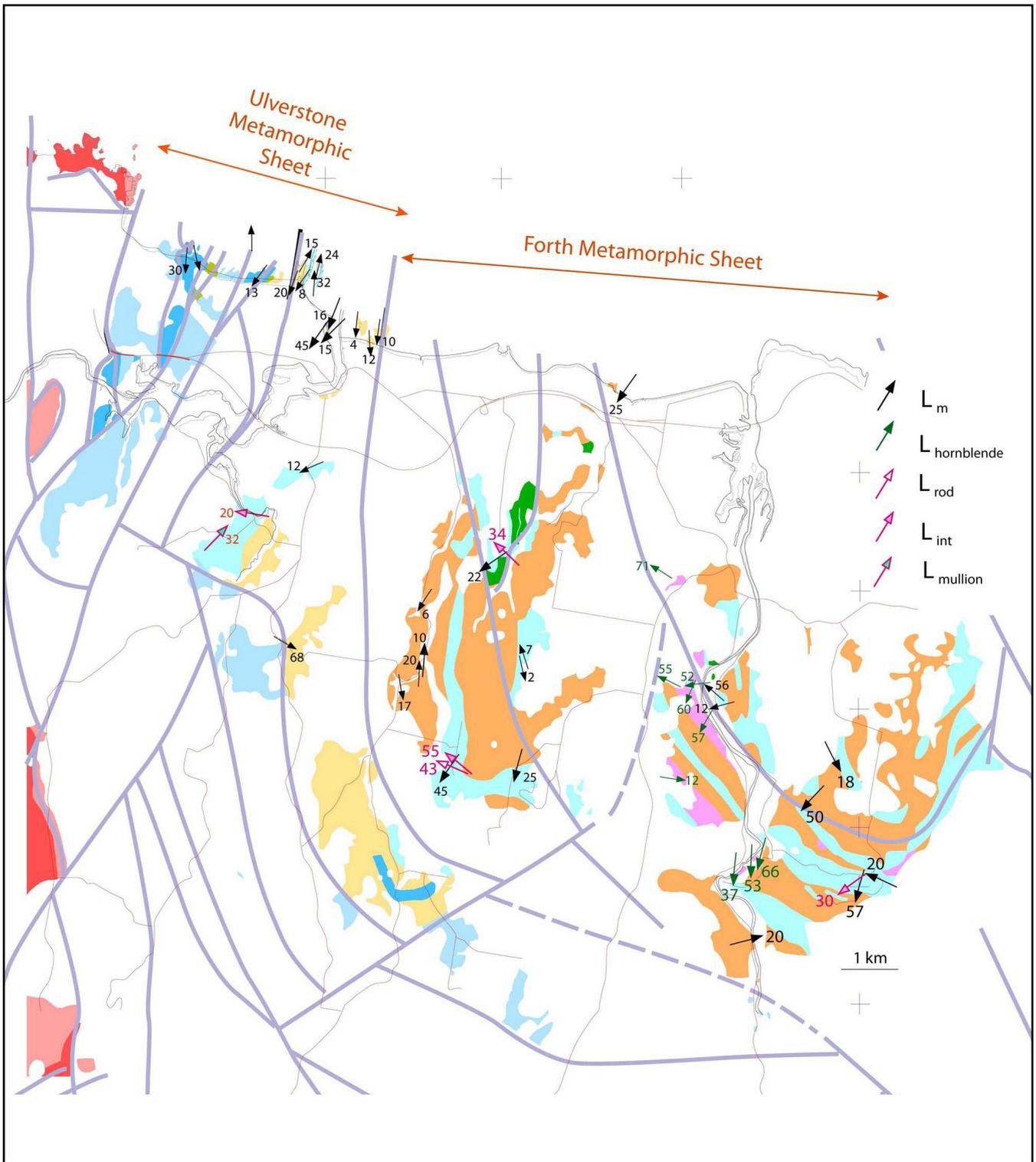


Figure 17. Lineation map of the Forth and Ulverstone-Oonah Metamorphic Sheets. The base map is modified from the MRT 1:25,000 and 1:250,000 digital atlas series. Faults and high strain zone interfaces are shown by the grey line traces. Lineation data is limited to data collected by the authors and data from Lewis (1991).

### 3.2.4 Transport Direction (TD) Pattern

Transport directions have been determined for the Forth and Ulverstone Metamorphic Sheets and the Penguin Luina Sheet (Figure 21). The movement planes were derived from 1) the lineation  $L_m$  and the dominant foliation plane  $S_m$  (designated MP1 and blue line traces, Figure 21), and 2) the shear band intersection with the foliation  $S_m$  (designated MP2, bright green line traces, Figure 21), and 3)

fault plane-slickenside data (designated MP3, red arrows, Figure 21). Most of the MP3 data are from faults within and at the base of the Luina Sheet (Figure 21).

The movement plane pattern in all sheets is dominantly north-northeast to south-southwest trending with a south-directed sense (see MP1, MP2 and MP3 vectors, Figure 21). The  $L_m$  movement planes (MP1) are considered to represent the shear direction in the "early" stage

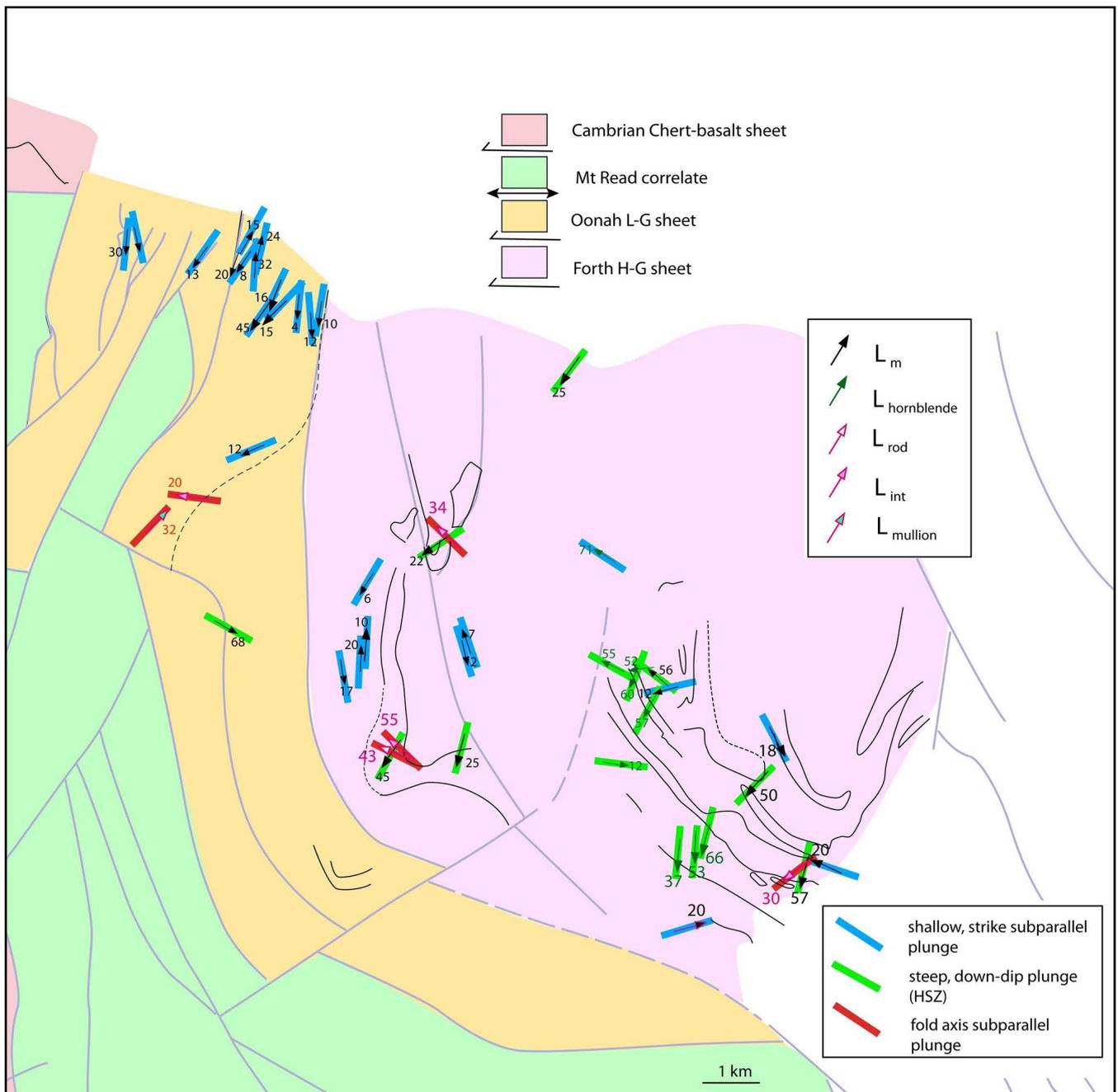


Figure 18. Lination trend summary map on a lithotectonic sheet map base. Three lineation groupings, based on lineation trend/plunge, are highlighted by the blue, green and red trend lines. The blue are strike parallel with gentle plunge. The green have moderate to steep plunge down dip of the foliation  $S_m$ . The red trend lines are sub-parallel to mesoscopic fold plunges.

of the deformation sequence, whereas the shear band movement planes (MP2) most likely indicate the shear direction in the "later" stages of the sequence during strain hardening of the foliation  $S_m$ .

The H-G Forth Metamorphic Sheet has limited shear sense data and is therefore restricted to  $L_m/S_m$  data to give restored MP1 trends (blue trend lines, Figure 21). This is because shear bands (Sb) were not recognised and/or measured in the H-G Forth Metamorphic Sheet by the authors. Lewis (1991), however, argued for west-directed transport of the sheet with a east-over west shear sense based on 1) angular relationships between deformation lamellae and quartz grain elongation in high-T quartz mylonites in the Forth Valley, and 2) sinistral sense,

west-dipping shear bands. Unfortunately no attitude measurements were given for Sb and the host  $S_m$  so that the west-directed transport could not be verified or restored to a pre-folding position.

MP1 shear sense data for the Forth H-G metamorphic Sheet suggest a similar transport direction to that of the overlying Ulverstone and Luina Sheets (Figure 21), in contradiction to the west-directed interpretation of Lewis (1991). As the interpretation of Lewis (1991) could not be verified, a simple geometric analysis of fold and lineation relationships was undertaken to test for south-directed versus west-directed emplacement sense of the Forth Sheet (see Section 5.2).

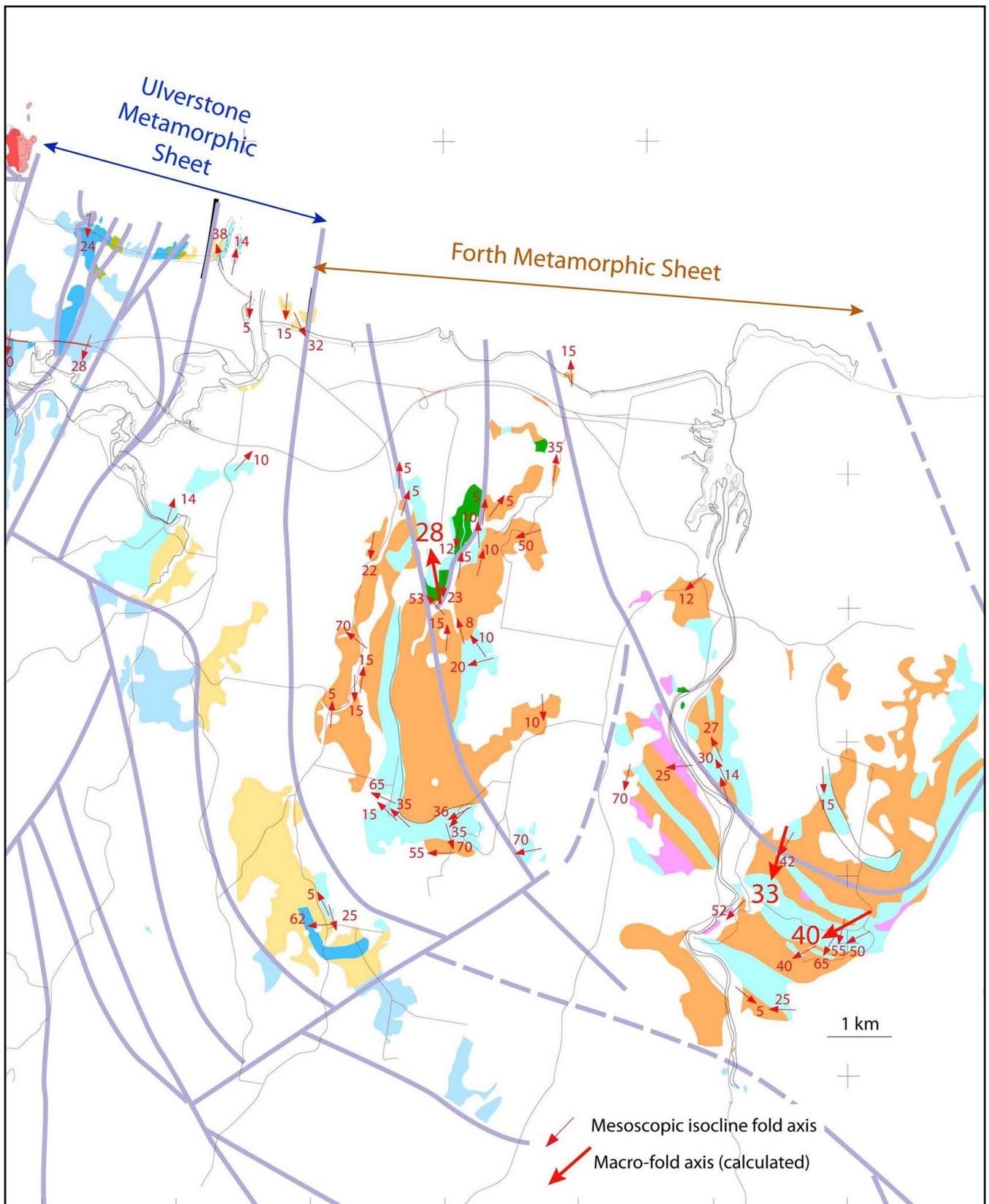
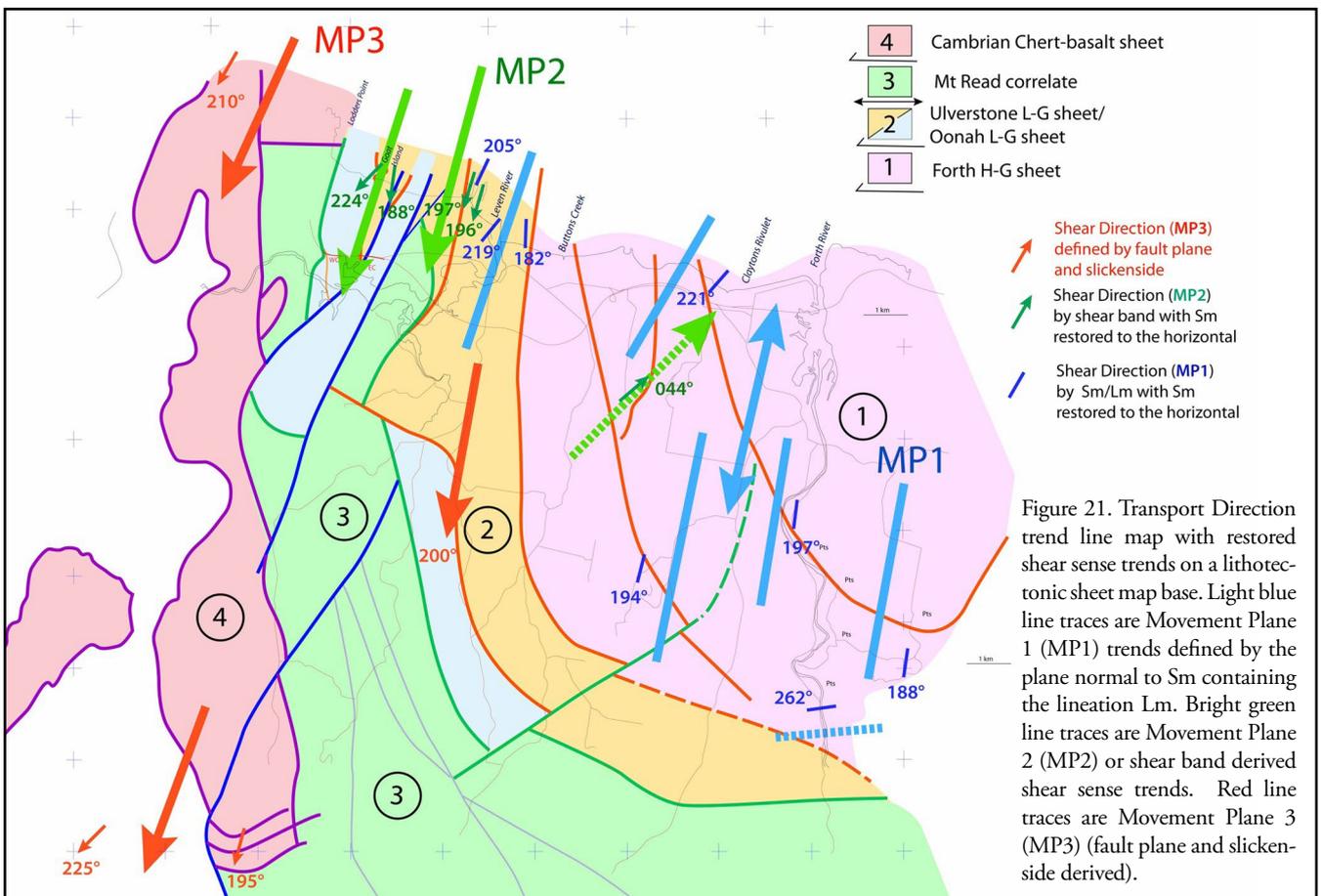
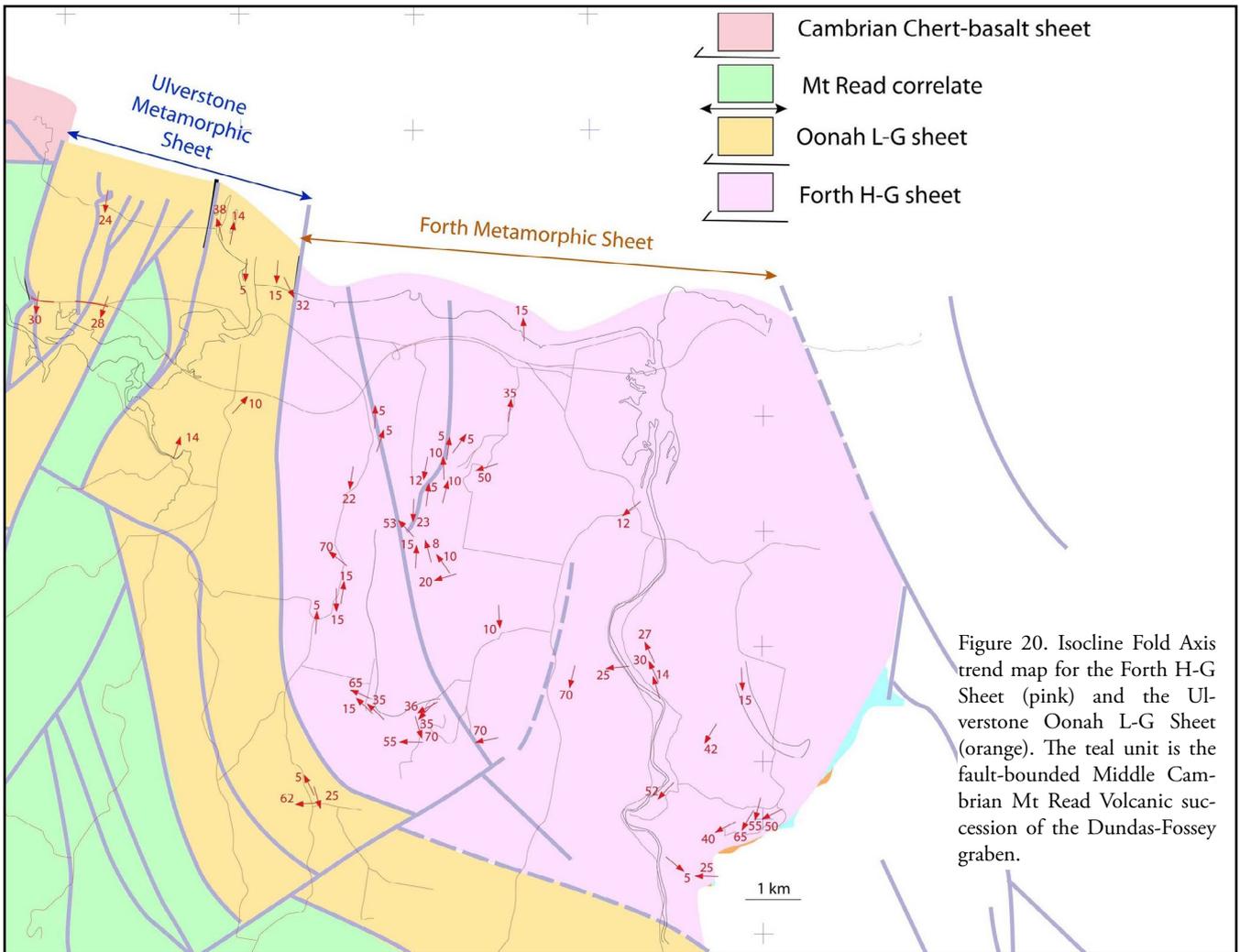


Figure 19. Fold axis trend map showing the plunge and plunge direction for early mesoscopic isoclinal folds (small red arrows) for the Ulverstone and Forth Metamorphic Sheets. The lithological map base is modified from the MRT 1:25,000 and 1:250,000 digital atlas series. The grey line traces are high strain zones (HSZ and faults).



#### 4.0 MESOSCOPIC STRUCTURES IN THE FORTH METAMORPHIC COMPLEX

##### 4.1 The Nature of the Schistosity Sm

The Forth Metamorphic H-G Sheet is characterised by a dominant schistosity Sm (Burns, 1963a; Lewis, 1991). This schistosity is a compound fabric, commonly with two fabrics visible (Figures 22, 23 and 24). An early fabric (Sm1) sub-parallel with, or at a low angle to, compositional layering (So/Sm) is crenulated to give a spaced foliation (Scc/Sm2) at 0.1-5.0 mm spacing (Figures 23 and 24).

##### 4.2 The Nature of Lineations

The quartzites contain an intersection lineation (Lint), as a subtle colour banding (Figure 25a) generally associated with quartz grainsize variations (Figure 25b), and a mineral elongation lineation defined by white mica (Figure 26a) and/or an elongate quartz grain alignment (Figure 26b). The gently plunging, strike-parallel lineations were interpreted by Lewis (1991) as intersection lineations. The more steeply plunging, down-dip the mineral elongation lineations were considered to reflect the positions of high strain zones within the metamorphic sheet (Lewis, 1991).

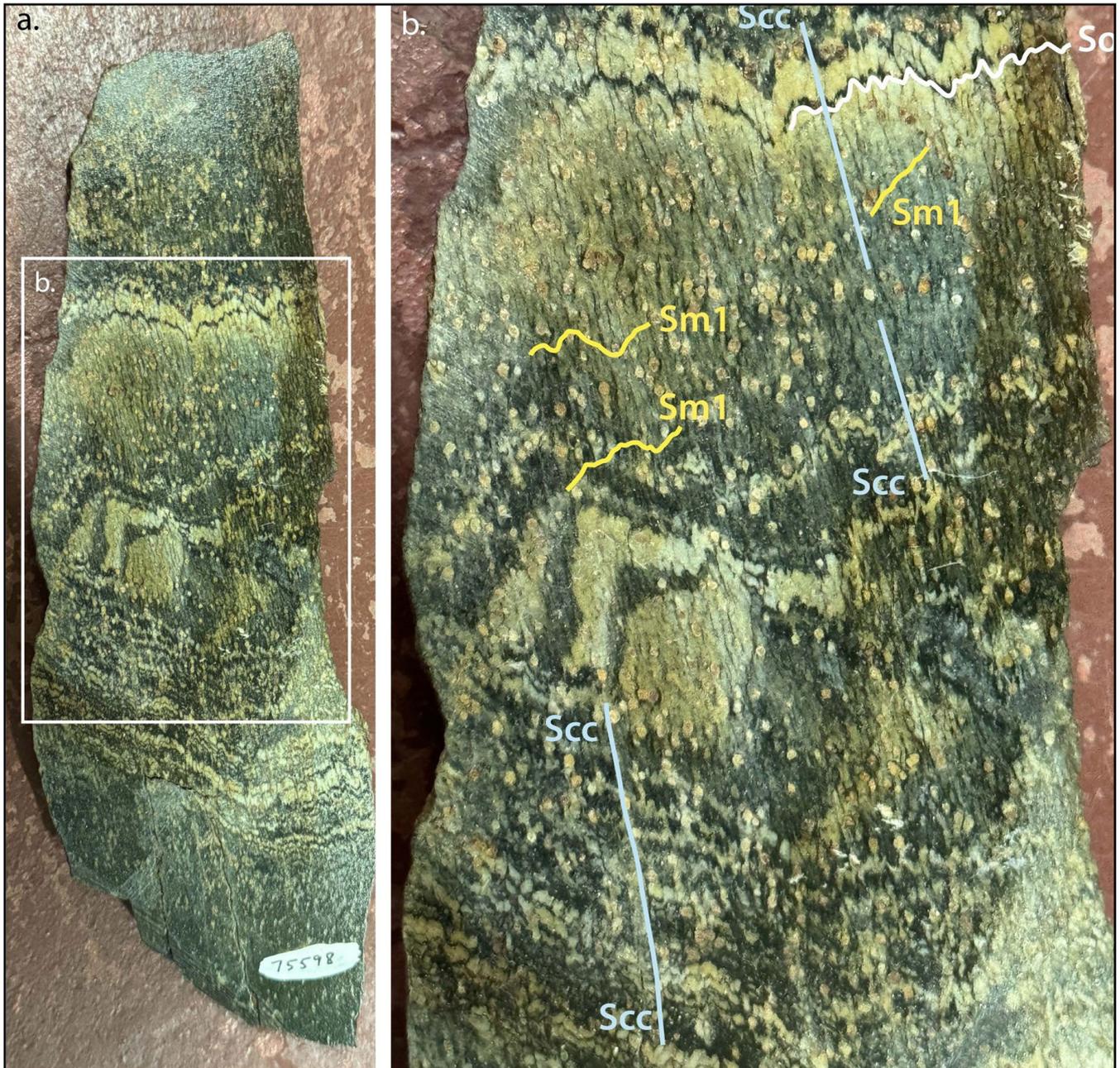


Figure 22. Typical schistosity (Sm) in garnet-mica schist of the Forth Metamorphic Complex (UTAS sample 75598). Photo (b) is an enlargement of area in (a) outlined by the white rectangle. The schistosity has evolved from a spaced crenulation cleavage (Scc) shown by the sub-vertical blue line traces. Compositional layering (So/Sm) is shown by the white line traces and the first foliation (Sm1) by the yellow line traces. Both So/Sm and Sm1 are crenulated by the sub-vertical schistosity. (Scc).

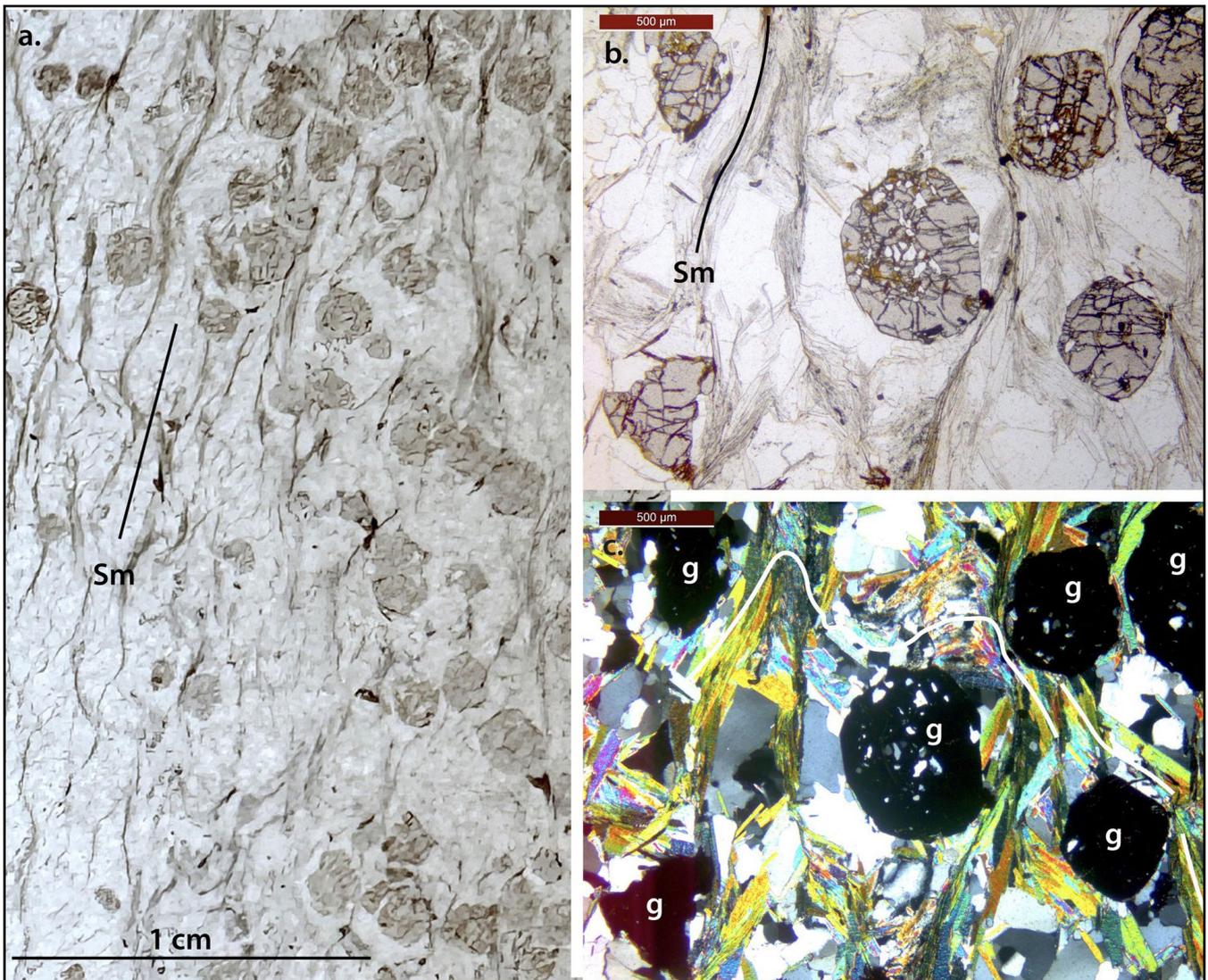


Figure 23. Garnet quartz-muscovite schist from outcrop on Pumping Station Road near Sayers Hill (field station DG88-49). a) Thin section photograph showing the dominant schistosity  $S_m$  defined by mica selvages that envelope mm-size garnet porphyroblasts. b) Enlarged photomicrograph of the schist microfabric with mica trains defining the schistosity  $S_m$ . The garnet porphyroblasts are largely inclusion free. PPL photomicrograph. c) Crossed nicols (XN) view of the microfabric photomicrograph shown in (b). The white line trace highlights white mica defining the early foliation  $S_{m1}$  (compare with Figure 24).

#### 4.3 Intrafolial Isoclinal Folds

Folds within the quartzite and the thin-bedded quartzite-pelite sequences are commonly intrafolial asymmetric fold pairs that have long planar limbs and angular, chevron, "arrow-head" fold hinges (Figures 27 and 28). These folds dominate in the thin-bedded quartzite layers and tend to have gentle plunges within  $S_m$  (Figure 29).

#### 4.4 High Strain Zone interfaces

Major HSZ zones are poorly exposed through the Forth-Ulverstone map area with outcrop details provided in this section (Figure 30). The HSZ were defined by truncation of lithological layering, truncation of  $S_m$  formlines, truncation of macro- isoclinal folds and the presence of serpentinite pods and slices (Figure 12). Extending over

10-15 kilometres the zones have been designated the Forth Valley HSZ, the Button Creek HSZ, the Clayton Rivulet HSZ (as a splay off the Button Creek HSZ), the East Ulverstone HSZ and the Picketts Road HSZ (Figure 12). Within the Forth Metamorphic Sheet the HSZ separate three slices within the folded metamorphic stack (sheets 1a, 1b and 1c, Figure 12). These HSZ are commonly overprinted by brittle faulting.

In outcrop they are marked by 1) ductile deformation as zones of intense foliation  $S_m$  (Locations A and F, Figure 30), 2) structurally interlayered high-T quartz mylonites and intensely foliated garnet schist (Location B, Figure 30), 3) bodies of serpentinite (Locations C and D, Figure 30) and foliated schistose zones overprinted by brittle faults (Locations E and G, Figure 30).

Figure 24. Photomicrographs showing the variations in mineralogy, microstructure and fabrics of the schistosity at the Camp Clayton beach outcrops. a), b) and c) show the fabrics and microstructure of an intensely foliated quartz-muscovite schist (Sample ROO4584). d), e) and f) show the fabrics and microstructure of a chlorite-albite-quartz schist (ROO4586) from a less deformed pod enveloped by the high strain foliation shown in (a).

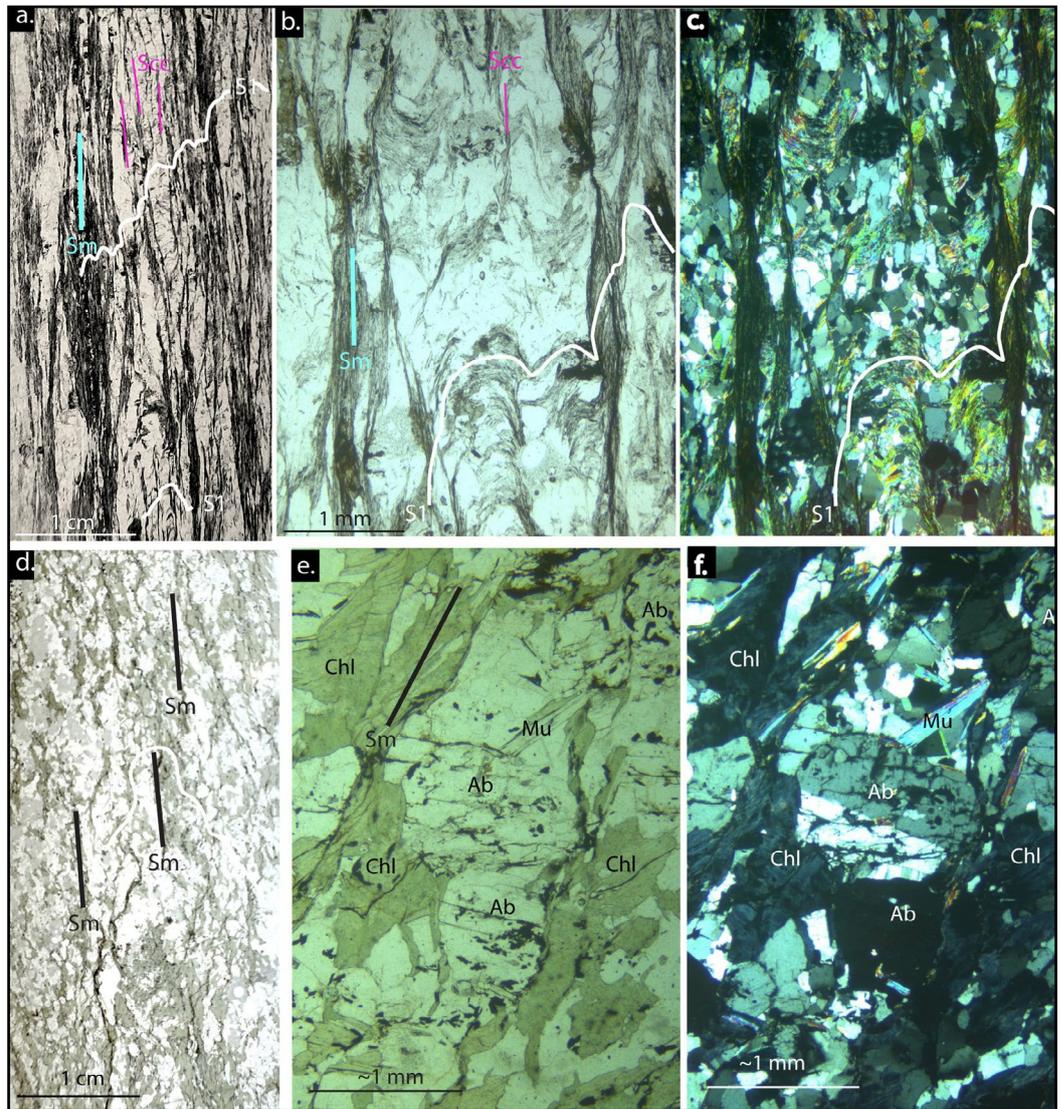
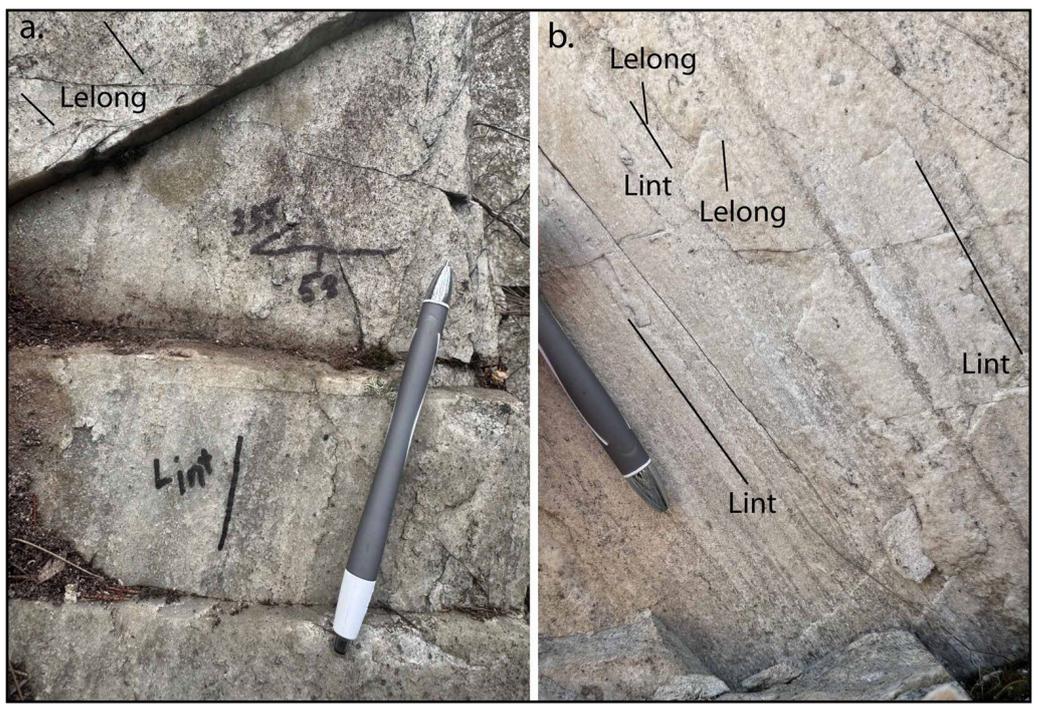


Figure 25. Intersection lineations Lint in strongly foliated quartzite. Lint in both examples is a subtle colour banding accompanied by domains of grain size variations. Note quartz grain elongation in the foliated quartzites defines Lelong in both examples. a) Old quarry wall exposure off Pumping House Road, near Sayers Hill. Station (DG25-16) b) Ellis Road quarry (Station DG25-38).



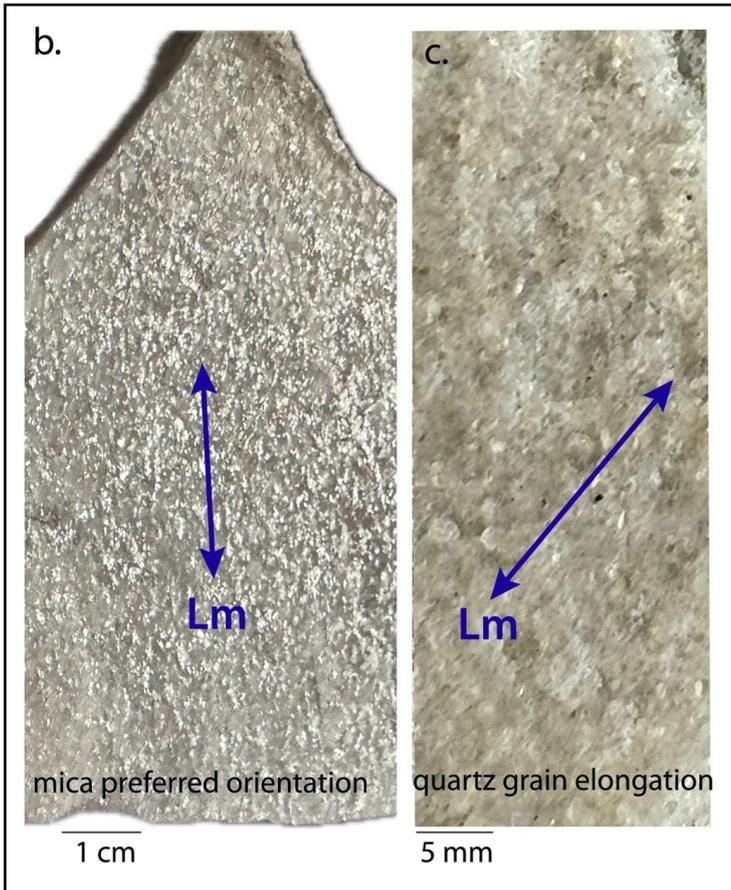
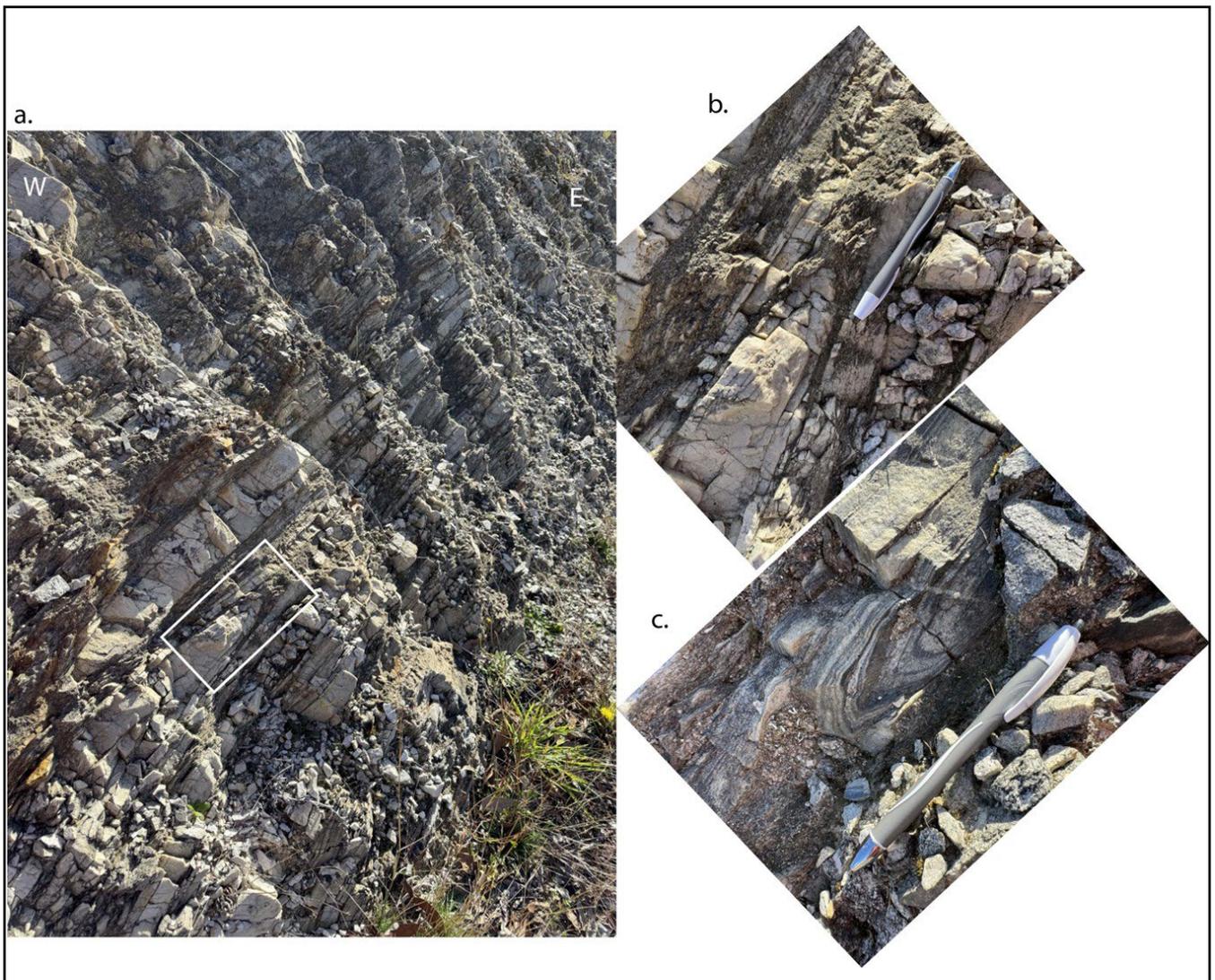


Figure 26 (Left). Variants of the mineral lineation Lm in mylonitic quartzite, Pumping Station Road near Sayers Hill (see Section 4.5.3). a) Mica preferred orientation in Sm in mylonitic quartzite. b) Quartz grain elongation in mylonitic quartzite.

Figure 27 (Below). Intrafolial isoclinal folds within a west-dipping, thin bedded quartzite-pelite sequence. [Sm: 355/80W mag] Station DG25-37, Ellis Road Quarry. b) Enlargement of fold hinge shown by the white rectangle in (a). c) Another isoclinal hinge within the homoclinally dipping sequence.



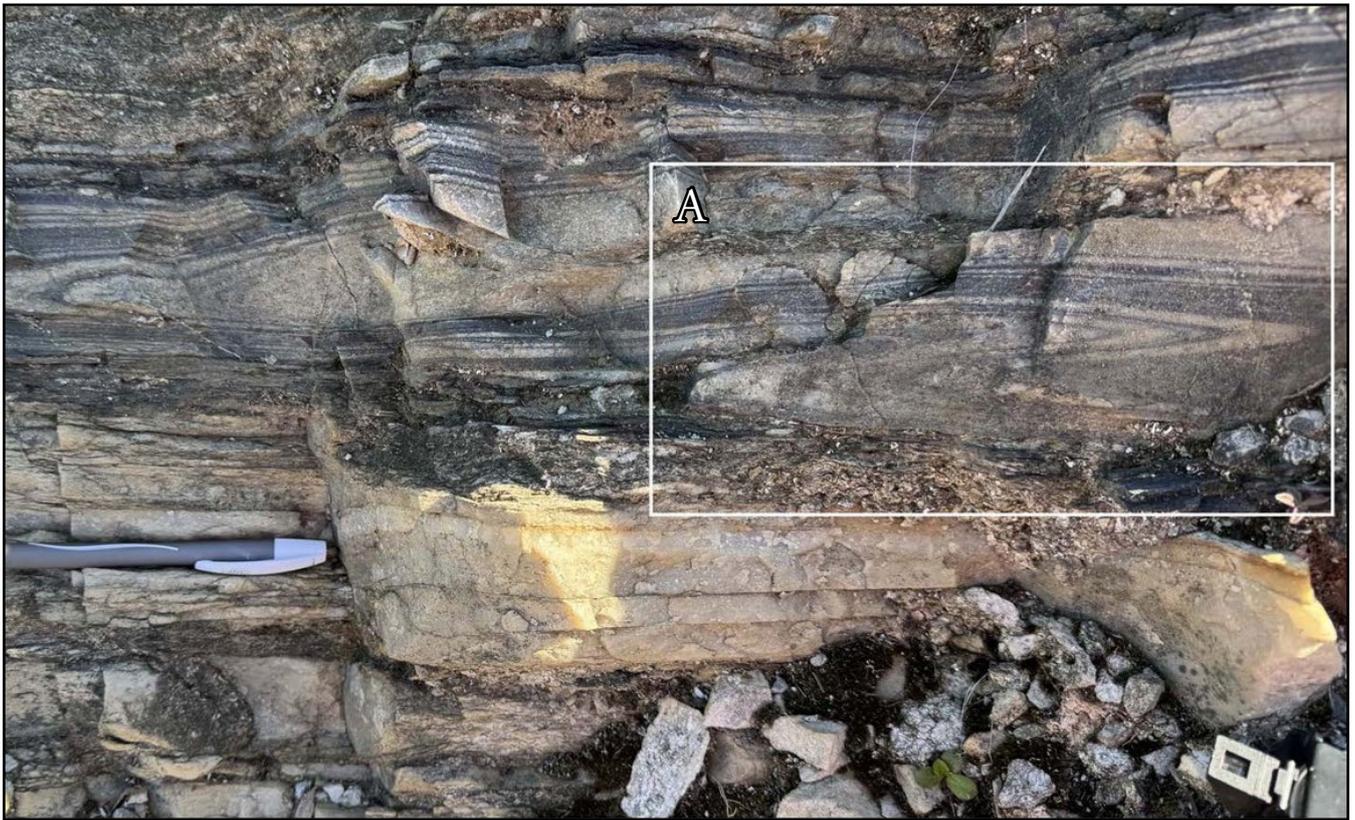


Figure 28. Intrafolial isoclinal folds [FA: 15/300 mag; AS: 13/45W mag]. So/Sm layering [150/55W mag] and Lm [45/200 mag]. Station DG25-37, Ellis Road Quarry.

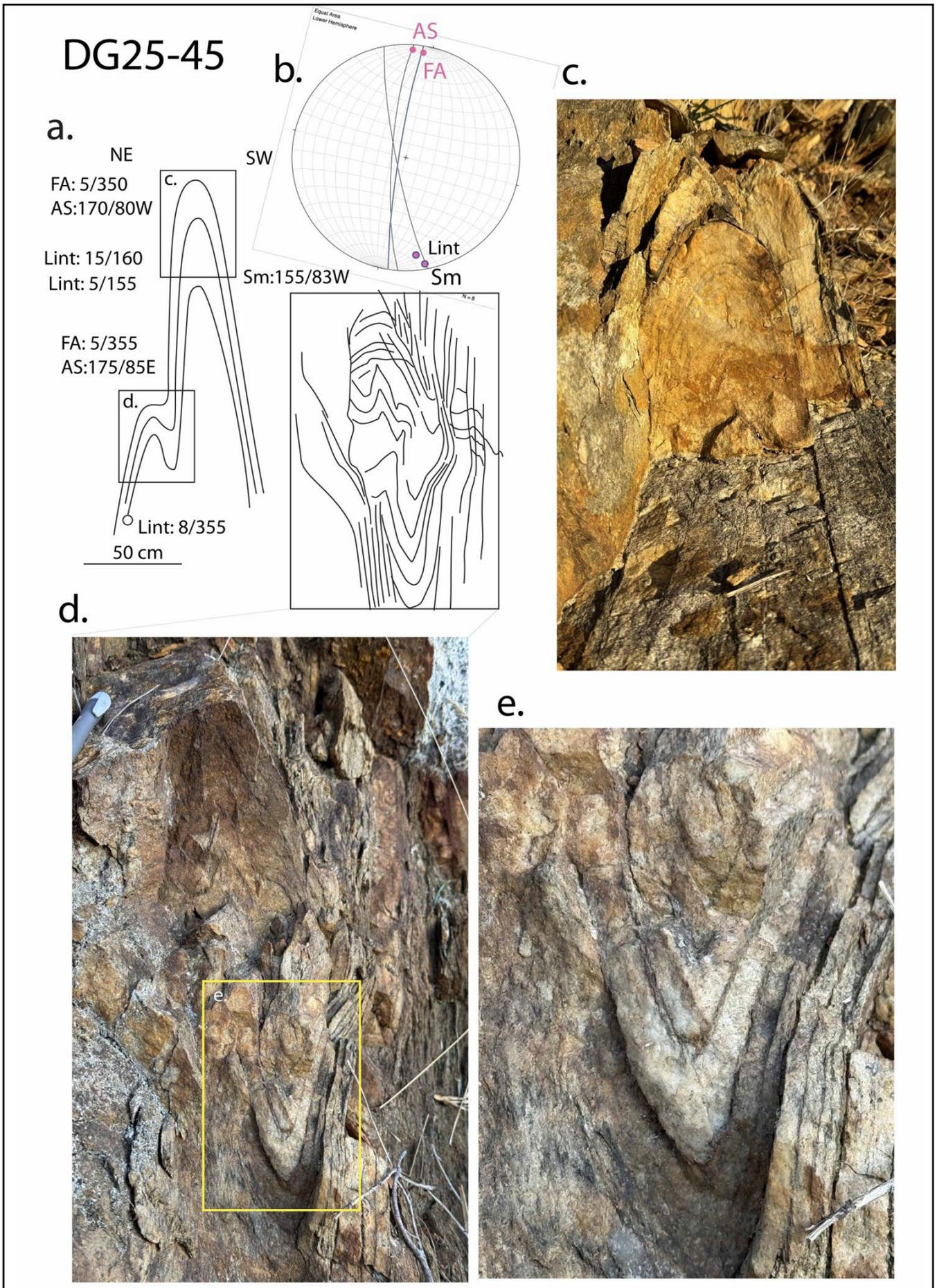


Figure 29. Upright, gently plunging, tight to isoclinal, intrafolial folds within thin-bedded quartzite. Outcrop is on Castra Road at the junction with Ricketts Road (Station DG25-45).

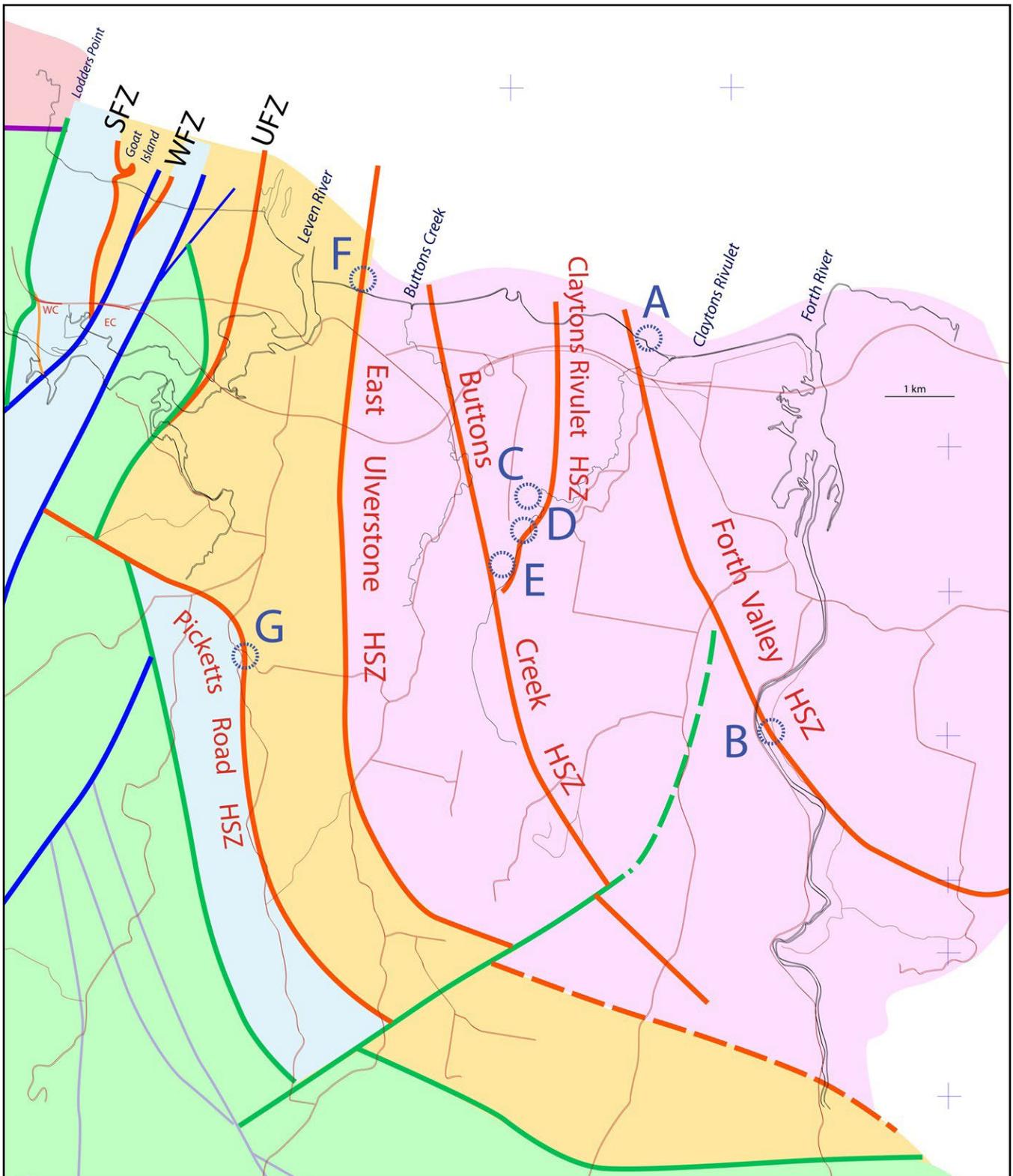


Figure 30. Map showing the locations of high strain zone interfaces (HSZ) described in the text. The HSZ are either within the Forth H-G Metamorphic Sheet (Locations A, B, C, D and E) or between the thrust sheets (locations F and G).

- A. foliated zone at Camp Clayton Beach (Forth Valley HSZ)
- B. Pumping Station Road (Forth Valley HSZ)
- C. Serpentine Quarry.
- D. quartzite-serpentine contact, Ulverstone Quarry
- E. Buttons Creek HSZ, Ulverstone Quarry
- F. East Ulverstone HSZ between Forth and Ulverstone Metamorphic Sheets
- G. Picketts Road interface between Oonah and Ulverstone L-G Sheets

4.4.1 Forth Valley HSZ at Camp Clayton Beach (location A, Figure 30)

The beach outcrops, exposed at low tide at Camp Clayton beach, are close to the non-exposed contact with the overlying Sheet 1b and represent a strain transition towards the HSZ interface (Figures 12 and 30). The outcrops are dominated by semi-pelitic, quartz-mica schist that shows markedly heterogeneous deformation. Zones of intense foliation containing relicts of disrupted, isoclinally folded quartz veins (Figures 31 and 32) enclose pods of more mafic lithology (Figures 24e, f). The dominant foliation is a composite schistosity that has evolved from a spaced crenulation cleavage with crenulation of an earlier fabric (Figures 32b and 33).

The schist microstructure shows two phases of fabric formation including 1) an initial high-P-T metamorphic fabric with interlocking quartz, mica and albite (Figure 24d, e, f), overprinted by 2) a low T-low  $\dot{\epsilon}$  (dissolution creep) deformation of the high-P fabric (Figures 24a,b and 34). Dissolution microstructures are shown by truncated grain boundaries and overgrowths as quartz-mica beards on now apparent elongated grains. Pressure shadow overgrowths on opaques (pink highlighted areas on Figure 34b) give an X-stretch of  $\sim 3.5:1$  (Figure 34b). This is considered part of a low-T dissolution-creep deformation in the late stages of sheet exhumation and juxtaposition with the overlying Ulverstone L-G Sheet.



Figure 31 (Above). Intense foliation Sm with relicts of disrupted, isoclinally folded quartz veins. Camp Clayton beach outcrops .a) View of steeply west-dipping foliation surface showing intersection traces of disrupted fold hinges within the isoclinally folded quartz veins. The veins have variable plunges (see Figure 32c and d). b) Approximate profile view of the variably plunging, isoclinally folded quartz veins with disrupted and isolated hinges. The limbs are flattened and extended with vein segments marking the former limb position. The foliation is a schistosity developed from a crenulation cleavage (see Figure 32b).

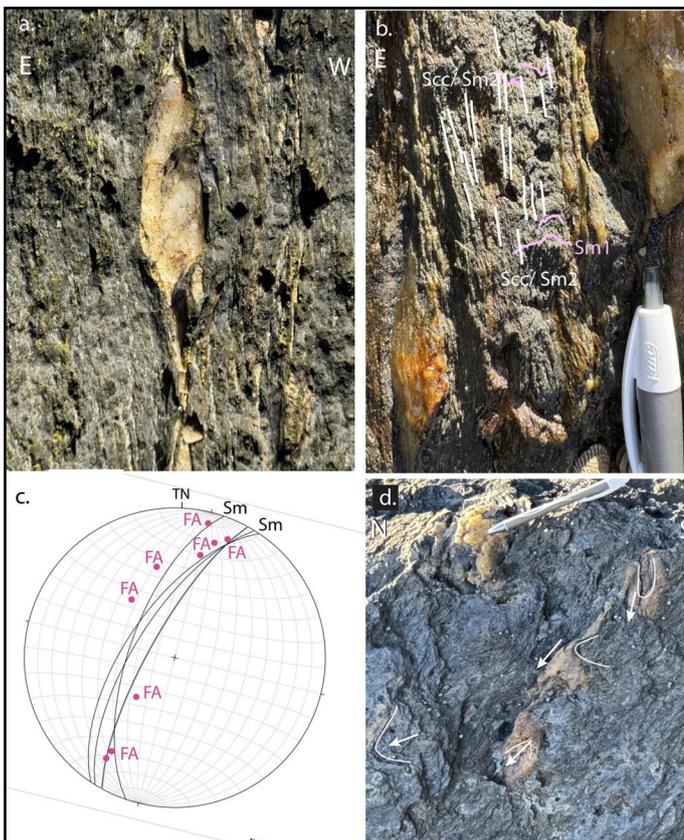


Figure 32 (Left). Schist fabrics, Camp Clayton beach outcrops. a) Boudinaged, pinched, isoclinally folded quartz vein in crenulated schistosity. Note the quartz vein fold limbs have been strung out and markedly thinned within Sm. b) Relict hinge zones showing that the dominant schistosity (Scc/Sm2: white line traces) has evolved from transposition of a crenulation cleavage folding an earlier cleavage (Sm1: pink line traces). c) Stereonet showing great circles traces of Camp Clayton Sm measurements and fold axis (FA: fold axis) variation within Sm. d) Hinge segments of an asymmetrically folded quartz vein within Sm showing the marked fold axis variability along one quartz vein "fold train".

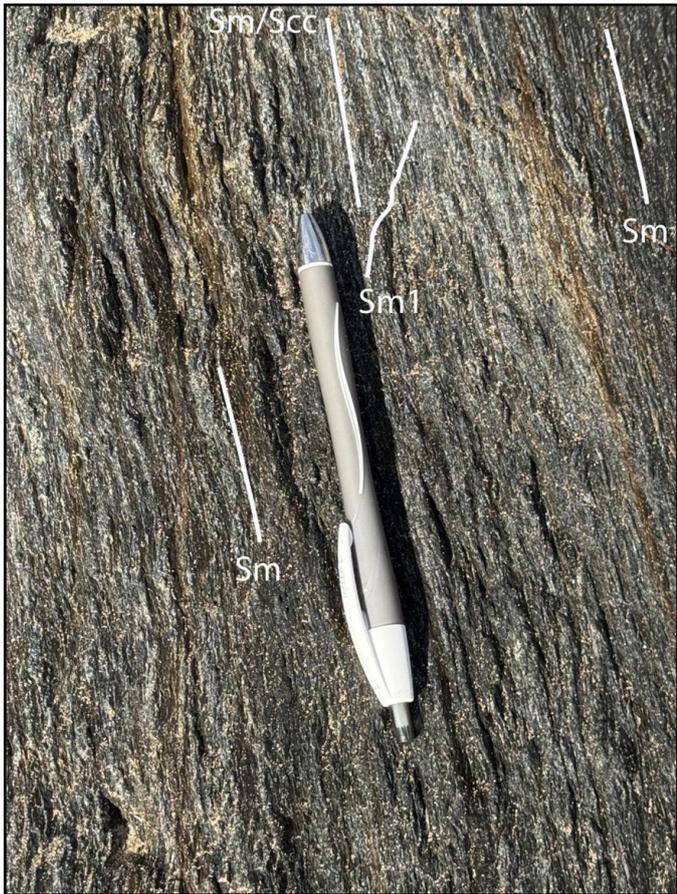
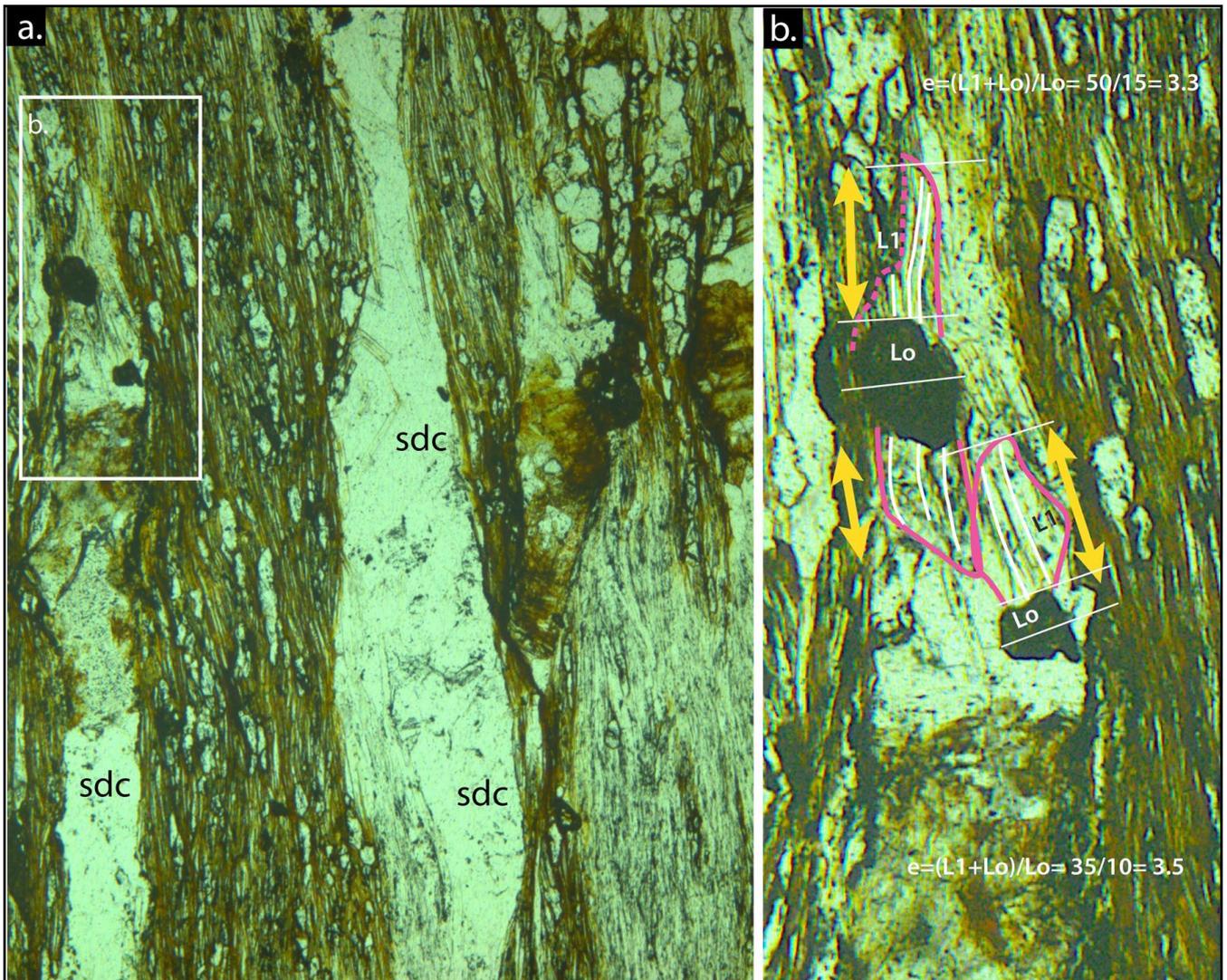


Figure 33 (Left). Close up view of the intense foliation Sm at Claytons Beach. This dominant foliation is clearly composite and has evolved from a spaced crenulation cleavage ScC that crenulates an earlier foliation Sm1.

Figure 34 (Below). Complex microstructural relationships in the intensely foliated, schistose Forth Metamorphics at Camp Clayton beach outcrop. The microstructure reflects a low-T dissolution creep type deformation overprinting the high T fabrics. Sutured dissolution contacts (sdc) are common along the boundaries of former quartz-rich microlithons with the intervening mica-rich domains containing elongated quartz mosaics (grains) also with sutured grain boundaries. Fibrous pressure shadow overgrowths on opaques give an X stretch of 3.3-3.5 based on a strain calculation where Lo: undeformed length (opaque half diameter) and L1 is the fibre length within the pressure shadows on the opaques. The X stretch from the pressure shows is given by:  $1+e = (L1+Lo)/Lo$ .



#### 4.4.2 Forth Valley HSZ at Pumping Station Road (location B, Figure 30)

The Forth Valley HSZ (Figure 30) occupies the Forth Valley constrained by a sub-parallel belt of amphibolite on the west (Figure 35) and quartz mylonite on the east (Figure 36). The HSZ has an estimated HSZ width of ~200 m. It cuts across and truncates lithological contacts in the

footwall or eastern side (Figure 35). Thin bands (~20-30 cm) of quartz mylonite are part of a broader zone that truncates the compositional layering at high angle. This relationship is shown by an intersection lineation Lm on the dominant mylonitic foliation Sm (Figure 25a). Further structural relationships are presented in Section 4.5.3.

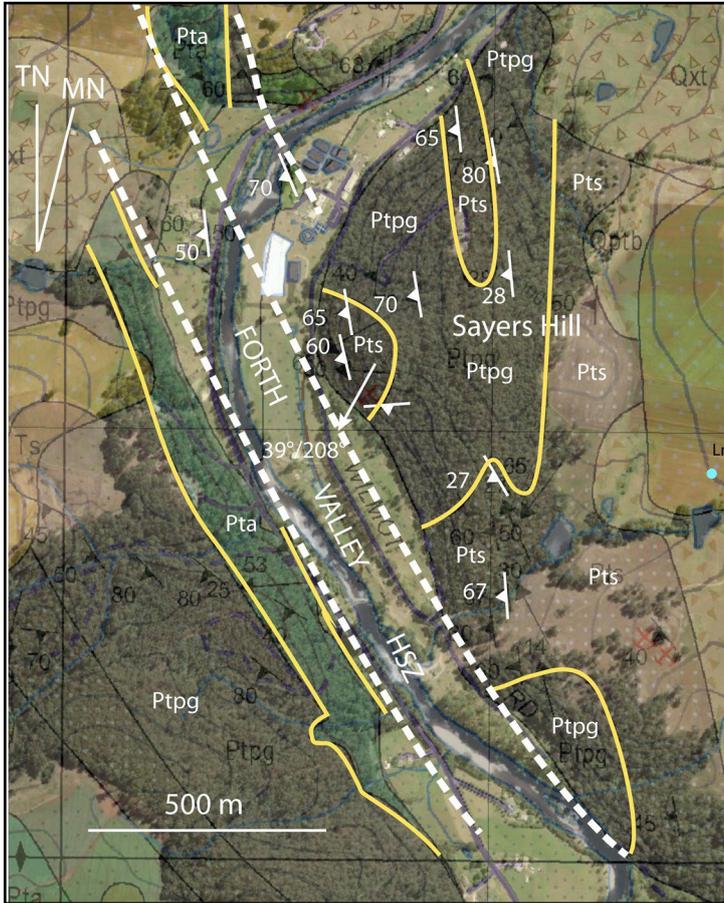
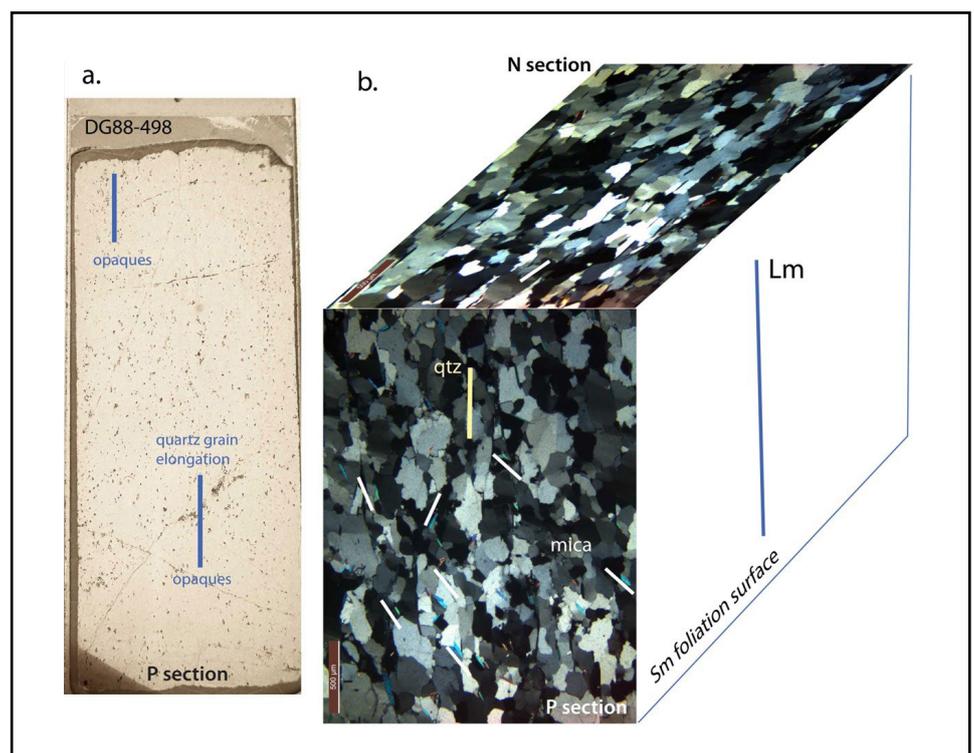


Figure 35 (Left). Structure map of the Forth Valley HSZ with truncation of lithological layering in the Sayers Hill-Pumping Station Road area. The base map is a ListMap Google satellite image with drape of the 1:25,000 digital atlas geology. Geological contacts are shown by the yellow line traces. Foliation attitudes are shown in white. Ptpg: garnet schist. Pts: schistose quartzite. Pta: amphibolite (see also Figure 52).

Figure 36 (Right). Quartz grain fabric in high-grade mylonitic quartzite from an outcrop along Pumping Station Road near Sayers Hill (DG88-498). a) Thin section showing preferred orientation of opaques sub-parallel to a strong quartz grain elongation. b) Block constructed from orthogonal thin sections showing the strong quartz grain preferred orientation to define the Sm foliation. P section: cut normal to Sm but parallel to Lm. N section: cut normal to Sm but normal to Lm. The quartz grain fabrics show textural equilibration at high temperatures ~700°C.



#### 4.4.3 Serpentinite Quarry (locations C and D, Figure 30)

The Claytons Rivulet HSZ sits below elongated pods of serpentinite that are structurally interleaved with quartzite, schist and amphibolite (Figure 37). The serpentinite pods are parallel with and transitional into the HSZ (Figure 37a). The northern pod appears isoclinally in-folded with quartzite. Sub-parallel with the compositional layering (So/Sm) and dominant foliation Sm the pods are folded about a large-scale, northwest-plunging, isoclinal macro-fold (Figure 37a). The hinge of the macro-fold is truncated by the Buttons Creek HSZ with the western limb "missing" (see Section 4.5.1).

Structural observations in the old, disused, serpentinite quarry made in 1988 by DRG (Figure 37b) and along Claytons Rivulet by Lewis (1991, p.39-42) showed the Claytons serpentinite body is strongly and heterogeneously deformed at all scales. Locally it has a complex, anastomosing shape fabric foliation, where pods and lenses of massive serpentinite are enveloped by intensely foliated serpentinite. Two sets of structures were observed independently. These include:

1. Dextral shear bands transitional into the intense north-striking, dominant foliation Sm (Figure 37b, c). In places an earlier, northwest-striking foliation (Sm1) is preserved and showing a dextral sense deflection along the shear bands (Figures 37b, c). The foliation surfaces are associated with sub-horizontal to gently south-plunging fibre lineations (Figure 37c).
2. A phacoidal fabric where lozenges (4x7x2 cm dimensions) are bounded by apparent conjugate slip surfaces showing striated slip surfaces (Lewis, 1991, p.37). Down-dip striations and fibre lineations indicate reverse west-over-east movement.

The dextral shear bands observed in the quarry floor (Figure 37b) must reflect earlier shear strain during emplacement of the serpentinite body. The movement plane (MP2) derived from the structural measurements is 044°-224° (TN) with a dextral sense.

The phacoidal, shear band-like elements of Lewis (1991) and mapped SW-dipping thrust and reverse faults (Figure 38) give west-over-east movement indicating deformational overprinting of the serpentinite and serpentinite-quartzite contact during the younger, east-directed Devonian deformation.

#### 4.4.4 Buttons Creek HSZ footwall, Ulverstone Quarry (Locations E, Figure 30)

The Buttons Creek HSZ (heavy black, dashed line trace, Figure 39) in the vicinity of the Ulverstone Quarry is inferred by the truncation of an inclined plunging, isoclinal macro-fold within quartzite and serpentinite. The macro-fold hinge is located within the juncture of the Clay-

tons Rivulet HSZ with the Buttons Creek HSZ (Figures 37 and 39a)). Strong to intense brittle faulting occurs in the quartzite in the south part of the quarry, with a dominant 165° trending set sub-parallel to the HSZ (Figure 39b). Other sets include 030° and 180° (minor) trending faults.

#### 4.4.5 East Ulverstone HSZ hanging wall, East Ulverstone beach (locations F, Figure 30)

The easternmost part of the beach outcrop at Ulverstone East beach show a marked increase in strain. The outcrop is just west of the inferred position of the Ulverstone East HSZ (Location F, Figure 30). There is a transition from thin-bedded quartzite into a schistose, platy quartzite mylonite intercalated with quartz mica schist (Figure 40b) and mica schist (Figure 41).

The dominant foliation (Sm) is clearly composite and has evolved from crenulation of an early formed foliation (Sm1) (Figure 41). The fabric intensification is accompanied by marked rodding of isoclinally folded quartz veins (Figure 40c).

#### 4.4.6 Picketts Road HSZ (Location G, Figure 30)

The Picketts Road HSZ is the interface between the easternmost slice of the sub-greenschist facies Oonah Sheet and the greenschist facies Ulverstone Metamorphic Sheet (Figure 42). The outcrop on Picketts Road near the intersection with Castra Road is the only exposure of the zone (Location G, Figure 30). Quartzite in the Ulverstone Sheet is isoclinally folded within the dominant foliation Sm and has a mineral lineation. The Oonah Sheet consists of interbedded sandstone and phyllite/mudstone. The interface is a zone of steeply, overall east-dipping undulating faults. A series of steeply plunging asymmetric folds with an axial surface crenulation cleavage are associated with the faulting in the Oonah Sheet. Faultkin™ analysis of one of the faults with measured slickenside gives a south-directed sense in a ~200° (TN) movement plane (Figure 43).

### 4.5 Structure of the Quartzite—Quarry exposures in the Forth Metamorphic Complex

Operating and disused quarries provide windows into the structure of the poorly exposed Forth Metamorphic Complex. Structural data for each quarry visited are presented in maps, photographs and stereonet.

#### 4.5.1 Ulverstone Quarry

The Ulverstone quarry sits within sheet 1b of the Forth Metamorphic composite sheet (Figure 12). The quarry is in schistose quartzite (Pts) in the core of a regional synformal fold, where the fold is outlined by serpentinite and garnet-mica schist (Ptpg) (Figure 44). The western limb of the regional fold is cut by the Buttons Creek High Strain Zone/brittle fault that offsets the major Units 1b and 1c of the Forth Metamorphic Complex (Figure 12).

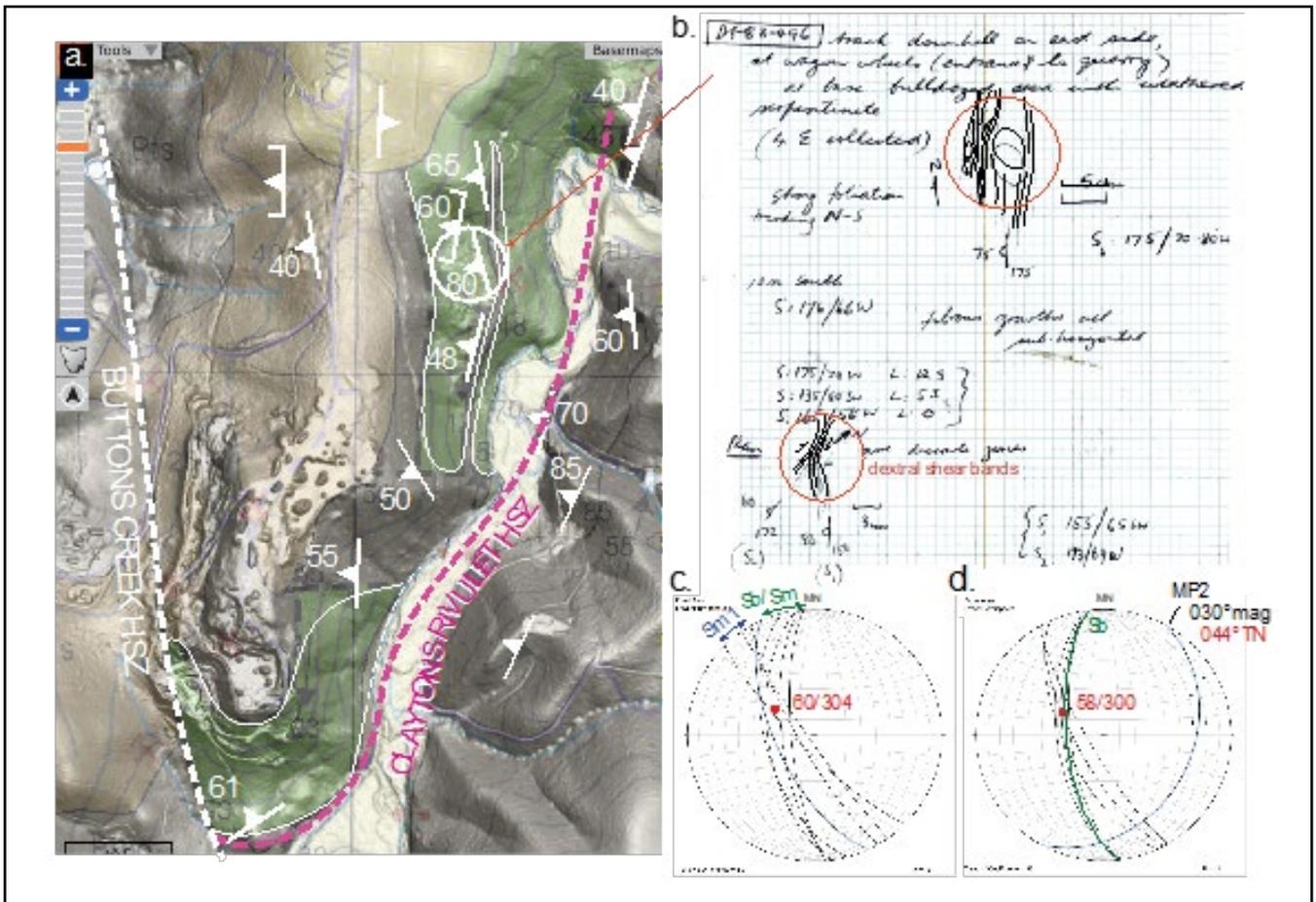


Figure 37. Structural map and attitude data of serpentinite bodies along Claytons Rivulet and near the Ulverstone Quartzite Quarry. The area of the old serpentinite quarry (station DG88-496) is now built on. The map shows contacts and foliation  $S_m$  attitude data. The map base is a LIST-Map grey-scale digital elevation/Lidar image with a 1:25,000 digital atlas geological drape. The serpentinite shows as a pale green colour. b) Field notebook data and sketches for the disused serpentinite quarry (DG88-496). c) Stereonet of great circle traces of a relict "early"  $S_{m1}$ , dextral shear bands (Sb) that are transitional into an intense, dominant foliation  $S_m$ . Fibre lineation attitudes are shown by red open circles Lslick d) Synoptic  $S_m$ -Sb stereonet showing the movement plane (normal to the intersection of the  $S_m$  and Sb surfaces) has an  $044^\circ$  trend (TN).

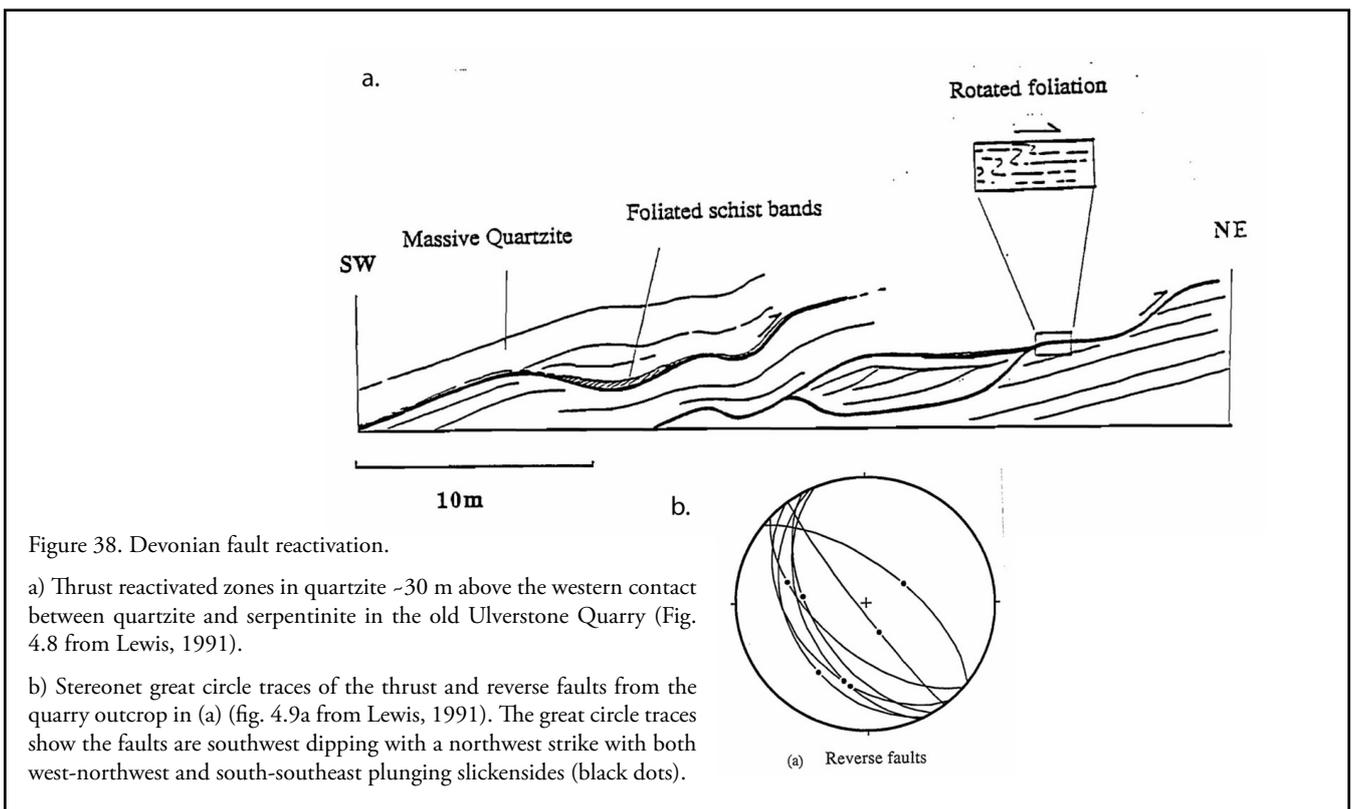


Figure 38. Devonian fault reactivation.

a) Thrust reactivated zones in quartzite ~30 m above the western contact between quartzite and serpentinite in the old Ulverstone Quarry (Fig. 4.8 from Lewis, 1991).

b) Stereonet great circle traces of the thrust and reverse faults from the quarry outcrop in (a) (fig. 4.9a from Lewis, 1991). The great circle traces show the faults are southwest dipping with a northwest strike with both west-northwest and south-southeast plunging slickensides (black dots).

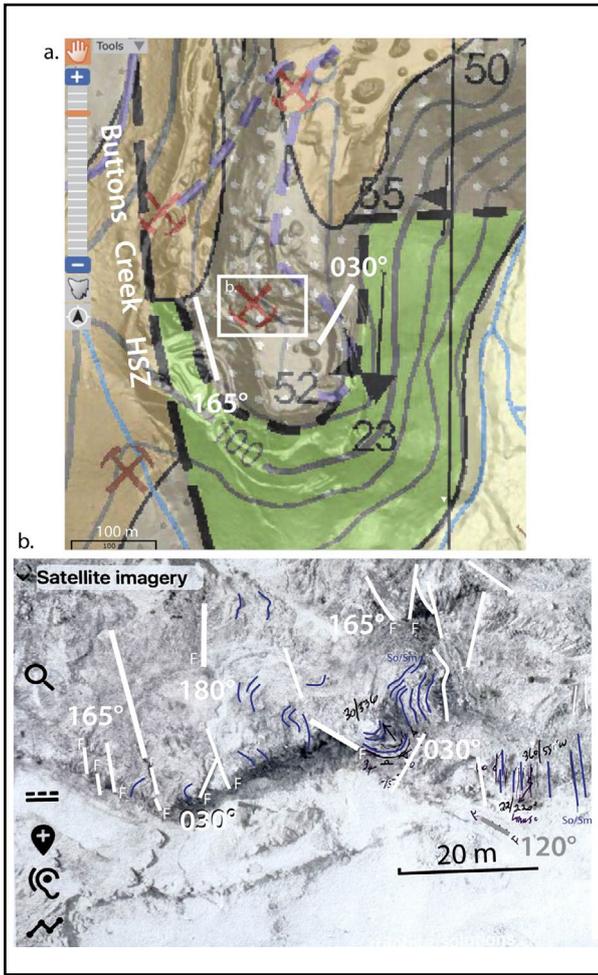


Figure 39. The Buttons Creek HSZ structural influence in the Ulverstone Quarry (compare with Figure 37).

a) LISTMap with the 1:25,000 digital atlas series map draped on a grey-scale Lidar image of the Ulverstone Quarry. The inferred position of the Buttons Creek HSZ is shown by the heavy black dashed line. Quartzite: grey with white stipple. Serpentinite: pale green.

b) Simplified structural map of the southern part of the Ulverstone Quarry on TrilobiteTM satellite imagery base. Form lines in So/Sm are shown by the dark blue line traces. Faults are shown by the white line traces.

Figure 40. Hanging wall of the East Ulverstone HSZ showing a fabric transition at the base of the Ulverstone L-G Metamorphic Sheet towards the underlying, non-exposed interface with the Forth Metamorphic Sheet.

a) Structural form line map of the beach outcrops at low tide on a black/white air photo base. Blue circles show the approximate locations of the outcrop photographs b and c. Blue circle d is the location of Figure 41.

b) and c) Photographs of schistose rodding fabrics in thin, platy quartz mylonites.

c) An enlarged view of the foliation Sm plane showing, an early intersection lineation Lint defined by compositional banding streaking-traces overprinted by a developing rodding fabric in isoclinally folded quartz veins.

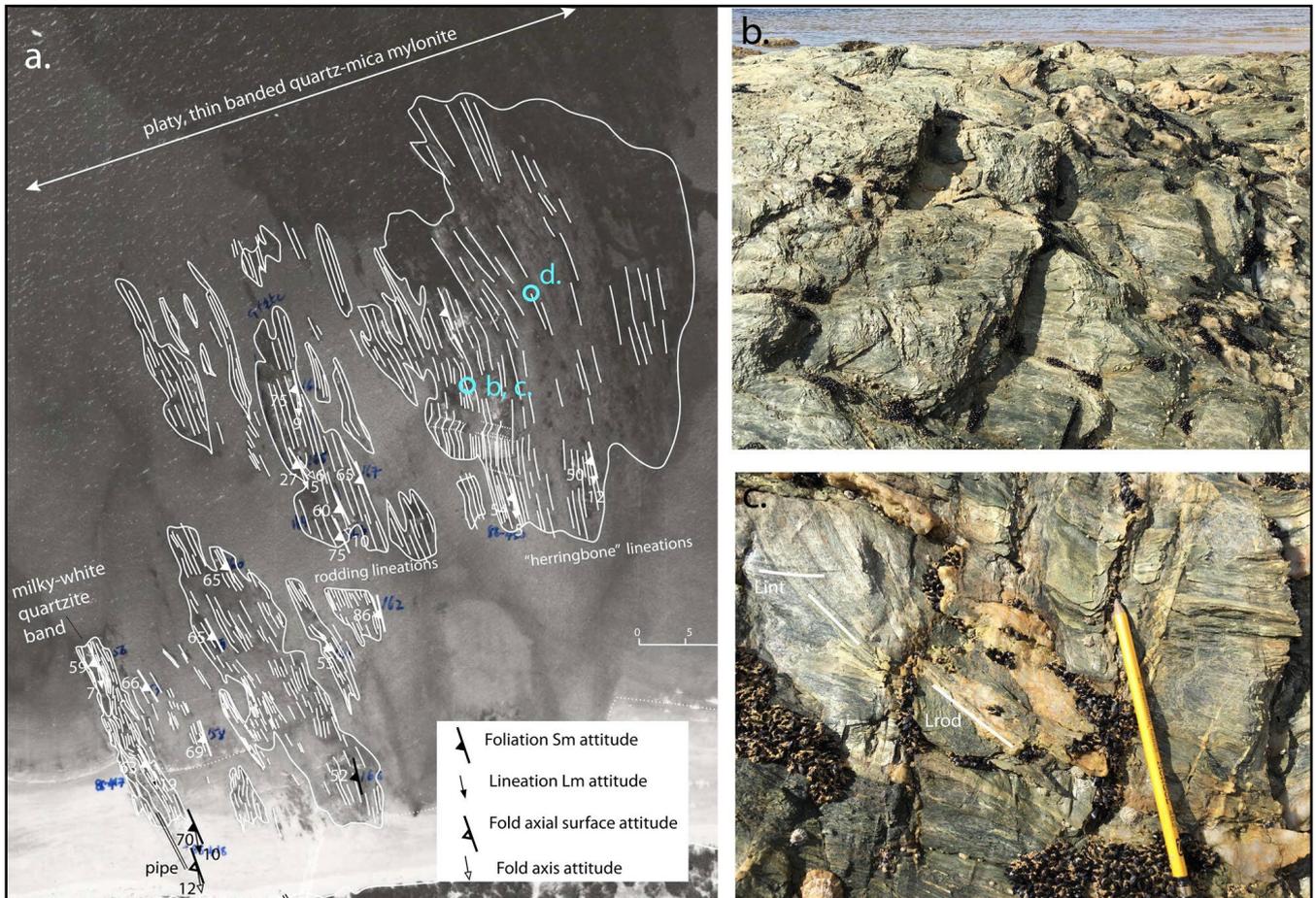


Figure 41 (Right). Dominant foliation  $S_m$  in mica schist at the easternmost part of the East Ulverstone beach exposure. Crenulated relicts of an earlier fabric  $S_{m1}$  are overprinted by this intense schistosity/foliation  $S_m$ .

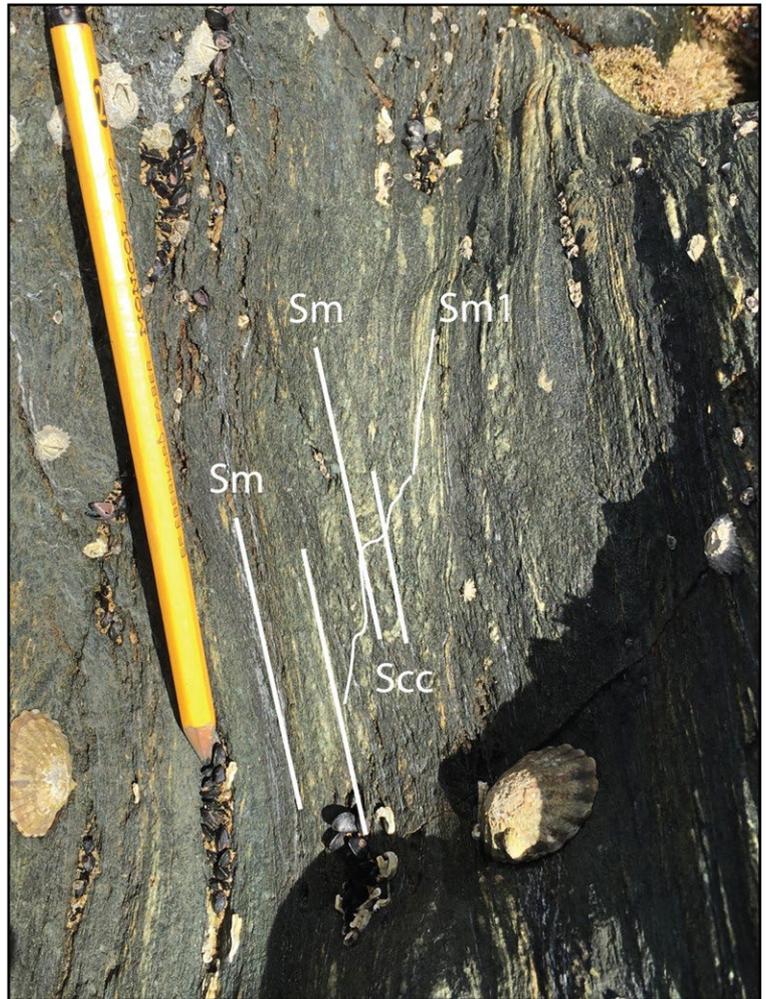
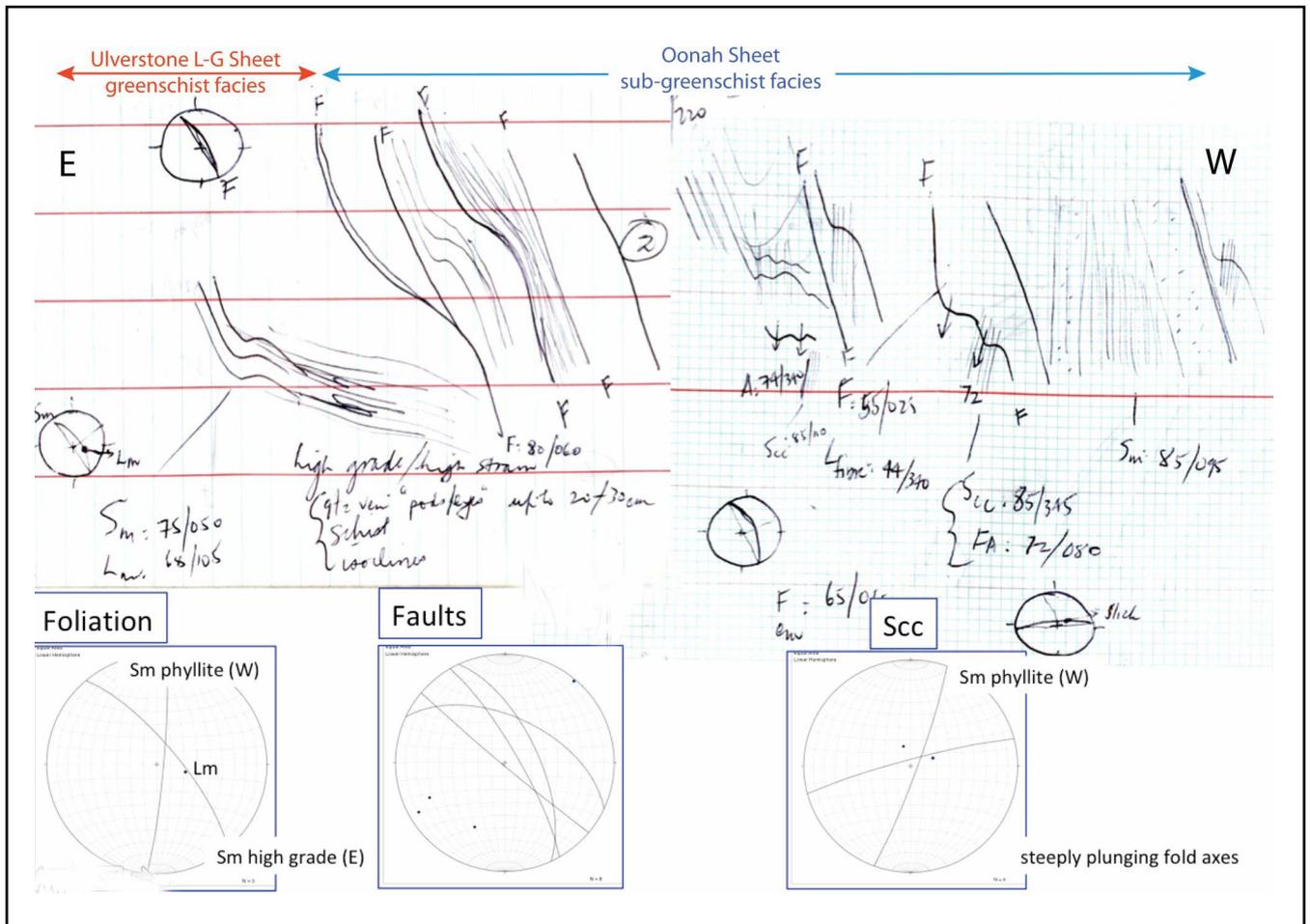


Figure 42 (Below). Sketch profile across the Picketts Road HSZ. Note the cutting is slightly oblique to the measured structural trends giving apparent dip traces in the cutting/sketch profile. The greenschist facies Ulverstone Metamorphic Sheet is on the east and the sub-greenschist facies Oonah Sheet on the west. All dips are to the east or northeast as shown in the stereonet.



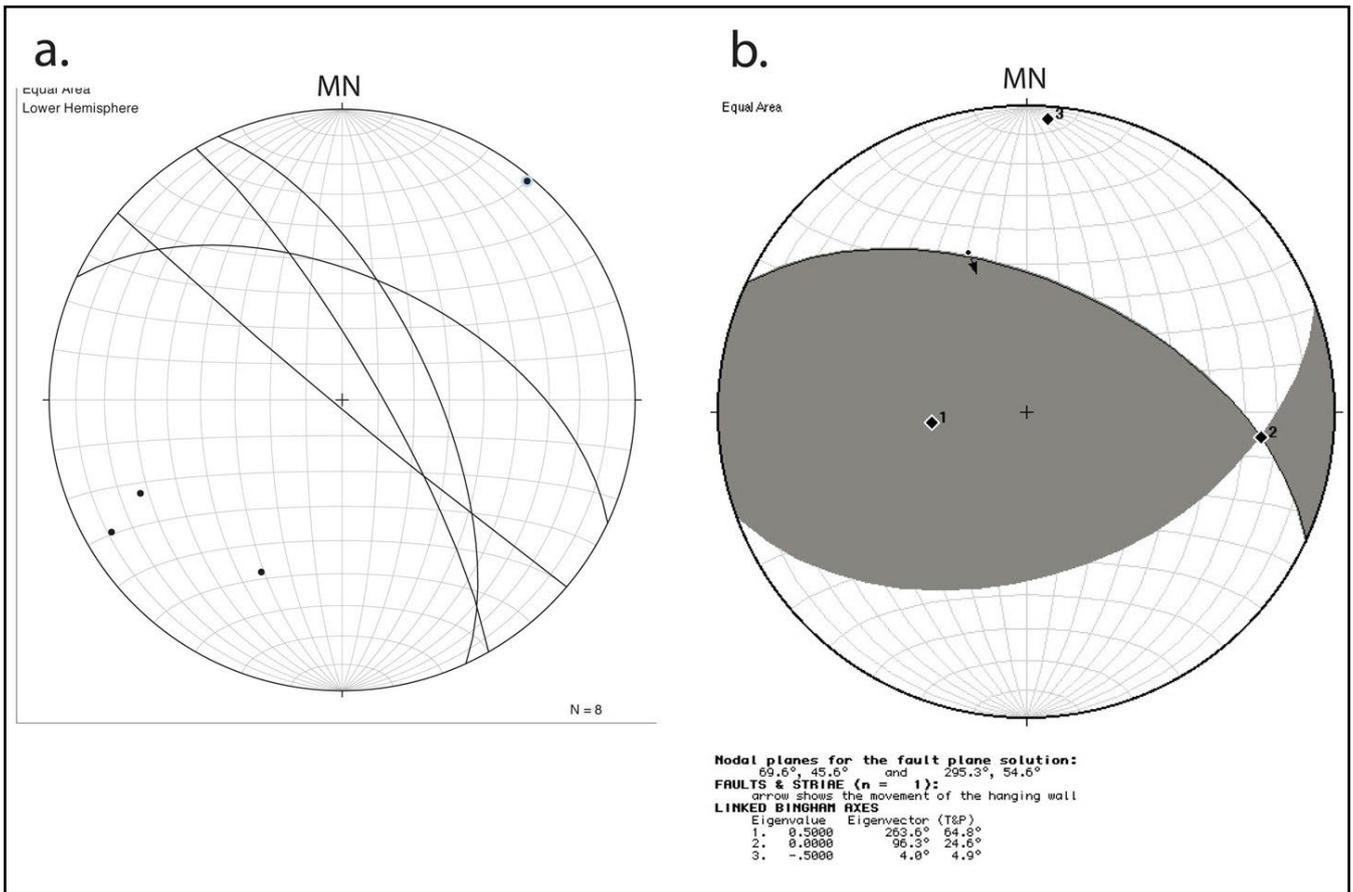


Figure 43. Stereonets of the fault population in the Picketts Road HSZ. a) Great circle traces of faults showing steep to moderate northeast dip. b) Faultkin analysis of fault [55/025 or 295/55NE with Lslick: 44/340 magnetic]. The calculated thrust vector is towards 184° (magnetic) or -200° TN.

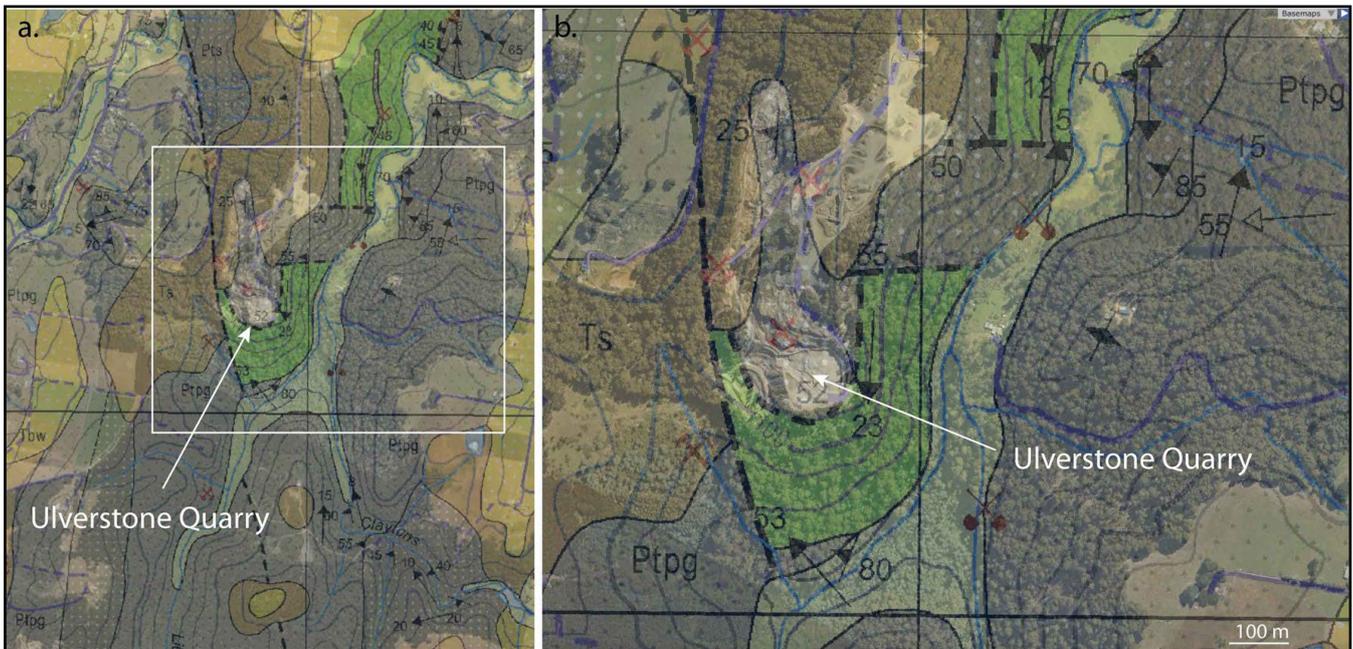


Figure 44. LISTMap of 1:25,000 digital atlas map draped on the Google satellite image showing the position of the Ulverstone Quarry within schistose quartzite (Pts) of the intercalated and isoclinally folded garnet-mica schist (Ptpg) and quartzite (Pts) package. The dashed line represents a major brittle fault zone superimposed on an original high strain discontinuity (HSZ).

The quartzites are disrupted by numerous brittle faults [F: 190/75W, F: 150/90, F: 155/85NE mag] that display fault gouge and have a spacing of 1-2 metres (Figures 45 and 46). These faults are part of a fault network associated with the reactivated Buttons Creek High Strain Zone (heavy black dashed line in Figure 44b) that truncates the western limb of the major synformal fold involving quartzite, serpentinite and garnet schist (Figure 44). They disrupt and offset a large-scale fold hinge exposed with the southern part of the quarry (Figures 46b and 47). This hinge in quartzite most likely mirrors the isoclinal macro-fold hinge highlighted by the quartzite-serpentinite contact (Figure 44).

#### 4.5.2 Ellis Road Quarry (Location E, Figure 30)

The Ellis Road Quarry is situated within Sheet 1c of the composite Forth Metamorphic sheet (Figure 12). The quarry (Figure 48a) exposes thin-bedded quartzite with alternating thin dark pelitic layers (Figures 27 and 28). The western part of the quarry contains classic, intrafolial folds (Figures 27, 28 and 49) that show variable plunge within the isoclinally folded, compositional So/Sm layering (Figure 48c). The overall foliation is north-northeast trending

with a general warping in So/Sm about an axis of  $52^{\circ}/241^{\circ}$  (Figure 48b, c and 50).

#### 4.5.3 Pumping Station Road/Sayers Hill Disused Quarry

The Pumping Station Road and Sayers Hill area (Figures 51 and 52) is dominated by a north-trending, steeply west dipping foliation Sm associated with sub-parallel, narrow cm-scale, quartz mylonite zones. The Sayers Hill area is part of a south-closing, southwest plunging fold closure with that is truncated by the major Forth Valley HSZ (Figures 35 and 52a). The second order Sayers Hill fold has inclined plunging geometry with a  $\beta$  axis of  $39^{\circ}/208^{\circ}$  (TN) (Figure 52e). Thin mylonite zones transitional into the broader Forth Valley HSZ truncate the western limb of the Sayers Hill fold (Figure 52). The outcrops closest to Pumping Station Road show a pronounced intersection lineation on mylonitic Sm in quartzite (Figure 53c), where the mylonitic zones truncate and therefore intersect with steeply, north-dipping compositional banding (Figures 52a, b and c). The compositional banding/layering is also folded by a series of west-plunging more open folds with an axial surface foliation Sm2 (Figure 53a and d) and more open south plunging folds (Figures 52c, f and g).

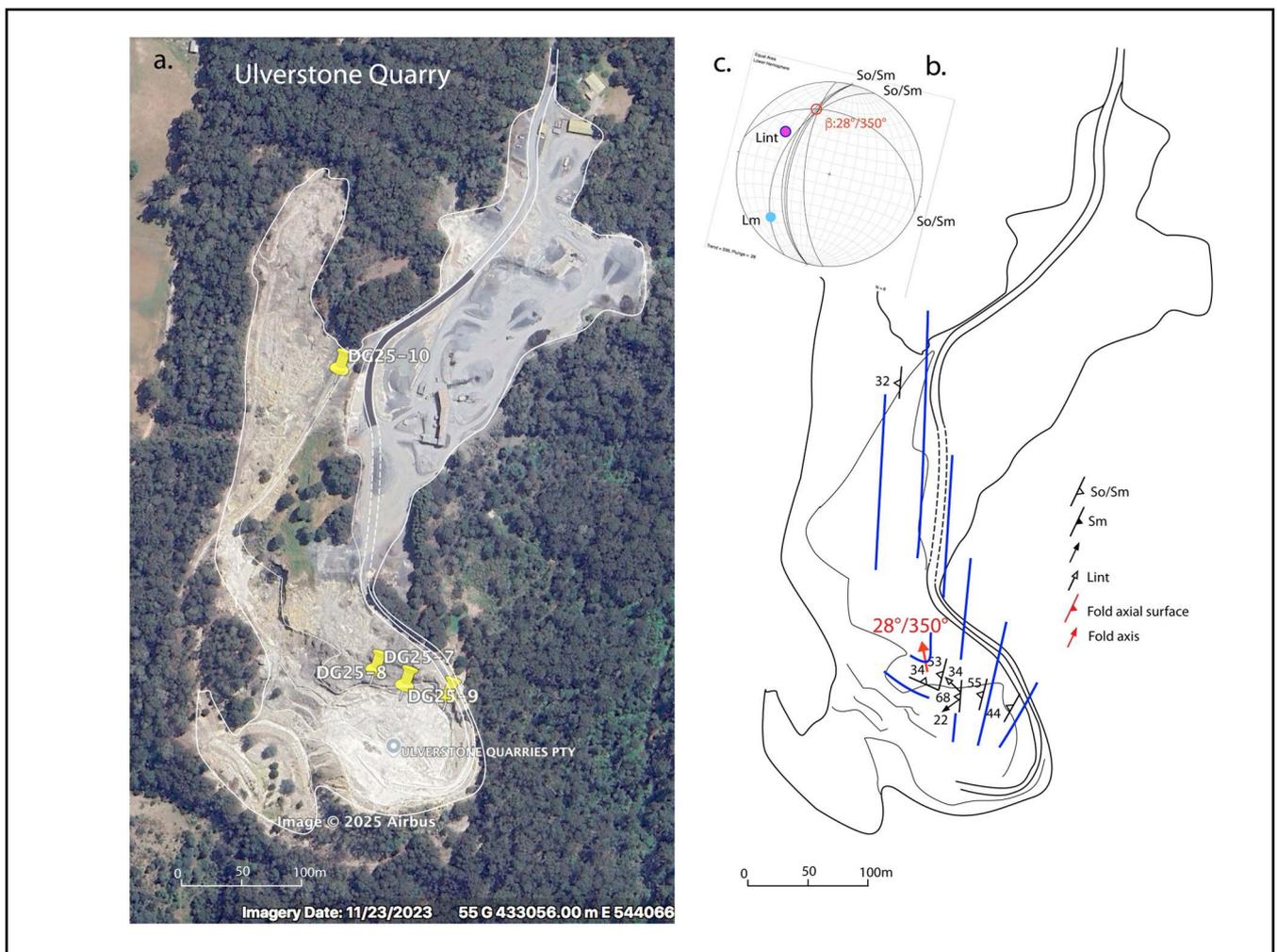


Figure 45. Structural geology of the Ulverstone Quarry at the southern end of Kimberleys Road. a) Google satellite showing the locations of DG25 measurement stations. b) Structure map of the Ulverstone quarry showing foliation, lineation and fold axis data. Form lines in So/Sm are shown by the heavy blue lines. Note the fold closure in the southern part of the quarry. c) Stereonet of the structural data for bedding foliation So/Sm, lineation Lm and Lint and fold axis ( $\beta$  axis;  $28^{\circ}/350^{\circ}$  TN) attitude.

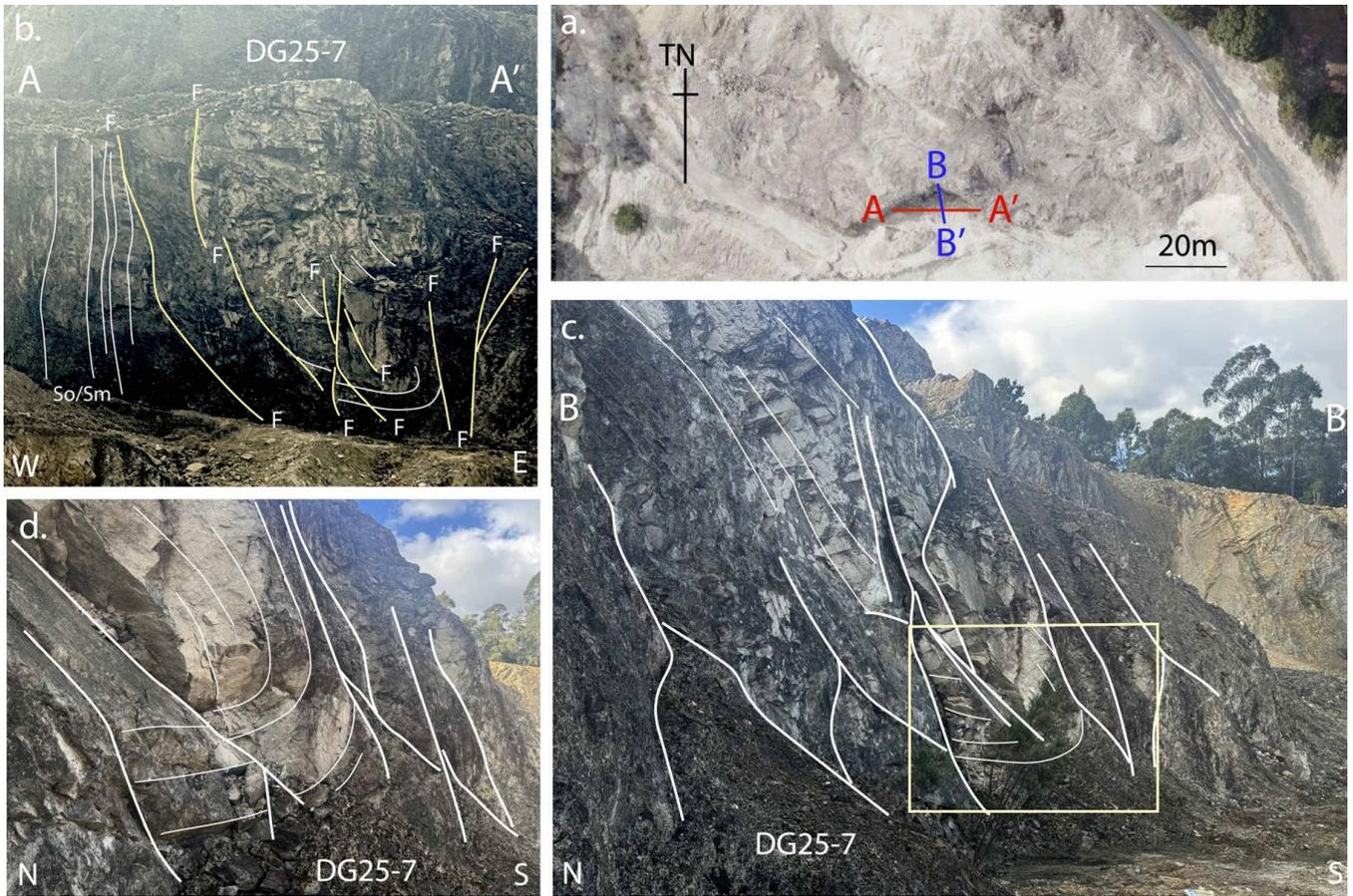
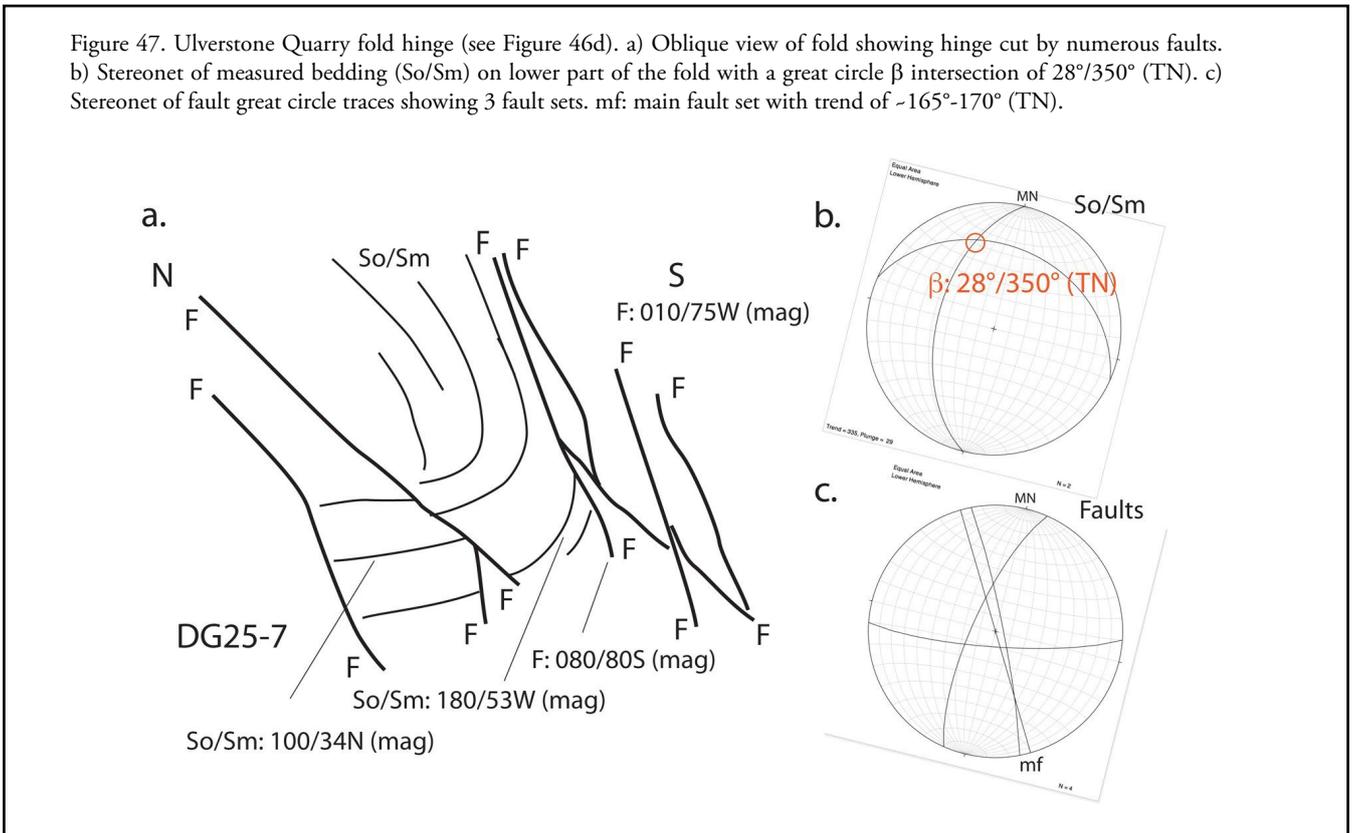


Figure 46. Major fold closure within the southern part of the Ulverstone Quarry. a) Google satellite image of the north wall of the southern part of the quarry. The location of photo profiles A-A' (red) and B-B' (blue) are shown. b) View of the south pit northern wall showing a fault-bounded "lump-like" body of thick bedded quartzite with the major fold hinge exposed at the base of the quartzite at the quarry floor. This is photo profile A-A'. c). Photo profile B-B' showing the faulted out fold-hinge. View is to the east. d) Enlarged view of the fold hinge.



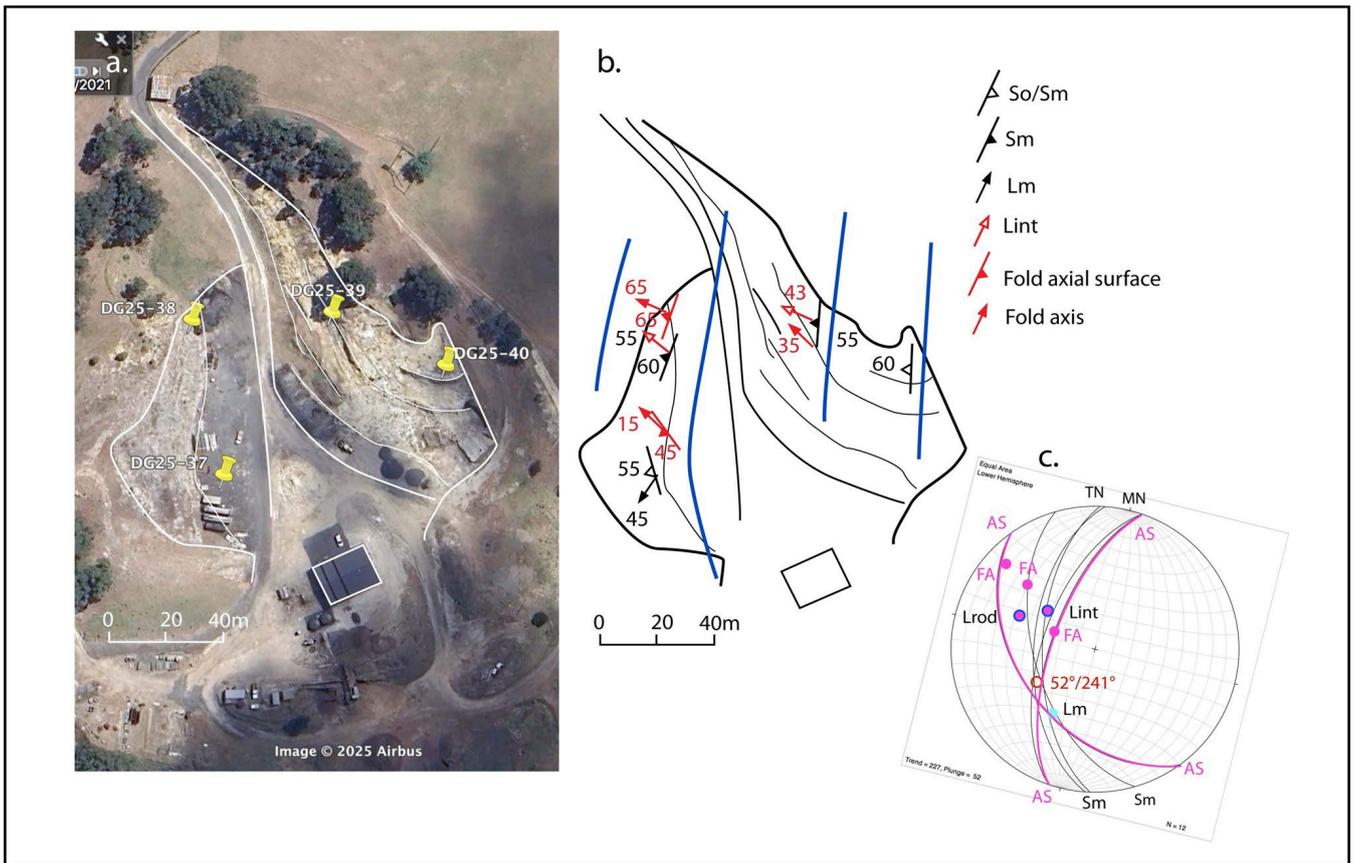


Figure 48. Ellis Road Quarry structural map. a) Google satellite image showing DG station locations. White lines define the quarry outline shown. b) Structural map of the quarry with form lines in So/Sm shown by the heavy blue lines. c) Stereonet of structural data for the Ellis Road quarry showing northwest plunges for folds (FA), Lrod and Lint lineations. Exposures on the west side of the quarry show a broad warping about an axis of 52°/241°.



Figure 49. Views of a steeply plunging [FA: 65/280 mag; AS: 195/65W mag], intrafolial fold hinge within a thicker bedded quartzite, Ellis Road Quarry. Station DG25-38. a) Oblique view of north-closing fold hinge. b) Approximate plunge view of hinge with weak mullion ribbing-structure at the layer interface (near pen).

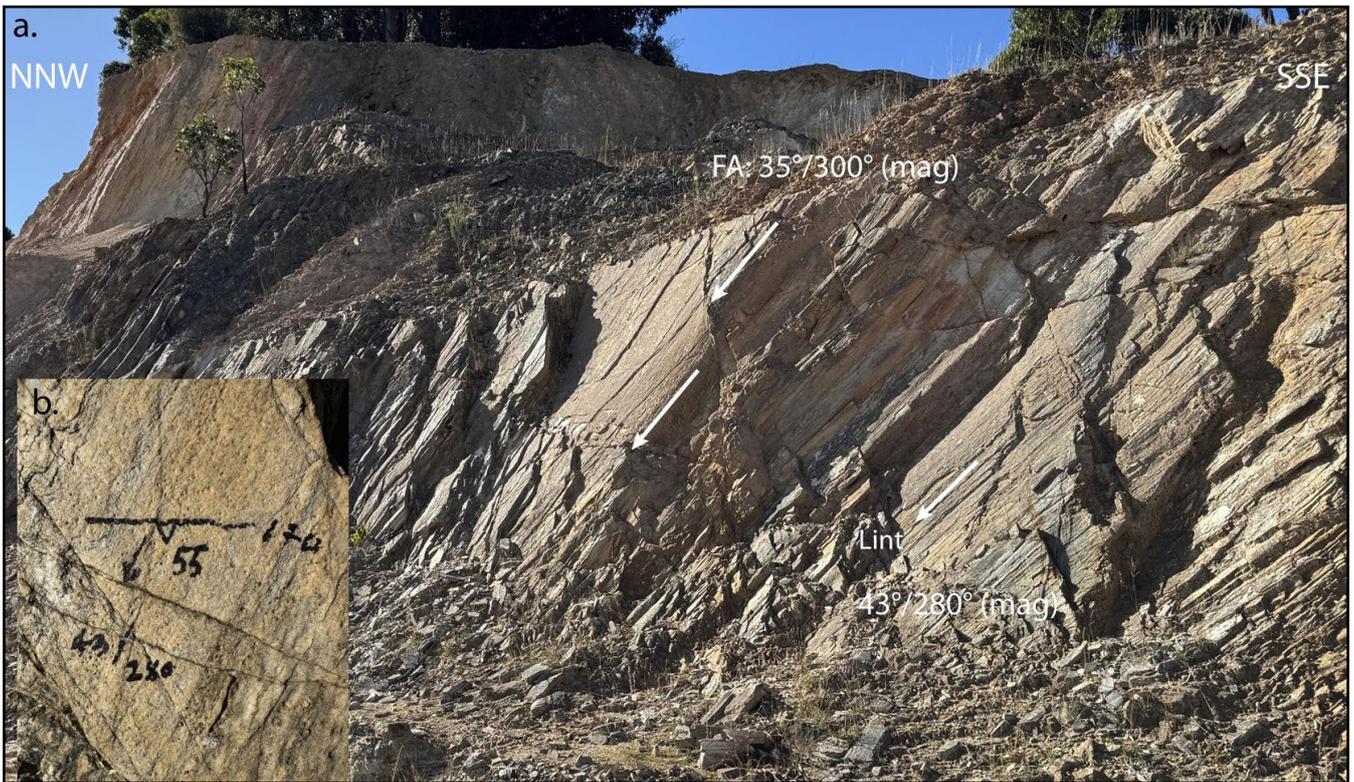


Figure 50. Plunging, open asymmetric fold within So/Sm along the eastern wall of the Ellis Road quarry. The fold plunge (FA: 35°/300° mag) is sub-parallel to a pronounced rodding intersection lineation (Lint: 43°/280° mag) in the thin-bedded quartzite. Overall quartzites along the eastern quarry face have homoclinal west dip (170°/55° mag).

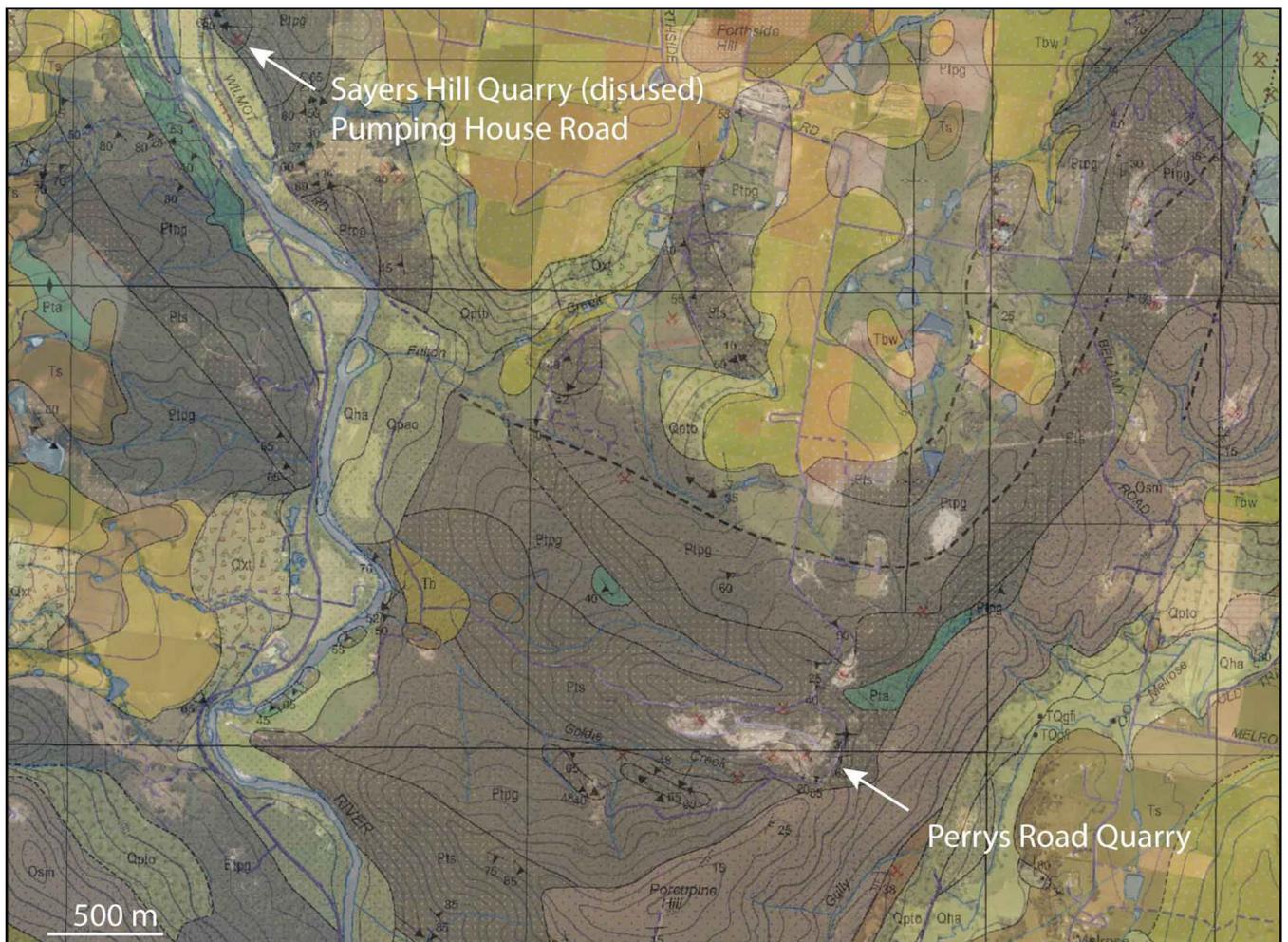


Figure 51. LISTMap of 1:25,000 digital atlas map draped on the Google satellite image showing the position of the Sayers Hill/Pumping Station Road Quarry and the Perry's Road Quarry. Both quarries are within schistose quartzite (Pts) intercalated and isoclinally folded with garnet-mica schist (Ptpg) and quartzite (Ptq).

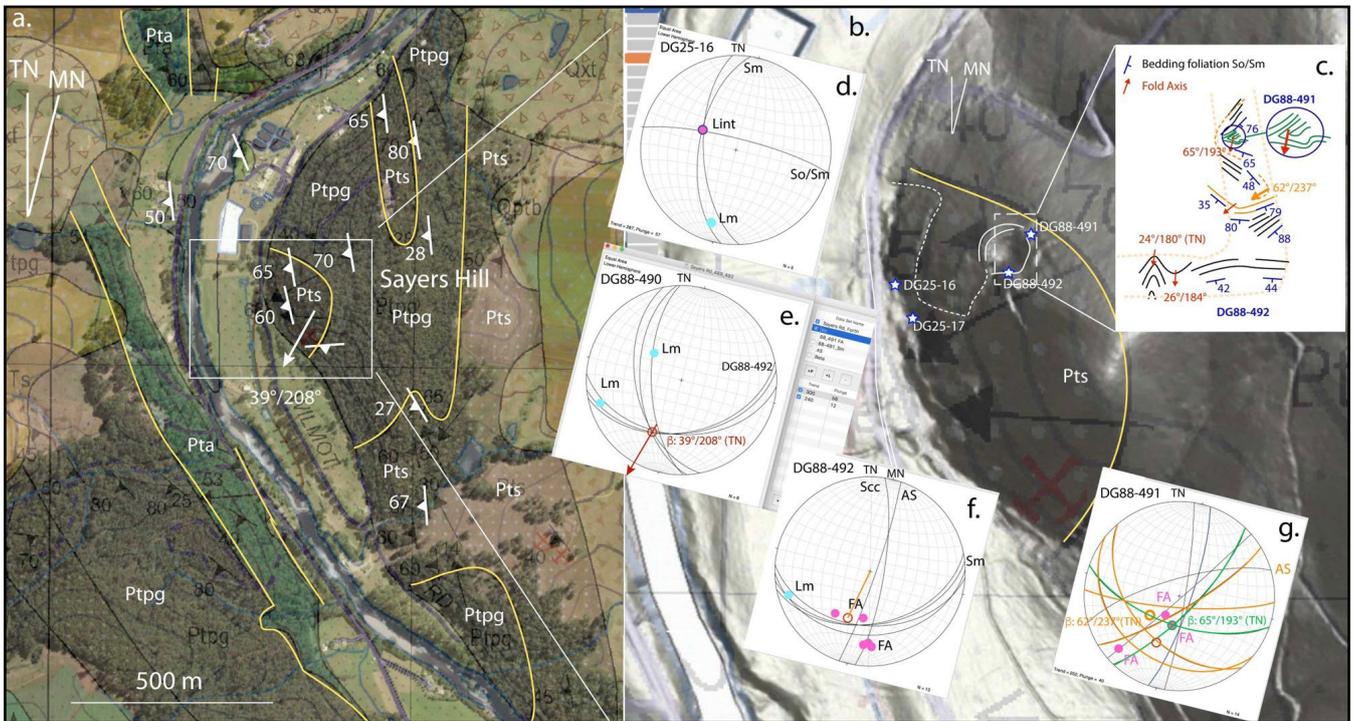


Figure 52. Structure map of the Sayers Hill-Pumping Station Road area and disused quarry. a) LISTMap Google satellite image with drape of the 1:25,000 digital atlas geology. Geological contacts are shown by the yellow line traces. Foliation attitudes are shown in white. Ptpg: garnet schist. Pts: schistose quartzite. Pta: amphibolite. b) LISTMap digital elevation-Lidar image with superimposed geological contacts (yellow line traces). The position of the disused quarry is highlighted in the image. c) Composite 1988 structural map of the old quarry showing form lines in So/Sm, fold plunges and foliation attitudes. d), e), f) and g) Stereonets of measurement stations DG25-16, DG88-490 and DG88-492, DG88-492 and DG88-491 respectively.

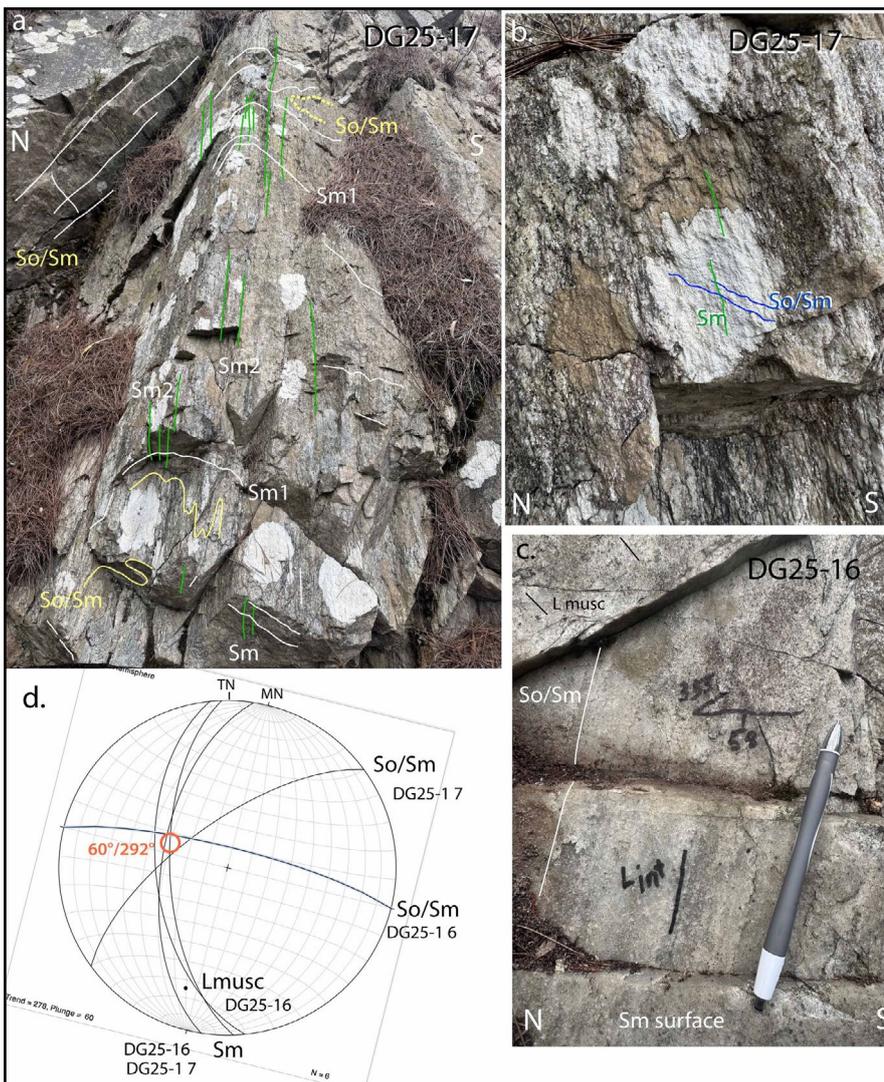


Figure 53 (Left). Structural relationships in the Pumping House road former quarry outcrops. a) Open, west-plunging fold in foliation Sm1 with a spaced axial surface crenulation cleavage (Sm2). Note the relict isoclinal folds within compositional banding So/Sm (top centre and bottom left). Station DG25-17. b) Crenulation cleavage character of the axial surface Sm2 foliation. Station DG25-17. c) View of dominant foliation Sm adjacent to quartz mylonite with similar attitude (Sm: 355/58W mag). Note the muscovite lineation Lmusc (top left) [Lmusc: 20/185 mag] and intersection lineation Lint [56/286 mag] with compositional banding So/Sm [090/80N mag]. See stereonet DG25-16 (Figure 52d).

Parts of the quarry visited in late 1988 (see sketch inset of outcrops DG88-491 and DG88-492) appear now hidden by thick vegetation. This older part of the quarry was not re-located in 2025 fieldwork, but was located in LIDAR imagery (Figure 52b). The 1988 field sketches show tight to isoclinal folds within So/Sm (Station DG88-491) re-folded by open, upright south-plunging anticlines and synclines (Station DG88-492).

#### 4.5.4 Perrys Road Quarry

The Perrys Road quarry is situated in the easternmost part of Forth Metamorphic Sheet 1b (Figure 12). It provides a structural window into an east-west trending segment of quartzite in the nose of the Forth Anticline. The quarry

is situated on the upper limb of an isoclinal macro-fold with an east-closing hinge in garnet mica schist, just to the north of the quarry (Figure 51). The quartzite layering in the quarry has an east-west strike with a moderate south-dip (Figure 54). Mesoscopic folds within the quartzite have inclined plunging to reclined geometry (Figures 54b, c and 55). They have south-dipping axial surfaces (AS) and west or southwest fold plunges (FA) (Figures 54b, c and 55).

The Perrys Road Quarry also shows an overprinting, spaced disjunctive cleavage (Ssp) within the quartzite (Figure 56). The cleavage attitude matches the axial surface foliation of the Forth Anticline (Figures 13 and 16).

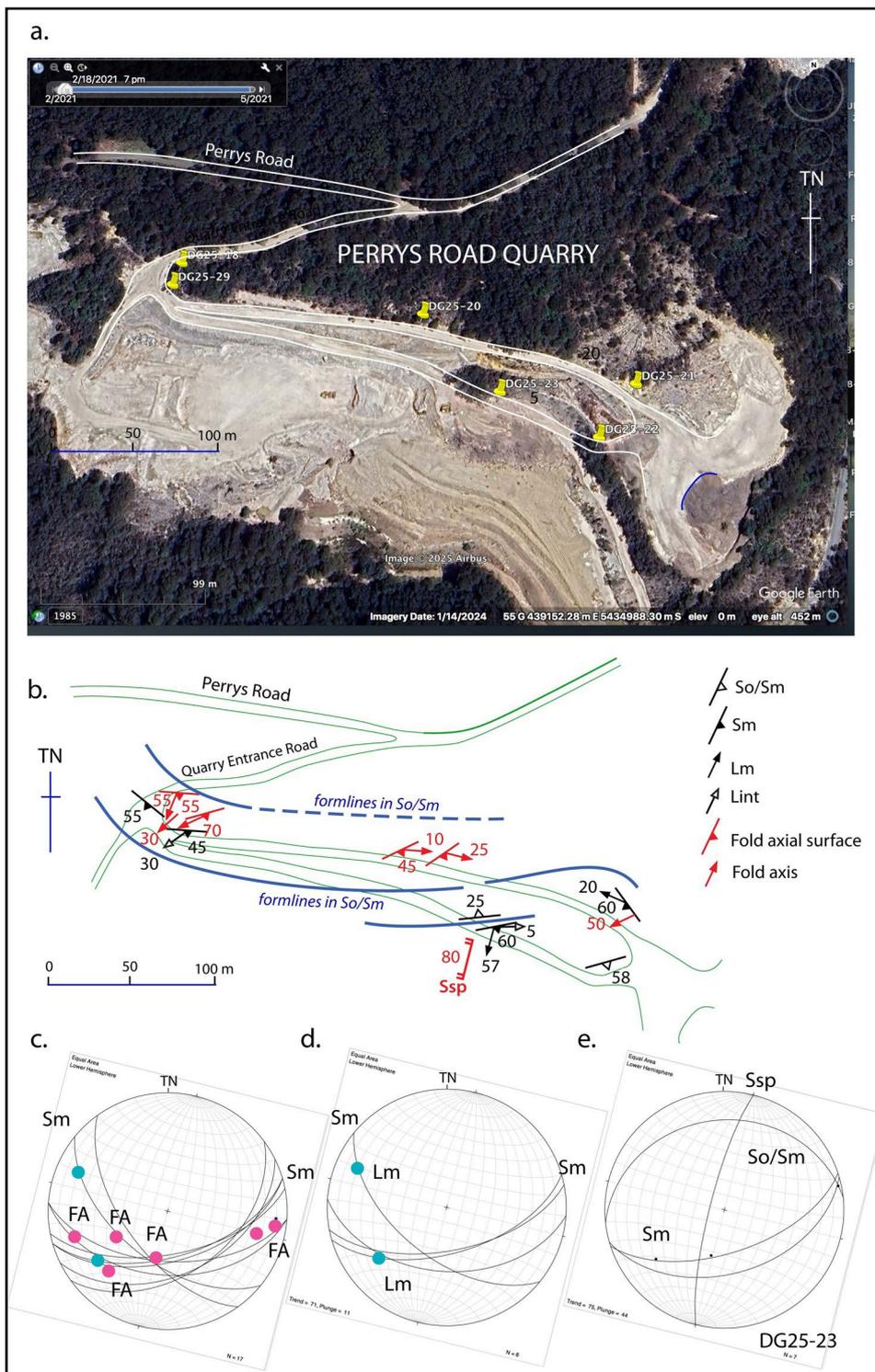


Figure 54. Current 2025 workings and structural data from Perrys Road Quarry. a) Google satellite image showing the quarry outline and the DG25 outcrop stations (yellow pins). b) Perrys Road quarry structural map with data plotted from the DG25 outcrop stations. c) and d) are stereonets of structural data from the quarry entrance area at stations DG25-18 and DG25-19 showing the fold axis and Lm attitudes. e) Stereonet of structural data from DG25-23 (see Figure 56).

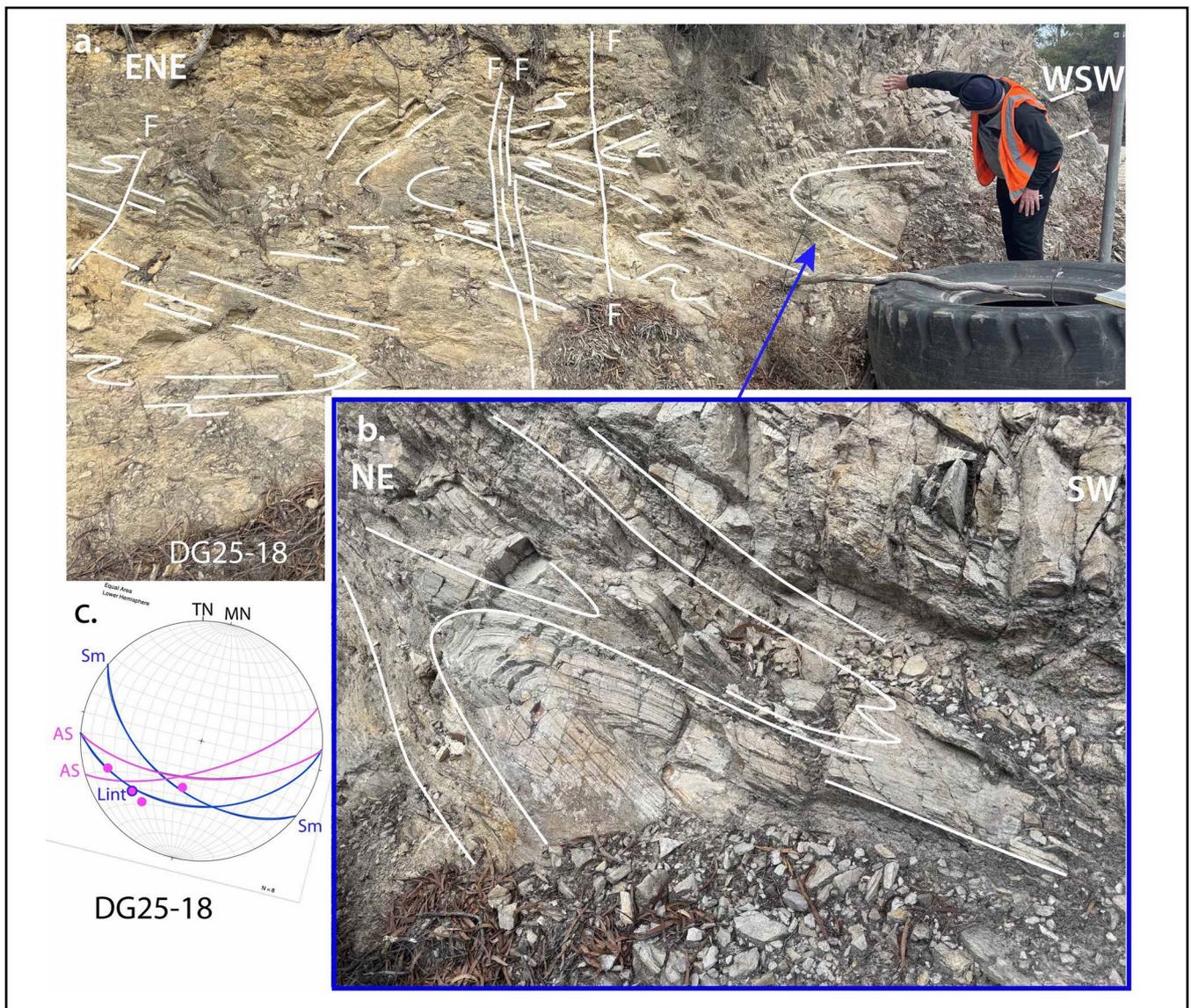


Figure 55. Tight to isoclinal folds within compositional layering So/Sm at the entrance to Perrys Road quarry. Station DG25-18 [438935/5435141]. a) Oblique intersection of folds in north-northeast trending cutting at the quarry entrance. The folds have inclined plunging to reclined geometry, have south-dipping axial surfaces (AS) and west or southwest fold plunges (FA). b) Approximate profile view of asymmetric fold pair within southwest dipping compositional layering So/Sm. c) Stereonet showing the geometrical relationships between the structural elements at DG25-18.

#### 4.6 Outcrop Relationships and the Regional Structure

All the observations made by the authors are incorporated into summary maps of 1) the 3D sketch geometry at individual outcrops (Figure 57), and 2) stereonet showing the attitude of structural elements (Figure 58) across the Forth Anticline.

The outcrop sketches (Figure 57) show variations in the geometry and inter-relationships of the early mesoscopic structures within the Forth Metamorphic Sheet across the Forth and Abbotsham Anticlines. The main features are:

1. Intrafolial folds with varying fold axis plunge and plunge direction within So/Sm,
2. Intense Sm zones showing rootless isoclinal folds in quartz veins and herringbone Lint patterns, with mesoscopic isoclinal fold axes steeply plunging within the dominant foliation Sm.

All of these elements, their geometry and structural inter-relationships have been incorporated into a geometric model for the Forth Metamorphic Sheet (see Section 5.1).

The stereonet map (Figure 58) shows 1) Sm attitudes (blue great circle traces) matching the large-scale arcuate form of the Forth Metamorphic Sheet due to refolding by the younger Devonian Forth Anticline, and 2) fold axis trends/variability defined by the red dots (measured isoclinal fold axes) and the intersection points ( $\beta$  axes) of So/Sm (purple great circles) and Sm (blue great circle traces).

Fold axis data collected by Burns (1964) and lineation data collected by Lewis (1991) were analysed to provide a greater understanding of the structural relationships across the Forth Metamorphic Sheet (Figures 59, 60 and 61). The Burns fold axis data (Figure 59) define a best-fit great circle ( $138^{\circ}/69^{\circ}\text{SW}$ ) that approximates the generalised southwest-dipping limb of the Forth Anticline. The markedly variable plunges within this generalised Sm plane are indicative of fold development in zones of higher shear strain. This is in agreement with the interpretation of the Goldie Creek style by Lewis (1991) as folds occupying mylonitic high strain domains in the Forth Metamorphic Sheet.

Figure 56. Foliation relationships in bedded quartzite, Perrys Road Quarry. Station DG25-23 [439143/5435055]. a) View of south dipping foliation surface Sm in quarry wall, with the lineations Lm and Lint highlighted. b) Enlarged part of (a). c) an enlarged part of (b) showing the intersection traces of a spaced disjunctive cleavage (Ssp) on the foliation surface. d) Oblique view of the quarry wall looking sub-parallel to the strike of Sm, with the gently north-dipping compositional banding So/Sm highlighted. Note the intersection lineation Lint is sub-horizontal. The stereonet (lower right) shows the geometrical relationships between the structural elements at DG25-23.

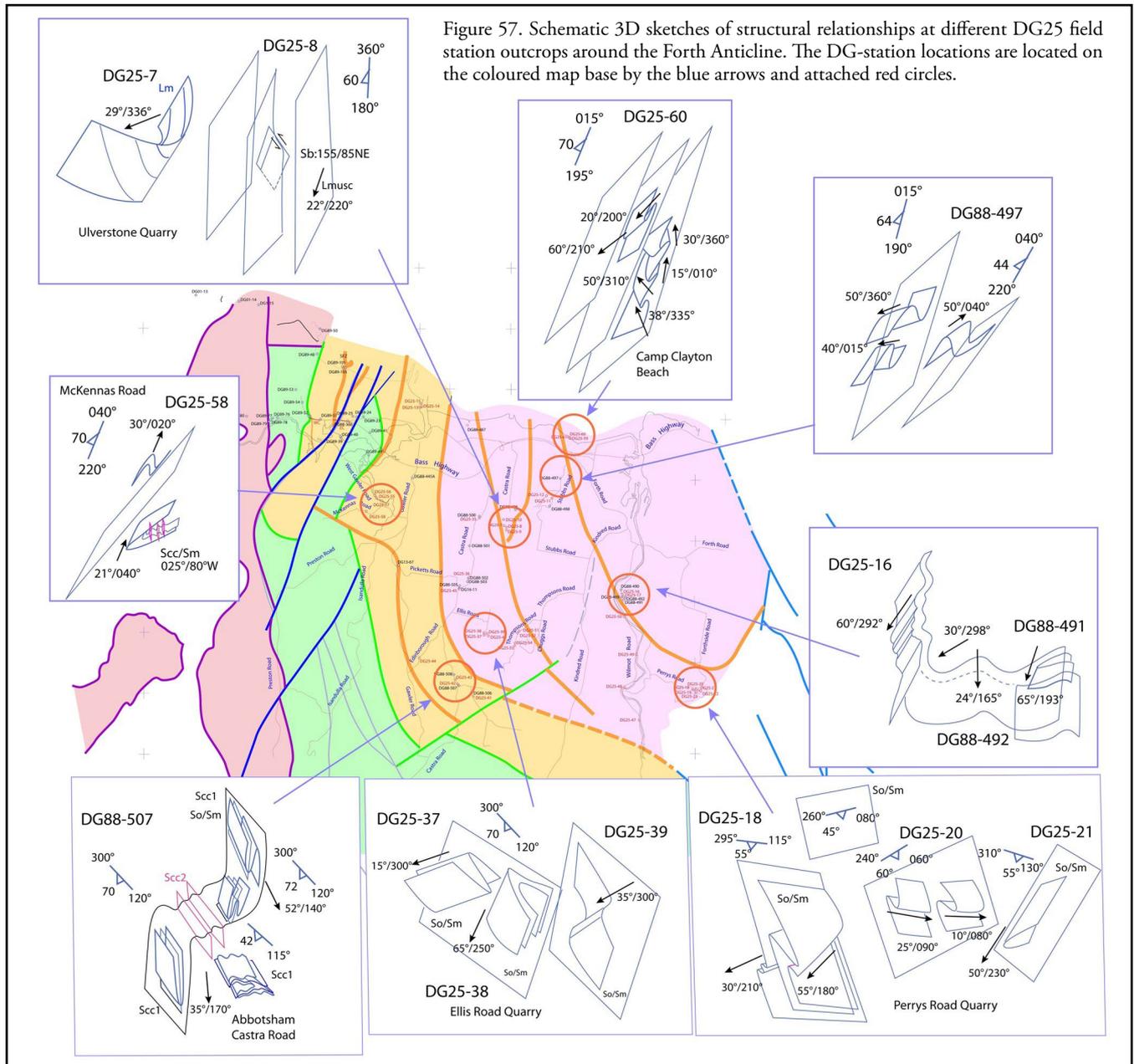
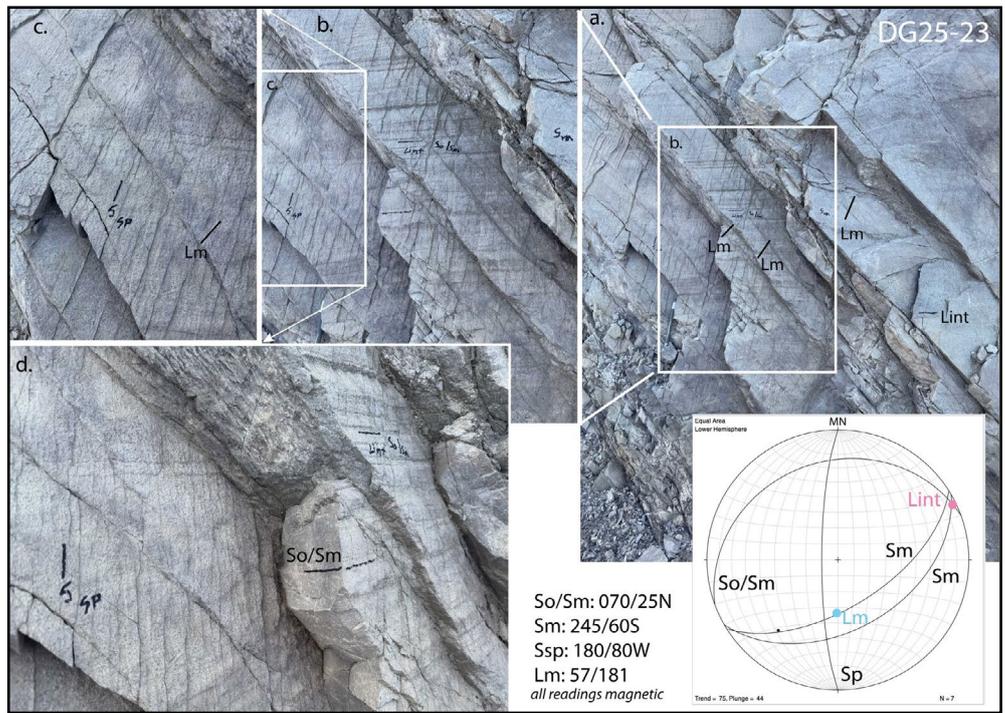


Figure 57. Schematic 3D sketches of structural relationships at different DG25 field station outcrops around the Forth Anticline. The DG-station locations are located on the coloured map base by the blue arrows and attached red circles.

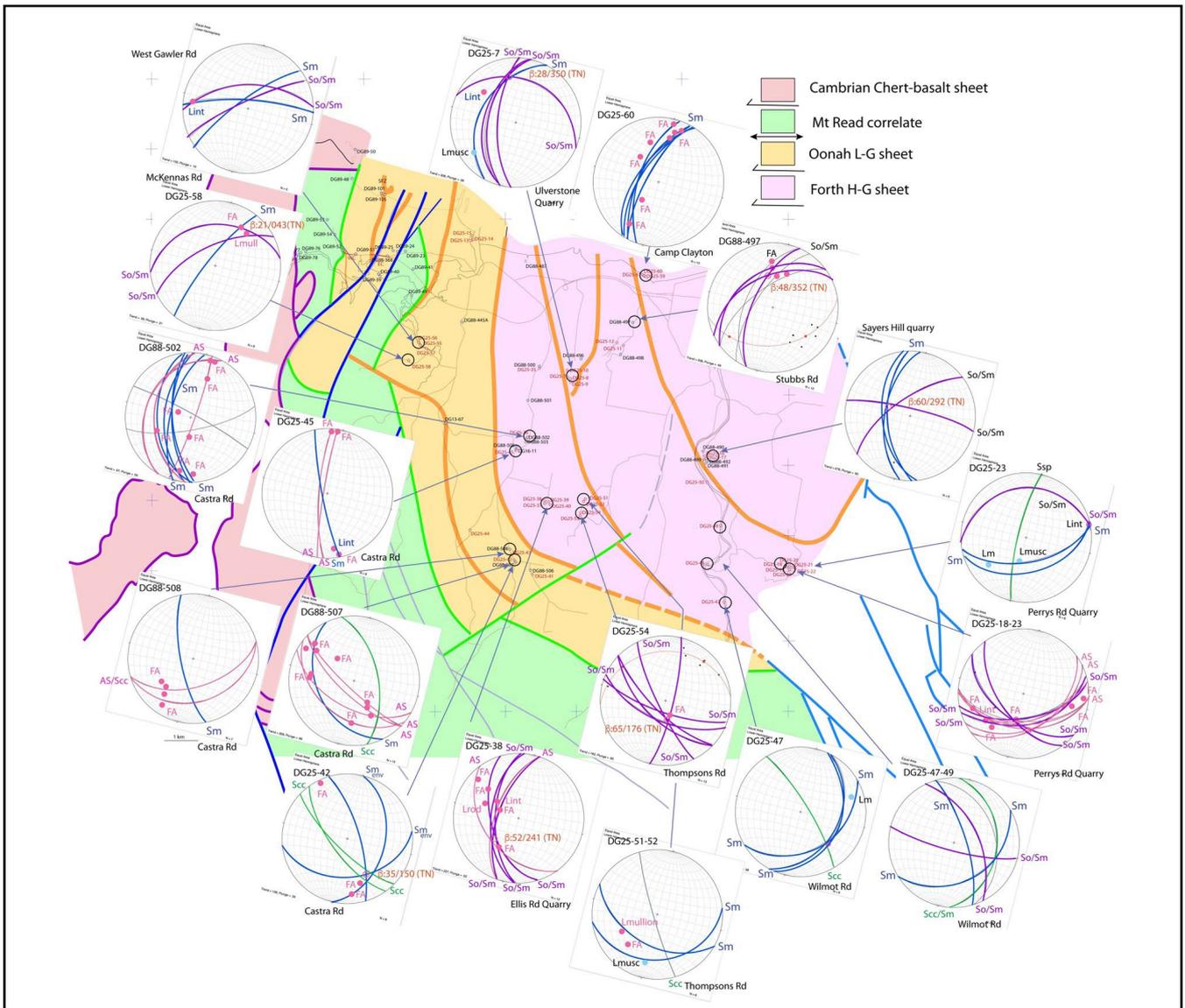


Figure 58. Forth Metamorphic Sheet structural data presented in stereonet form from DG outcrop stations. Blue great circle traces represent the attitude of foliation Sm. Purple great circle traces represent the attitude of So/Sm. Red great circle traces represent the attitudes of isocline axial surfaces. Green great circle traces represent the attitude of crenulation cleavages Scc. Red dots represent the attitude of isocline fold axes.

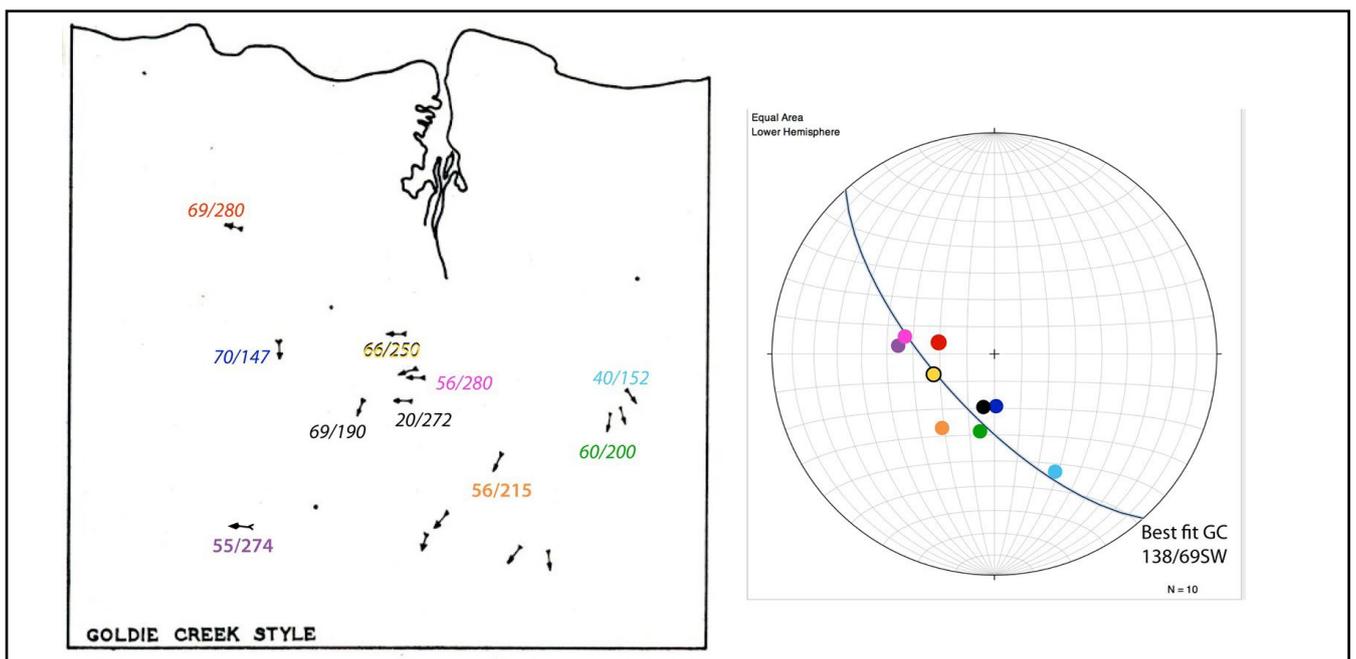


Figure 59. Burns (1964) fold axis attitudes for mesoscopic isoclines within high strain domains (Goldie Creek style). The actual fold axis measurements were derived from the Devonport 1:63,000 map sheet (Burns, 1963b) plotted from Burns field data. The fold axis data are coloured-coded on the map and coordinated with the attitudes shown on the stereonet. The best-fit great circle ( $138^{\circ}/69^{\circ}\text{SW}$ ) approximates the generalised southwest-dipping limb of the Forth Anticline.

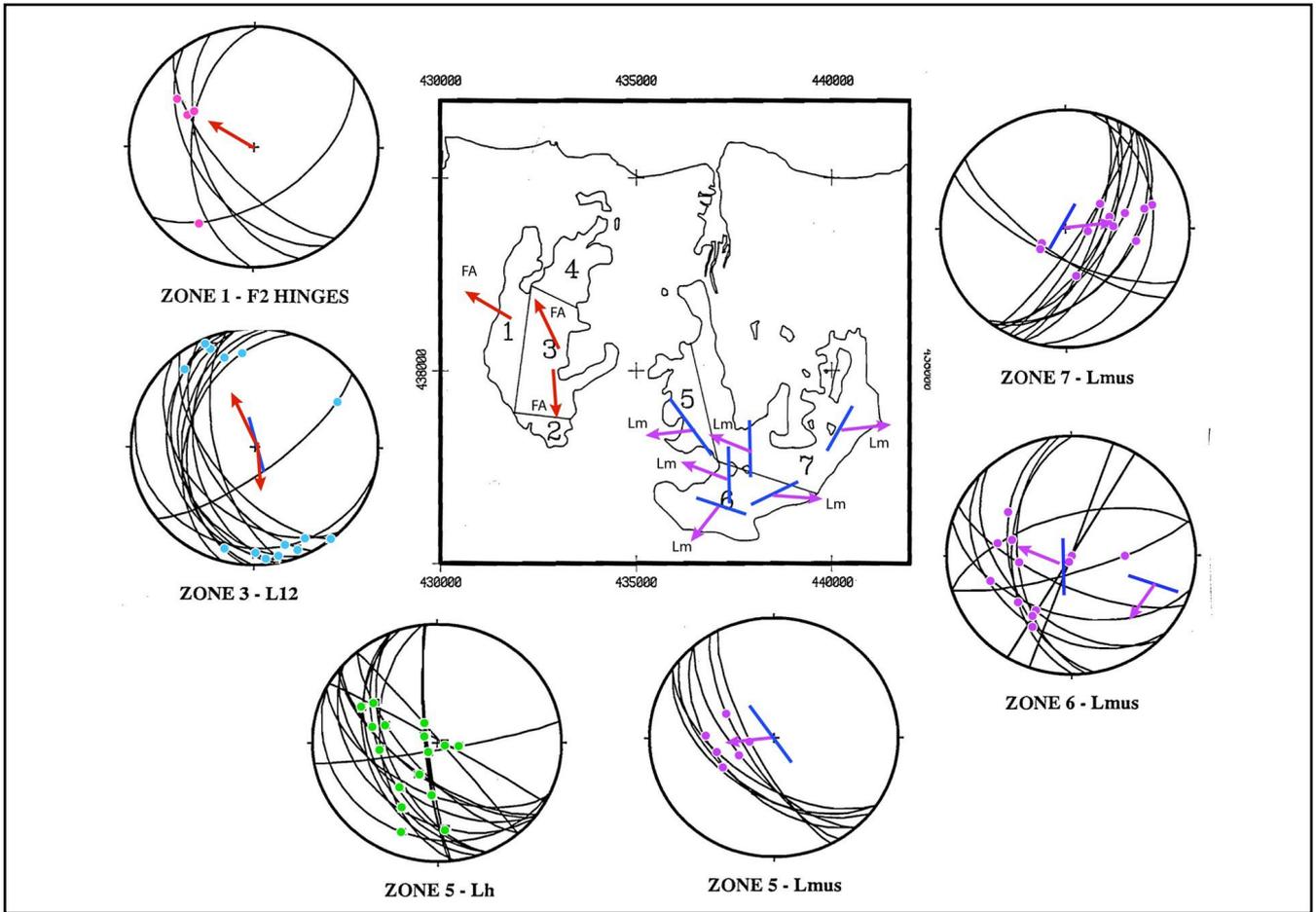


Figure 60. Lination trend diagram for the Forth Metamorphics across the Forth Anticline (combined from figs. 4.2 and 4.3, Lewis, 1991). The respective zones of Lewis (domains) are shown by the numbered polygons on the map. The stereonets show foliation great circle traces and lineation data (dots) for the corresponding zones.

*Blue line traces:* generalised foliation Sm strike within each zone. *Purple arrows* show the generalised lineation (Lmus) trend associated with the particular foliation trends. *Red arrows* are generalised fold axis (Zone 1) and L12 intersection lineations (equivalent fold axis) for Zone 2. *Green dots:* hornblende lineation (Lh) in Zone 5.

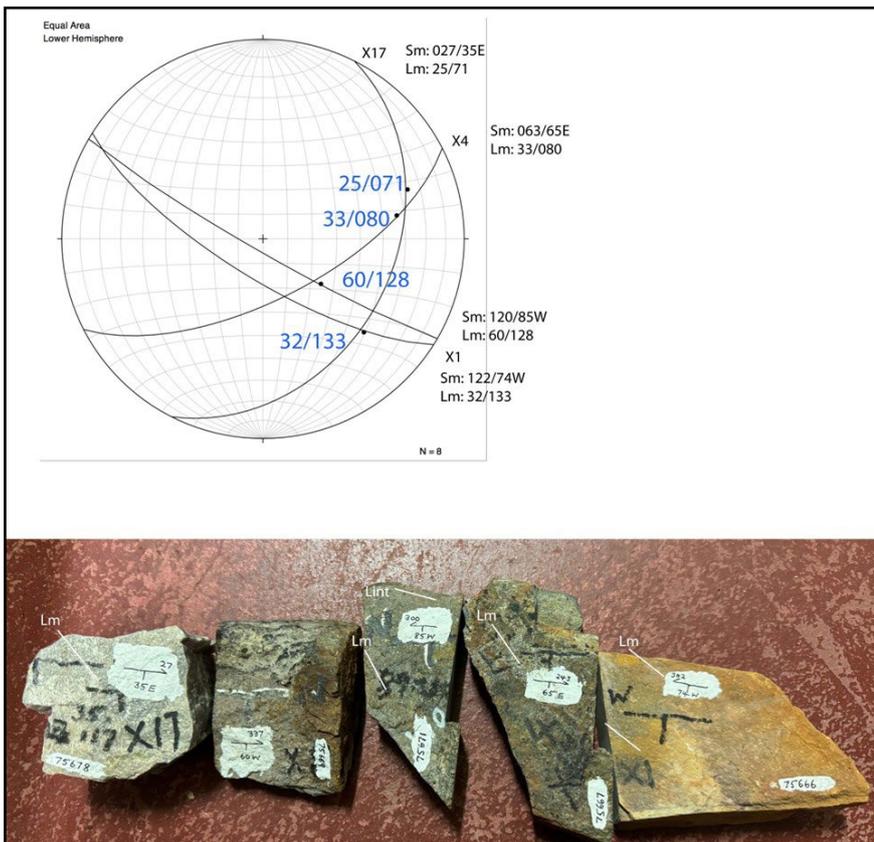


Figure 61 (Left). Lination attitude determination from Lewis (1991) oriented hand samples. Lm/Lmus pitches were measured in the Sm plane and plotted in stereonet form (a) to calculate Lm attitude as plunge and plunge direction. This was done as a check, given that limited Lm attitude data were recorded in Lewis (1991), apart from the zone stereonet compilations (see Figure 60).

Analysis of the Lewis lineation data (Figures 60 and 61) were undertaken, as most of the data were not recorded on the structural map, but presented in stereonet form for individual structural domains. Synoptic Sm (blue strike line), synoptic Lm (purple line traces) and synoptic fold axis (red line traces) were selected from each stereonet (Figure 60). The lineation data (purple lines, Figure 60) from the western limb the Forth Anticline are west-plunging, from the western part of the Anticline hinge are south-west-plunging, and from the eastern limb of the Anticline are east plunging (Figure 60).

The presence of the east and east-southeast plunging lineations are critical to the macro-structural interpretation of the Forth Metamorphic Sheet. A test was undertaken on oriented samples collected by Lewis (1991) to validate east plunging lineation attitudes. Lm attitudes were calculated using the measured foliation plane and pitch of the lineation on the foliation surfaces (Figure 61). It is important to note that the derived east-plunging lineations must occur on the eastern limb of the Forth Anticline (based on the east-dipping Sm great circle traces Figure 61), although southeast-plunging lineations can occur on west dipping limb segments (based on the west-dipping Sm great circle traces Figure 61), Unfortunately the locations of the samples utilised in Figure 61 were not given in the Honours Thesis.

Two simple geometric fold models were used to test or establish the pre-Devonian foliation Sm/lineation Lm relationships within the Forth Metamorphic Sheet (Figure 62). Scenario 1 involves a uniform lineation pattern in a planar, tilted foliation sheet (Geometry 1a, Figure 62). Scenario 2 involves a lineation pattern within an isoclinal fold stack, where F1/F2 isoclinal folds at varying scales fold the early lineation Lm, resulting in plunge direction changes across fold hinges (Geometry 2a, Figure 62). Simple warping/open folding of a tilted sheet with a uniform lineation pattern (Geometry 1b, Figure 62) cannot reproduce the present state foliation-lineation pattern across the Forth Anticline. This pattern Lm plunge direction change can only be reproduced by refolding, or open warping, of an isoclinally folded stack (Geometry 2b, Figure 62). Compare the lineation Lmusc patterns in Zones 5, 6 and 7 of Figure 60 with Geometry 2b of Figure 62). Simple open folding of a uniform or consistent Lm trend cannot produce the observed Lm reversal pattern (Geometry 1b, Figure 62).

In summary, the changing attitudes in Sm and Lm reflect both internal isoclinal folding of the Forth Sheet and subsequent open folding by the Forth Anticline. The varying Lm east plunge versus the Lm west plunge, as well as the map pattern (Figure 13), indicates the presence of a first order southeast closing, isoclinal macrofold (Geometry 2a, Figure 62) that has been refolded by the Forth Anticline (Geometry 2b, Figure 62). Note Lm east plunges occur on the structurally lower limb and Lm west plunges on the structurally higher upper limb (Geometry 2a, Figure 62).

## 5.0 FORTH METAMORPHIC SHEET- INTERPRETATION AND SIGNIFICANCE

The Forth Metamorphic Complex is interpreted as a major, 1st order, southeast-closing regional fold-nappe disrupted and offset by two major mylonitic, high-strain zones (Figures 63 and 64). The interpreted macro-fold has a reclined geometry with southwest fold plunge and west- and southwest-dipping upper and lower limbs.

The macro-fold also accommodates:

1. a strain transition shown by the change in nature of the axial surface Sm/S2 foliation. In the west it is a spaced crenulation cleavage/schistosity transitioning into strong to intense schistosity Sm, and
2. a change in structural level with an apparent metamorphic difference in estimated PT as well as metamorphic assemblages with staurolite-chloritoid schists in the west (upper macro-fold limb) and kyanite-garnet-biotite schists in the east (lower macro-fold limb).

The structural geometric model is based on:

- outcrop lithological patterns showing close-out or pinch-out of layers as inferred isoclinal hinges (Figures 11 and 13);
- a broad, inter-digitating hinge zone due to alternating northwest and southeast closing 2nd order fold hinges displaying mullion structure (Figure 13);
- a variation in Lm/Lint trends across the Forth Valley (Figure 60), where:
  - upper or western limb has Lm/Lint with west or northwest plunge (Zone 5, Lewis 1991) (Figure 60).
  - hinge zone centred on the Forth Valley has Lm/Lint with southwest plunge (Zone 6, Lewis 1991) (Figure 60).
  - lower limb or eastern limb has Lm/Lint with east plunge (Zones 6 and 7, Lewis 1991) (Figure 60).

The lineation pattern can be explained by isoclinal folding of Sm containing a lineation Lm with 20°-30° angular discordance to the isoclinal fold axis (Scenario 2, Figure 62a).

### 5.1 Geometric Model

Structural elements and relationships of the Forth Metamorphic Complex (Figures 57 and 58) have been used to construct a geometric model (Figures 63 and 64). The 3D model is based on the extensive early work by Burns (1963a, 1964) and Lewis (1991), as well as observations by the authors. The model portrays the Forth Metamorphic Complex as a composite sheet made up of three slices separated by two major high strain zones (HSZ). Small-scale ductile deformation zones (DDZ) occur throughout Slices 1a and 1b. They isolate, envelope and transect the apparent fold closures internal to the slices. The apparent fold closures are defined by pinch outs of both quartzite and garnet schist units, by convergence of So/Sm form lines and lithology terminations.

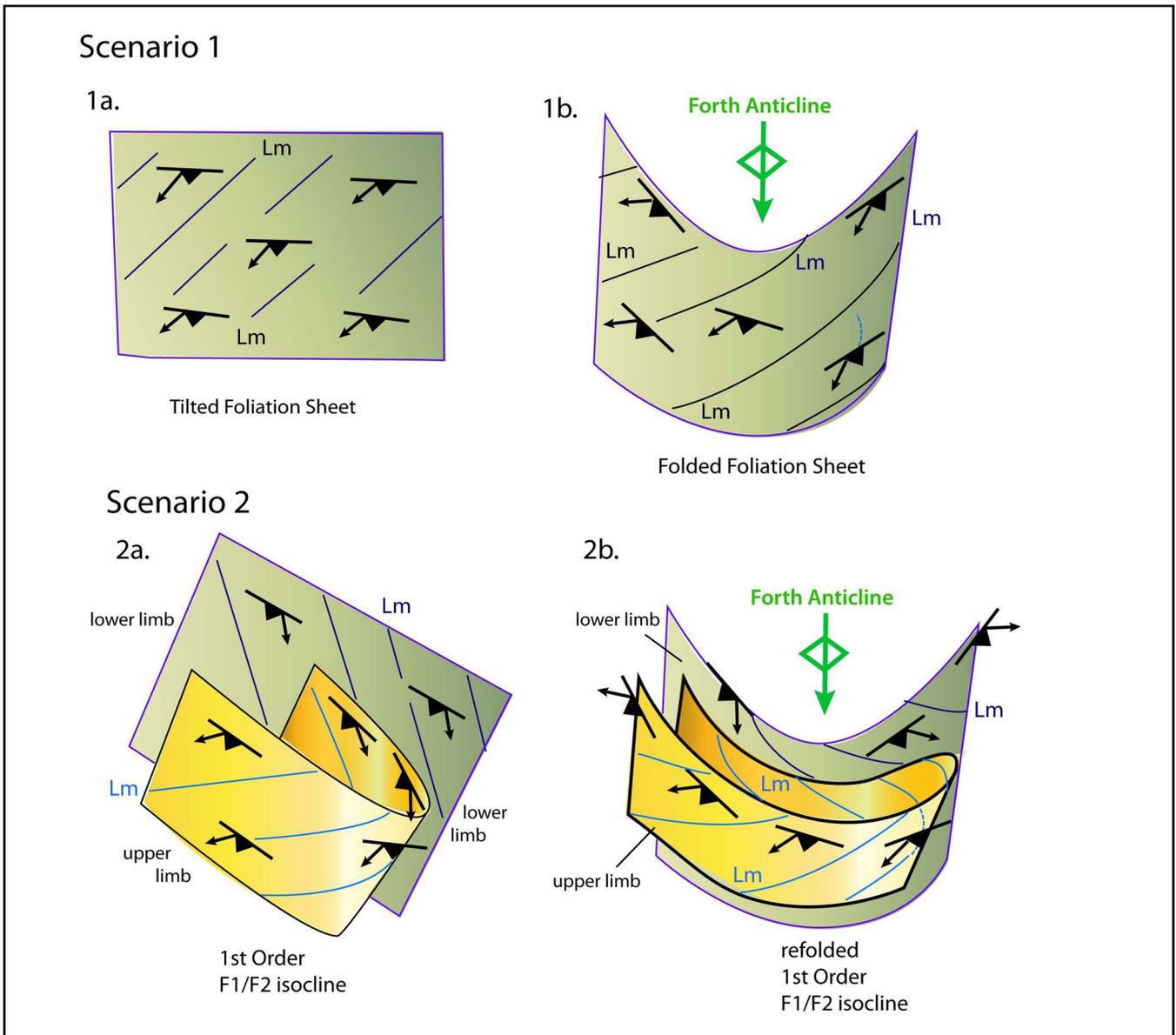


Figure 62. Simple geometric fold models to test the lineation pattern across the younger Devonian Forth Anticline.

Scenario 1: a uniform lineation in a planar, tilted foliation sheet.

Scenario 2: Lineation pattern folded by F1/F2 isoclinal folds at varying scales within an isoclinal fold stack. The presence of an inclined plunging isoclinal macro-fold produces lineation plunge direction changes from the upper to the lower limb across the macro-fold hinge (Geometry 2a). Refolding of this isoclinal macro-fold by the south-plunging Forth Anticline produces the observed Lm relationships (Geometry 2b).

Structurally, the map pattern can be produced by 1) structural interleaving of stretched and segmented lithological layers, 2) isoclinal folding of lithological layers accompanied by attenuation and pinch out fold hinges, and 3) combinations of (1) and (2).

A macro-fold hinge within the Forth Metamorphic composite sheet has been interpreted from the Lmusc data of Lewis (1991, fig. 4.3). The eastern part of the outcrop area shows an east-plunging Lmusc and the western parts a north-west-plunging Lmusc (Figure 50), interpreted to be on the opposite limbs of a major, first order, southeast closing isoclinal macrofold. Isoclinal folding of Sm and the contained Lm can produce the observed geometrical relationships (Scenario 2, Figure 62). Slices 1b and 1c occupy the western part of the Forth Anticline and uppermost limb of the macrofold, whereas the main fold hinge occurs within slice 1a.

The macrofold is a former fold-nappe within the isoclinally folded H-G stack. It has reclined geometry with a southwest plunge. The interpreted hinge zone is marked by a series of second-order, interdigitating isoclinal folds hinges typical of a large-scale mullion structure.

There is a distinct variation in Lm across interpreted macrofold hinge (see Figures 60 and Figure 62, Model 2a), where:

- upper western limb has a W- or NW- plunge (coincident with Zone 5 of Lewis, 1991);
- hinge has a SW plunge (coincident with Zone 6 of Lewis, 1991);
- lower or eastern limb has an E-plunge (coincident with Zones 6 and 7 of Lewis, 1991).

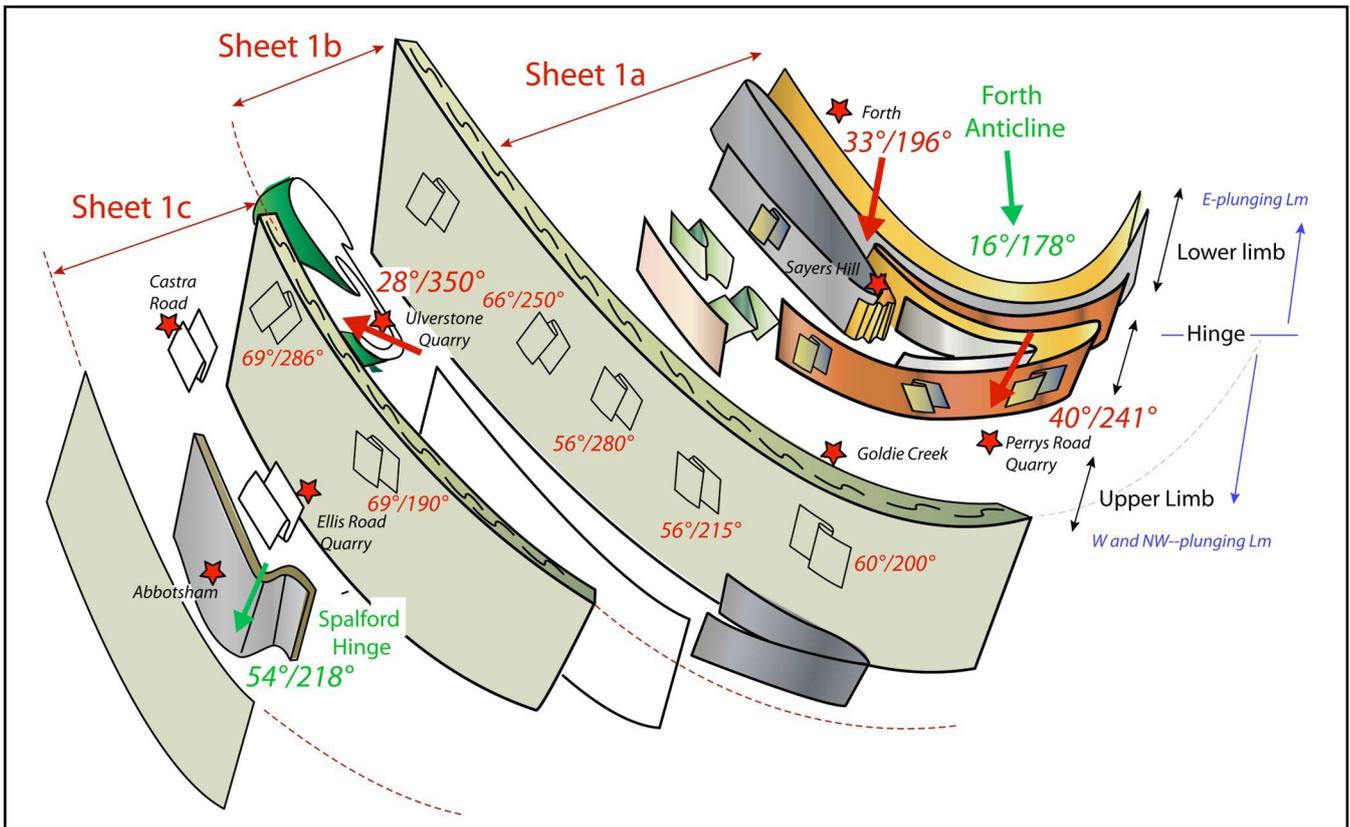


Figure 63. 3D geometric form of the H-G Forth Metamorphic Sheet with a schematic representation of the main structural elements and relationships within the composite sheet stack. This includes the structurally lowest sub sheet 1a, and the overlying sub-sheets 1b and 1c. High strain zones (HSZ) separate the sub sheets. Sub-sheet 1a incorporates an east-closing isoclinal macrofold with a southwest plunging, reclined geometry. The macro-fold hinge, upper and lower limbs are highlighted. Fold plunges of large-scale, early, isoclinal macro-folds are shown by the red arrows. Plunges of intrafolial early isoclinal fold pairs (black schematic outlines) are given as plunge/ plunge directions in red text. These have varying geometry within and between high strain zones. The red stars are geographic locations that constrain the interpreted macro-geometry. Fold plunges of the Devonian Forth and Abbotsham Anticlines are shown by green arrows and green text.

## 5.2 Transport Direction and Sheet Emplacement- A Discussion

Emplacement sense for the Forth H-G Metamorphic Sheet remains problematic. There are issues with 1) lack of observed and measured shear sense data for the Forth Metamorphic Complex, despite an argued east-over-west sense by Lewis (1991), and 2) a north-over-south transport for the Ulverstone L-G Sheet and a southwards emplacement of the Luina Sheet. Questions remain as to whether the Forth Sheet was emplaced with different transport sense to that of the overlying sheets.

### 5.2.1 Test of Fold Attitude and Geometry in Simple/General Shear

A geometrical test was applied to match the documented geometrical relationships for fold attitude, Lm and Lint lineation attitudes within the Forth Metamorphic Complex with those expected for east-directed emplacement (involving east-over-west shear sense) versus south-directed emplacement (involving north-over-south shear sense). The approach was to apply a geographic reference frame to the general shear model (Figures 65 and 66) thereby providing geometrical templates of the expected patterns and attitudes of lineations Lm and lint, the fold shape/form, fold asymmetry and fold plunge variations for each emplacement scenario (Figures 67 and 68).

Simple 3D geometric simulations (models) are used to test east-directed versus south-directed emplacement of the H-G Forth Metamorphic Sheet (Figures 67 and 68). The models attempt to simulate structural relationships due to younger refolding of structural elements developed by east-directed versus south-directed emplacement of the H-G Forth Sheet. The simple models produce distinct differences in the attitudes and geometrical relationships between mesoscopic folds, intersection lineations (Lint) and mineral elongation lineations (Lm), as well as shear band sense on the western limb of the Forth Anticline.

#### 5.2.1.1 East-over-West Shear Emplacement

Tilting and folding of the Forth Sheet in this model (Figure 67b) produces:

- a sub-horizontal Lm;
- a steeply plunging Lint;
- mesoscopic folds plunging down the foliation dip;
- dextral shear sense for reoriented shear bands on the north-rending, west-dipping western limb of the plunging anticline.

The above relationships reflect an approximate coaxial re-folding of the early folds about a south plunging fold axis (Forth Anticline). All the relationships are not consistent with the observed patterns of fold axes, Lm and Lint and shear sense.



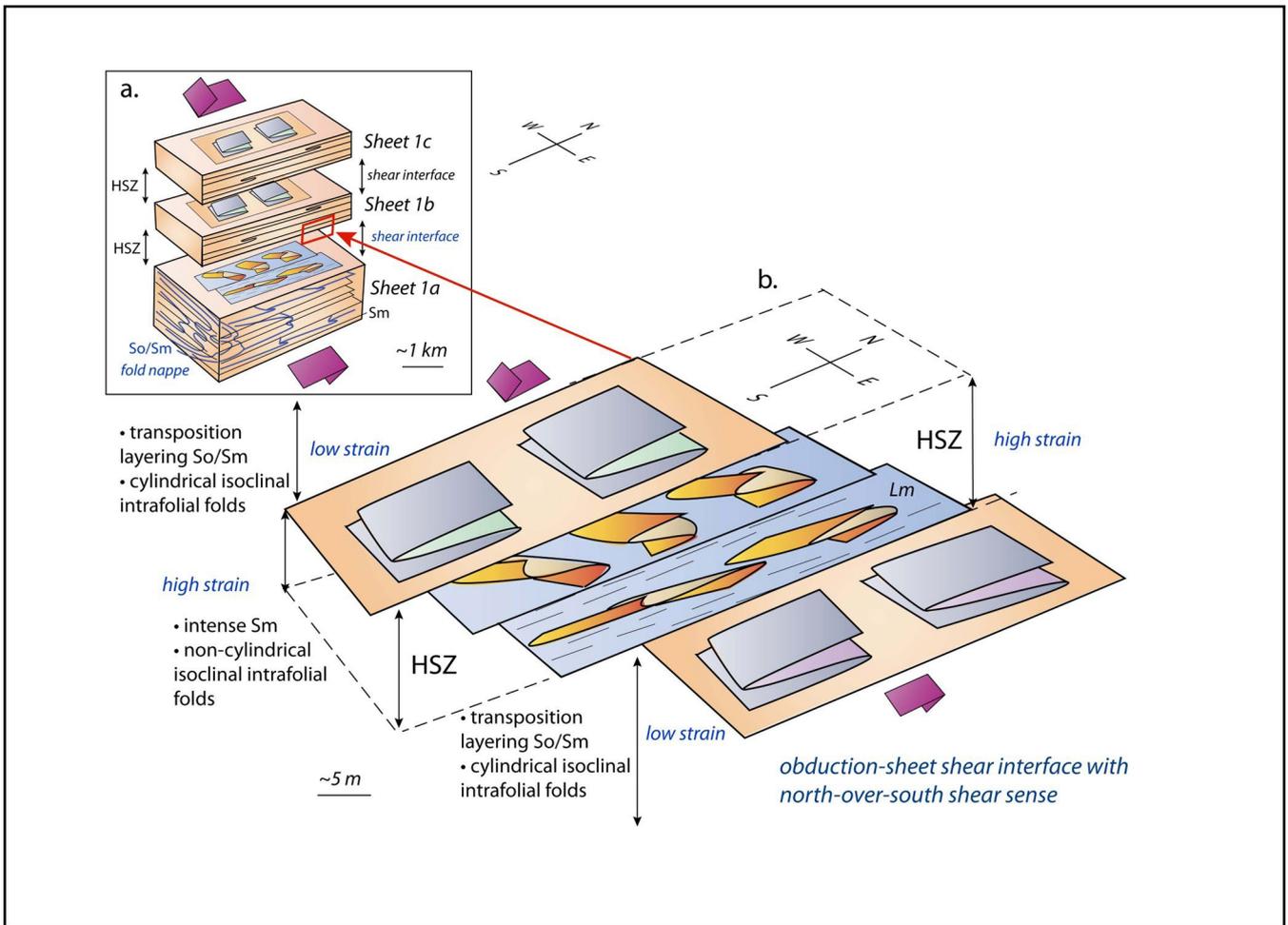


Figure 66. Schematic sheet stacking within the Forth Metamorphic Sheet (see Figure 12). a) Simple 3-sheet stack of the Forth Metamorphic Complex with the structurally lowest sheet (Sheet 1a) made up of an east-closing isoclinal macro-fold. b) Structural elements and relationships in a shear interface within and between obduction thrust sheets. The coloured elements match and represent strain intensity variants shown in Figure 65. Compare these geometrical relationships with those in Figure 63.

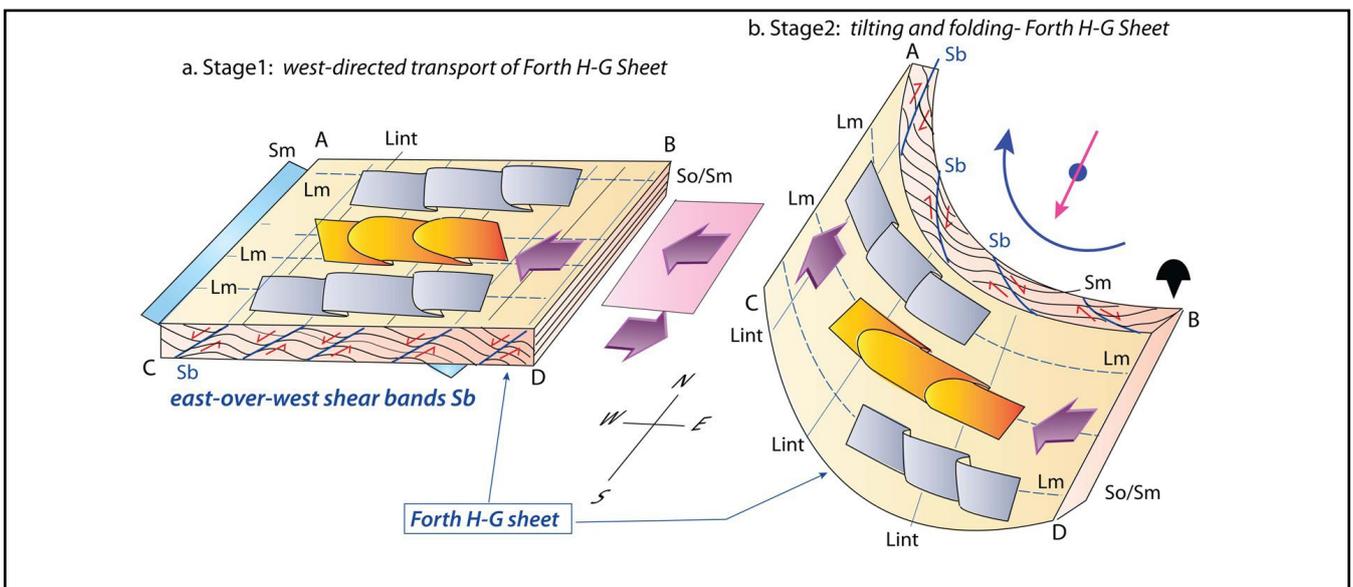


Figure 67. Geometric model of a sub-horizontal H-G Forth Metamorphic Sheet that has undergone sinistral, east-over-west shear strain during west-directed emplacement. a) Stage 1 emplacement with west-side down shear bands (Sb), east-west trending Lm and north-south trending Lm. Folds in grey-coloured layers represent low strain domains, whereas folds in orange-coloured layers represent folds with curved hinge lines in high strain domains. b) Stage 2 tilting and folding of the Forth H-G sheet shown in (a) with formation of the younger Devonian Forth Anticline. The model assumes a clockwise pivotal rotation about a south-plunging rotation axis (fold axis) with a pinning point (black thumb tack) at B. Similarly gold formation could occur by counterclockwise rotation about the same axis with a pinning point (black thumb tack) at A.

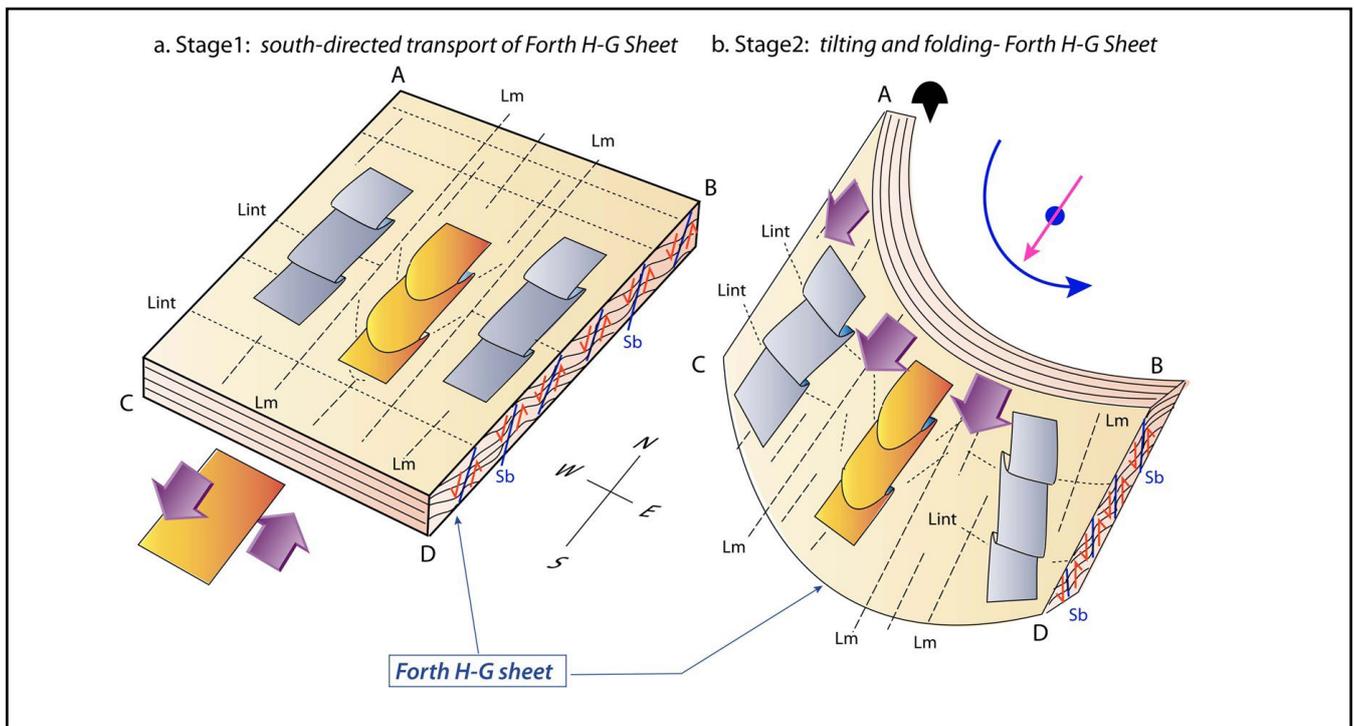


Figure 68. Geometric model of a sub-horizontal H-G Forth Metamorphic Sheet that has undergone sinistral, north-over-south shear strain during south-directed emplacement. a) Stage 1 emplacement with south-side down shear bands (Sb), north-south trending Lm and east-west trending Lint. Folds in grey-coloured layers represent low strain domains, whereas folds in orange-coloured layers represent folds with curved hingelines in high strain domains. b) Stage 2 tilting and folding of the Forth H-G sheet shown in (a) with formation of the younger Devonian Forth Anticline. The model assumes a counter-clockwise pivotal rotation about a south-plunging rotation axis (fold axis) with a pinning point (black thumb tack) at A. Similarly fold formation could occur by clockwise rotation about the same axis with a pinning point (black thumb tack) at B.

### 5.2.1.2 East-over-West Shear Emplacement

Tilting and folding of the Forth Sheet in this model (Figure 68b) produces:

- a steeply plunging Lm;
- an overall sub-horizontal Lint, with variable more steeply plunging Lint in high-strain domains;
- sub-horizontally plunging mesoscopic folds in low strain areas (grey folds) and more steeply plunging folds in high strain domains (orange folds);
- a sinistral shear sense for reoriented shear bands on the north-trending, west-dipping western limb of the plunging anticline.

The relationships shown in Figure 68 reflect refolding of the east-west trending early folds about a south plunging, north-south trending fold (Forth Anticline). The relationships are consistent with the observed patterns of fold axes, Lm and Lint and shear sense (see Figures 67 and 68).

### 5.2.2 A Test of Shear Band Geometry

Given the presence of 1) west-dipping, sinistral shear bands (Lewis, 1991) in the Forth Metamorphic Sheet, and 2) an argument of east-over-west shear sense (Lewis, 1991), simple geometric simulations (Figure 69) were also undertaken modelling the subsequent deformation (tilting and fold rotation) of the expected shear band pattern/attitude for east-directed emplacement (Scenario 1: Figure 69, 1a and 1b) versus south-directed emplacement (Scenario 2: Figure 69, 2a and 2b).

Scenario 1 involves tilting and folding of east-over-west shear bands formed in west-directed sheet emplacement (Figure 69, 1a). The applied deformation includes a southwards-tilting and regional folding about a south-plunging axis. This results in west-dipping, dextral sense shear bands along the west dipping, western limb of the Forth/Abbotsham Anticline pair (Figure 69, 1b), contradictory to that observed by Lewis (1991).

Scenario 2 also tilting and folding of north-over-south shear bands formed in south-directed sheet emplacement (Figure 69, 1a). The applied deformation includes a westwards-tilting of the sheet involving regional folding about a south-plunging axis. This results in the observed sinistral shear bands within the west-dipping foliation Sm along the western limb of the Forth/Abbotsham Anticline pair (Figure 69, 2b).

### 5.2.3 Summary

Post-Cambrian tilting and folding geometrical simulations of 1) fold attitude and geometry and 2) shear band geometry developed in simple/general shear have shown that the Forth Metamorphic Sheet (Unit 1, Figure 12) must have been emplaced with north-over-south shear sense involving south-directed emplacement. This matches the south-directed emplacement of the overlying Ulverstone-Oonah L-G Sheet (Unit 2, Figure 12) and the Penguin-Luina Sheet (Unit 4, Figure 12).

The emplacement of the northern Tasmanian subducted and exhumed metamorphic sheets and the obducted oceanic sheets is southwards, therefore in contrast to the overall westward emplacement of the Tyennan Domain metamorphic sheets (see Gray et al., 2023).

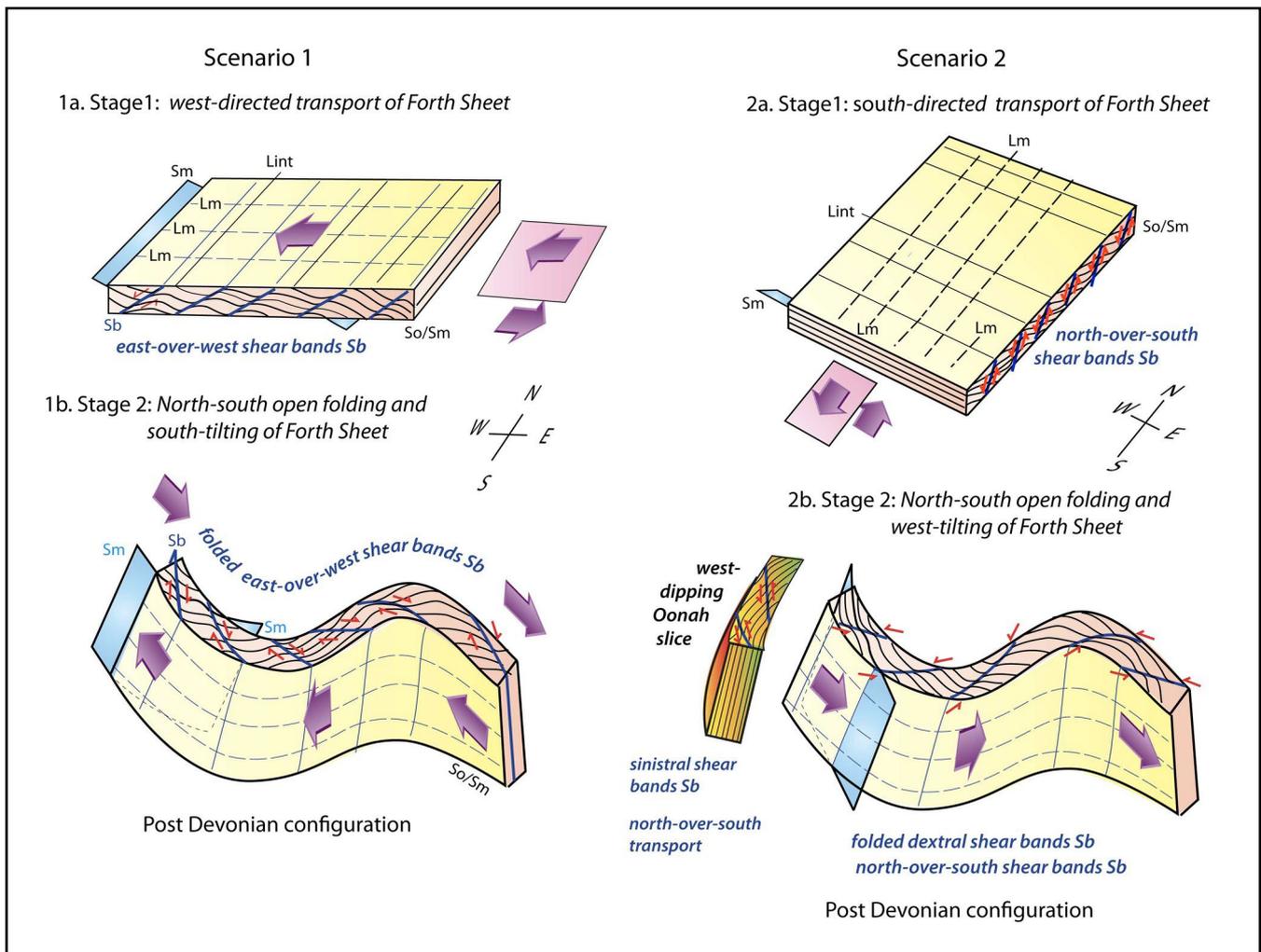


Figure 69. Schematic block models of the Forth Metamorphic Sheet illustrating shear band (Sb) structural relationships for west-directed emplacement (Scenario 1) and south-directed emplacement (Scenario 2). The two block models show the relationships between the foliation (Sm), mineral (Lm) and intersection (Lint) lineations, and shear bands within a geographic reference frame. The model variants aim to show the potential changes of shear band attitude and shear sense across the Forth Anticline. The emplacement shear sense is shown by the purple arrows.

Scenario 1: 1a) Simple block diagram after Stage 1 west-directed obduction emplacement. 1b) Geometric block models of the Cambrian structural relationships after south tilting and open folding to form the Forth Anticline. The result is dextral sense shear bands.

Scenario 2: 2a) Simple block diagram after Stage 1 south-directed obduction emplacement. 2b) Geometric block models of the Cambrian structural relationships after west tilting and open folding to form the Forth Anticline. The result is sinistral sense shear bands.

## 6.0 IMPACTS AND INFLUENCES OF A COMPLEX DEFORMATIONAL HISTORY

The structures within, the regional fold and fault pattern, and the faulting history of the Forth Metamorphic Sheet reflect a complex deformational history. The Sheet has been affected by six different fault systems (coloured circled numbers, Figure 12) including 1) a Cambrian subduction/exhumation "thrust" system that created the lithotectonic sheet stacking, 2) Mid-Cambrian extensional fault system that created the Dundas-Fossey graben, 3) a Late Cambrian brittle obduction thrust system involving southwards sheet transport, 4) a Devonian reverse fault system developed along the western limb of the Devonian Forth Anticline, and 5) a post-Permian extensional fault system that created the Mersey Graben. As a consequence the complexly deformed Forth Metamorphic Sheet now exists as a relict Middle Cambrian extensional horst modified by Devonian thrusting and the post-Permian normal faulting (Figure 70).

## 6.1 The Devonian Deformational Overprint

There is a clear Devonian deformational overprint on all three sheets, including:

1. Reactivation and overprinting of ductile deformation zones (DDZ) and high strain zone (HSZ) interfaces and contacts between the sheets by east-directed brittle thrust/reverse faults (Figure 38).
2. Development of a major, north-trending, south-plunging regional anticline and syncline pair (the Forth Anticline and Eugenana Syncline).
3. Development of sub-vertical, north-trending cleavage, as a spaced stylolitic cleavage within the H-G quartzite and localised crenulation cleavage in schist (Forth H-G Metamorphic Sheet) and phyllite (Ulverstone L-G Metamorphic Sheet).
4. Development of the West Ulverstone Imbricate Zone from splay, short-cut, back thrusts developed off steeply, west-dipping, normal faults along the margin of the Dundas Graben.

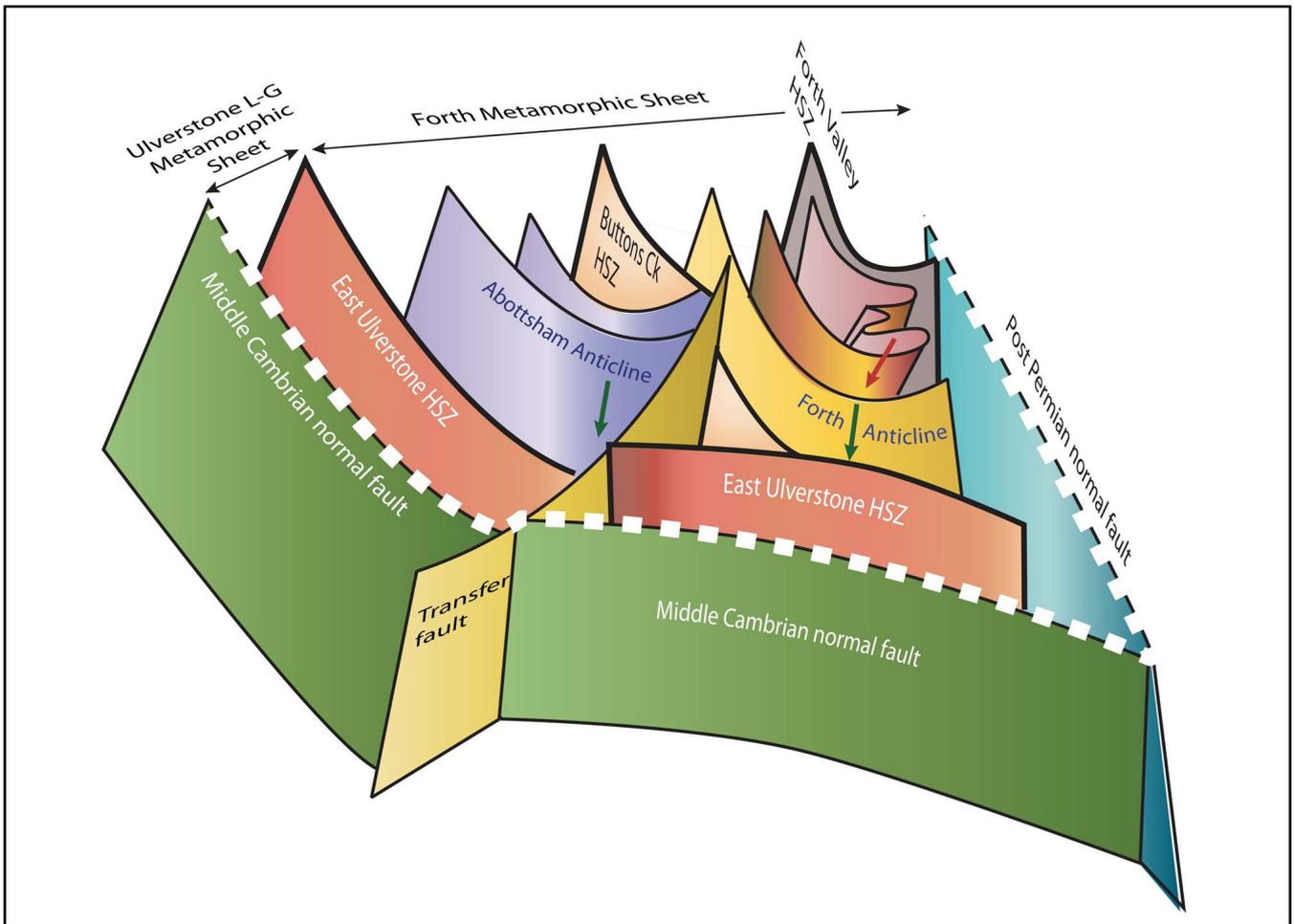


Figure 70. Schematic 3D block diagram illustrating the current, relict-horst geometry of the normal fault-bounded Ulverstone-Forth Metamorphic Sheets. The horst boundaries are highlighted by the thick-dashed white lines. The Proterozoic rocks of the deformed Forth and Ulverstone Sheets are part of a remnant basement high formed by 1) Middle Cambrian extensional faulting of the Dundas Fossey Graben system along the western and southern flanks, and 2) post-Permian extensional faulting along the eastern flank.

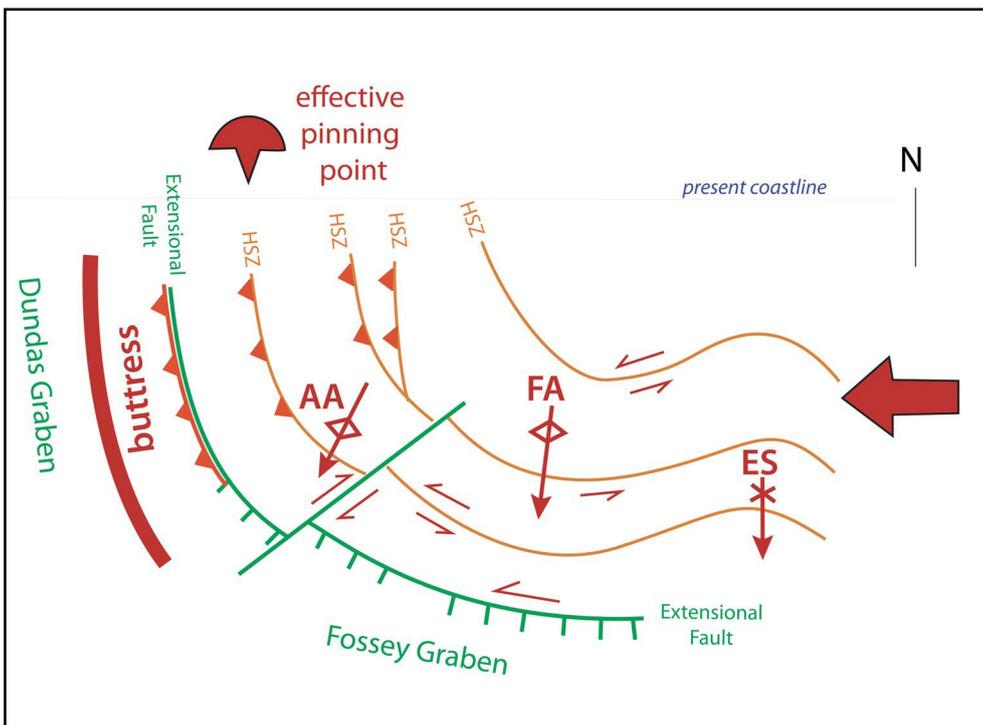


Figure 71. "Buttress" compressional fold model for the Devonian development of the Forth Anticline. Push is from the east (bold red arrow) with reactivation of both 1) the Early Cambrian high strain zone (HSZ) interfaces between the thrust sheets, and 2) the Middle-Late Cambrian extensional faults bounding the Dundas and Fossey Grabens. Note the older structures with E-W trending segments would display strike-slip movement whereas reoriented segments that become N-S trending undergo thrust/reverse fault reactivation (compare with Figure 61). AA: Abbotsham Anticline. FA: Forth Anticline. ES: Eugena Syncline

### 6.1.1 Origin of the Forth Anticline

The Devonian deformation has a significant impact on the structural geometry of Northern Tasmania (e.g. Woodward et al., 1993) and potentially on the development of the Devonian age Forth Anticline. A series of folding modes have been proposed including:

1. The mode of Devonian folding is not simple buckling but linked to a form of buttress folding and flexing against the northern extension of the mid Late Cambrian Dundas Graben (Figure 71). The position of the graben, just west of the Forth Anticline, is defined by the Middle-Late Cambrian volcano-sedimentary deposits of the Mt Read Volcanics. The graben has an apparent termination at the coastline with the eastern margin of the graben defined by a series of inferred west-dipping, mid-Cambrian normal faults that are reactivated as thrust/reverse faults. The composite, amalgamated Ulverstone and Forth Metamorphic Sheets are effectively pinned against the northern part of the Dundas Graben and undergo a tilted-pivoting clockwise rotation to produce the regional anticline-syncline pair of the Forth Anticline and the Eugena Syncline.
2. The Forth Anticline is a Devonian ramp anticline developed over a footwall ramp in the Forth Sheet (Figure 72, a1 and a2). As part of this model faults within the West Ulverstone Imbricate Zone are potential back-thrusts at the leading edge of the fold on the hanging wall flat.
3. The Forth Anticline is a Devonian ramp anticline accommodated by footwall duplexing of the Forth Metamorphic Sheet at a footwall ramp (Figure 72, b1 and

b2). As part of this model faults within the West Ulverstone Imbricate Zone are potential back-thrusts at the leading edge of the fold on the hanging wall flat.

## 7.0 CONCLUSIONS

The Forth H-G Metamorphic Sheet is the structurally lowest sheet in a separate and unique allochthonous thrust stack in northern Tasmania. The Forth Sheet has undergone subduction to ~70 km coupled with south-directed exhumation and emplacement. Structurally the Forth Sheet is distinct from, as well as being isolated from, the major Tyennan Domain Proterozoic rocks. Separated by the Dundas-Fossey Graben, the structural geometry and architecture of northern Tasmania is strongly influenced by the Early Cambrian subduction event, the Middle Cambrian rifting event of the Mount Read Volcanics and the Devonian thrust-folding event. The Forth Anticline that folds the Forth Sheet may have formed as a ramp anticline above a subsurface Devonian thrust ramp within the Forth Metamorphic Sheet at depth, as part of the extensive Devonian thrusting within northern Tasmania.

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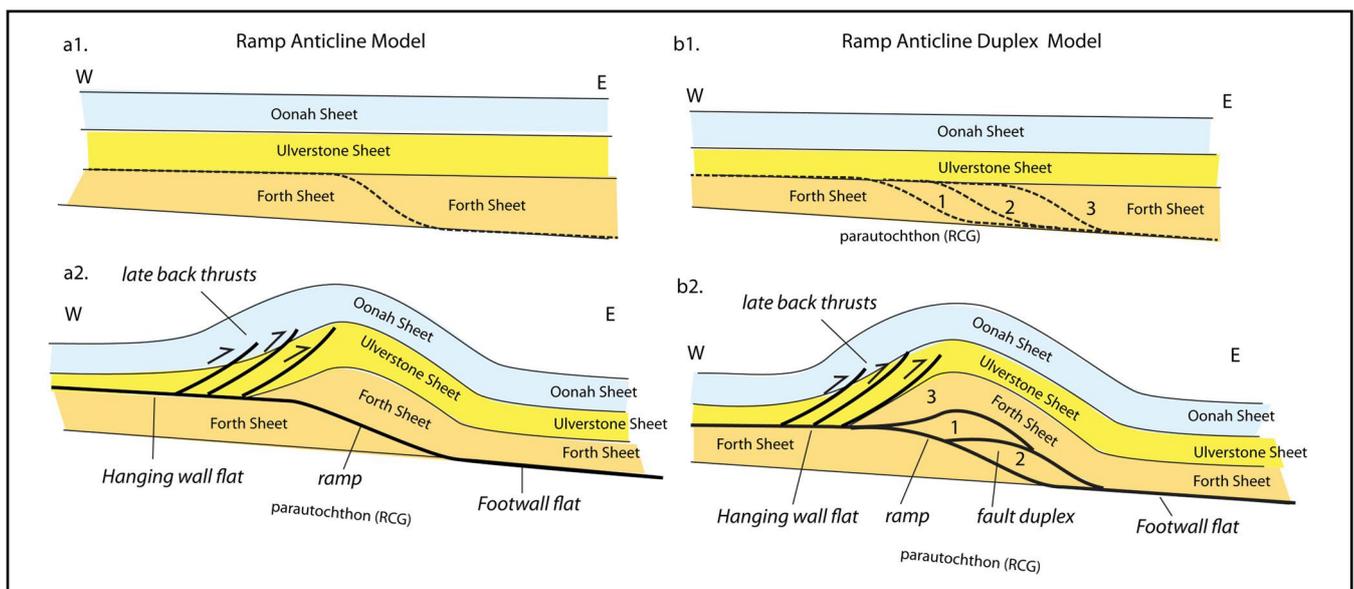


Figure 72. Thrust interpretations of the Forth Anticline influenced by Nick Woodward (Woodward et al., 1993). a) Simple ramp anticline model with the subsurface ramp in the Forth Sheet. b) Ramp anticline model as an antiformal stack above a thrust duplex developed on a footwall ramp within the Forth Sheet. Note the initial sheet stacking is a product of the Cambrian subduction and exhumation deformation at the leading edge of the Tasmanian microcontinent. Back thrusts are initiated on the hanging wall flat where the Forth Sheet enters the hanging wall flat. These equate to the Ulverstone West Imbricate Zone.

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