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Geological Survey Paper 18:

Structural Geology of northern Tasmania An Overview and Structural Synthesis

Part 3: Structure of the Luina Obduction-Thrust Sheet

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Early Cambrian bedded chert at Lodders Point west of Ulverstone. The chert (Barrington Chert) occurs along the eastern margin of the Penguin-Luina slice as a large block associated with mélange (Lodders Point Mélange) and basalt (Motton Spilite). The chert is broadly folded with an overall west-dip and is cut by cataclastic fault zones. The view is looking south from Lodders Point. It is part of a slab of obducted oceanic lithosphere made up of ocean floor derived sedimentary chert-mudstone sequences and basalt with pillows. The Penguin-Luina Slice was thrust to the SW during Late Cambrian deformation.

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Abstract

The Luina Sheet is an obducted thrust-sheet of an Early Cambrian chert-basalt ocean floor sequence, now preserved as a series of fault-bounded blocks (klippe) of greywacke, mudstone, chert and tholeiitic basalt lavas. The klippe are a series of erosional remnants representing parts of a once continuous, allochthonous sheet with a basal fault contact.

The Luina Sheet is the structurally highest thrust-sheet overlying an exhumed stack of subducted slabs of continental margin rocks of the Tasmanian microcontinent. Its emplacement represents a Late Cambrian reactivation of an Early Cambrian arc-microcontinent collision involving obduction of oceanic crust (ophiolite) preserved as ultramafic slices coupled with the Luina Sheet seafloor remnants across Western Tasmania.

The klippe are preserved within the extending parts of a Middle Cambrian basin system linked with the Mt Read Volcanics (MRV) volcano-sedimentary sequence. Remnants of the Luina Sheet from the Penguin coast southwards through Barren Knob (the Leven River-Penguin domain) are preserved within the north-south trending Dial Range Trough (graben), whereas the southeastern Devils Gate-Sheffield domain remnants occur within the east-west trending Fossey Mountain Trough (graben).

The Luina Sheet slices show elements typical of shallow level, brittle crustal deformation typified by slickensided fault surfaces and cataclasite breccia zones. Structures reflect the thrust-transport of the sheet along a basal fault, with internal deformation by brittle faulting, folding and kink band development. The folding and kink bands typify deformation within the chert and sedimentary facies, whereas the basalt shows faulting and inhomogeneous strain with cataclasite development.

Sheet emplacement kinematics determined from faults with slickensides, kink bands and fault-quartz gash veins, show that the Luina Sheet transport direction (TD) is consistently from northeast to southwest with a north-over-south sense. This TD is consistent for all sheets at all levels in the northern Tasmania "thrust" stack, including the uppermost Luina Sheet, the Oonah Sheet, the Ulverstone L-G Metamorphic Sheet and the lowermost Forth H-G Metamorphic Sheet.

Parts of the Luina Sheet (the northernmost Penguin slice) contain olistostromal sedimentary, lithic-wacke mega-breccias reflecting the seafloor depositional environment. These are breccia zones up to ~500 m in width that separate massive, kilometre-scale blocks of basalt and chert. These breccias host: 1) smaller (~10-100 m size) blocks of basalt, chert, chert-breccia blocks and laminated, silicified cherty siltstone (Beecraft Megabreccia), 2) smaller (~10-23 m size) blocks of dolomite, limestone and banded jasper-chert (Teatree Point Megabreccia), and 3) ~20-50 m scale, fault-bounded blocks of basalt, basaltic volcaniclastic rocks, black siliceous shale, green to maroon mudstone and chert in a foliated, scaly mudstone matrix.

Basal faults of the individual klippe are sub-horizontal to gently north-dipping and occur at different topographic levels. This suggests the northern Luina Sheet consists of at least two thrust sheets, an upper sheet with an ~300 m base level, and the main or lower sheet ramping from sea level at the coast to ~100 m (Leven River area) increasing to 200 m towards the south (Sheffield area). The basal fault is best observed at Barren Knob where a series of low angle, gently north-dipping faults and cataclasite breccia zones require chert thrust southwards over, or emplaced over, basalt with apparent "down-cutting" into the underlying MRV sequence. The apparent "down-cutting" reflects younger Devonian reactivation of the earlier thrust system and the Middle Cambrian extensional fault architecture of the Dial Range-Fossey Mountain Troughs (grabens).

The mapped areal distribution of the upper and lower thrust sheets of the northern Luina Sheet suggests transport and/or displacement was partitioned by transfer faults (steep lateral ramps) sub-parallel to the transport direction, with frontal ramps in the basal fault occurring at different levels in the separate or distinct sheets.

Emplacement of the oceanic Luina Sheet was from ~496 to ~492 Ma with north-over-south thrusting involving: 1) syntectonic thrust-sheet erosion and development of sedimentary breccias at the sheet leading edge, with 2) eventual overriding of breccias and incorporation with syn-MRV deposition as well as 3) intrusion into the advancing thrust sheet. The timing of the allochthon emplacement was synchronous with the development of the last phase of volcanism of the Mt Read Volcanics (Zig Zag Hill Formation) and the onset of regional compression. The Zig Zag Hill Formation, developed in the volcanic hinterland south of Luina Sheet emplacement and in contrast to the syn-emplacement sedimentary breccia in the Dial Range Trough (Sprent Formation), is largely composed of recycled volcanic material.

The group of faults responsible for emplacement of the Luina Sheet are part the newly-defined Narawntapu Thrust Belt. This thrust belt consists of north-dipping, approximately north-northwest-trending thrust and reverse faults in a zone extending from Wynyard/Doctors Rocks in the west, to Badger Head/Beaconsfield in the east. The extent of the thrust belt in the transport direction is approximately 50 km, constrained by the current position of the Mt Bischoff Klippen relative to the modern coastline. This fault system is a major element responsible for much of the structural and tectonic architecture of northern Tasmania.

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Structural Geology of northern Tasmania— An Overview and Structural Synthesis

PART 3: STRUCTURE OF THE LUINA OBDUCTION-THRUST SHEET

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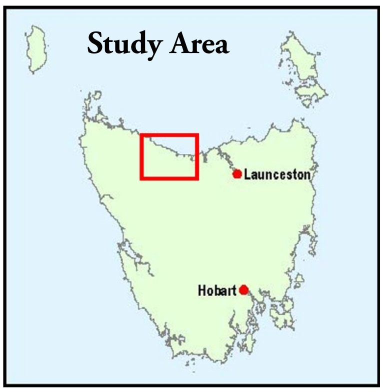


1.0 INTRODUCTION

Northern Tasmania, particularly the almost continuous coastal exposures along the north coast, provides a unique window into the structural relationships between sheets of subducted and exhumed, high-grade metamorphic rocks (Forth Metamorphic Sheet) and overlying, allochthonous, low-grade (L-G) Neoproterozoic–Early Cambrian sequences (Figure 1).

The Luina Sheet is an obducted, Early Cambrian chert-basalt ocean floor sequence (Everard and Calver, 2014)). It is the structurally highest preserved thrust sheet overlying the subducted and exhumed sub-greenschist facies Oonah Sheet, and the greenschist facies Ulverstone Sheet, both of Neoproterozoic protolith (Mulder et al., 2018) (Figures 1 and 2).

All of these sheets represent different parts of, and/or slices from, different levels of a Cambrian margin subduction and exhumation system involving arc-microcontinent collision (see Berry, 2014; Mulder et al., 2018 and Gray et al., 2023). The last phase of the collision involves obduction of the ophiolite preserved as ultramafic slices with the Luina Sheet seafloor remnants (chert-basalt association) across western Tasmania (Sproule, 1994; Everard and Calver, 2014).

This publication is the third in a series of MRT Geological Survey papers dealing with the structural character and inter-relationships of the major lithotectonic elements of northern Tasmania. Earlier MRT Geological Survey publications on northern Tasmania include GSP16 on the Forth Metamorphic Sheet (Gray and Vicary, 2026a) and GSP17 on the Ulverstone Metamorphic Sheet (Gray and Vicary, 2026b). The current paper: 1) defines and describes the structure, structural elements and structural associations of relicts of the Luina Sheet in the Penguin-Sheffield area of northern Tasmania, and 2) considers the implications of Luina Sheet structure for tectonic models (Figure 3). Details of the lithology and gen-

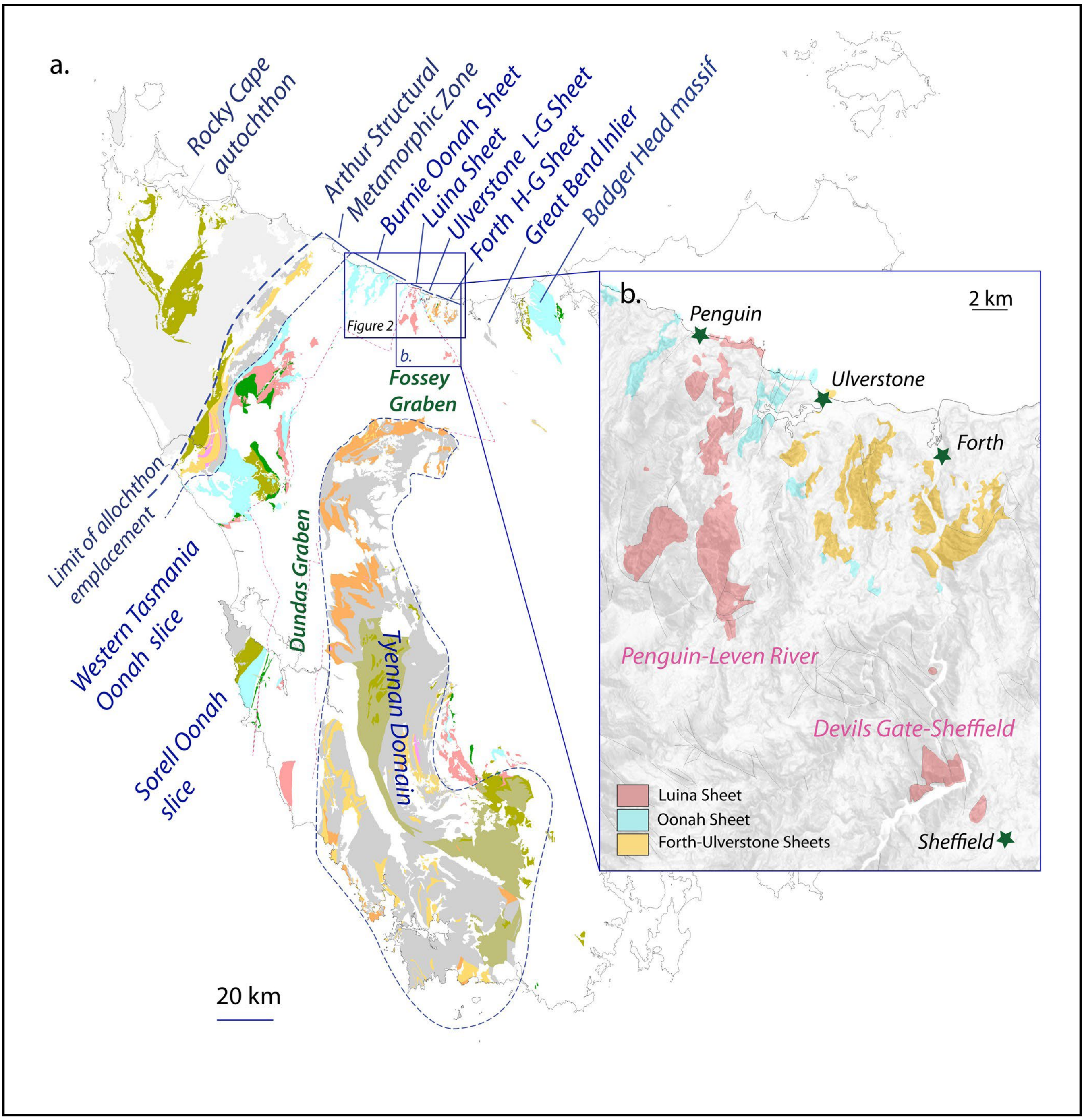


Figure 1. The major tectonic elements of western Tasmania shown in a). Map base is Mineral Resources Tasmania 1:25 000 and 1:250 000 digital geological atlas. b) Enlarged map with the location of the Luina Sheet. The approximate Luina Sheet map polygon boundaries are 5450000 mS (northern boundary), 5417000 mS (southern boundary), 415000 mE (western boundary) and 442500 mE (eastern boundary).

eral lithologic relationships of the northern Tasmanian Luina Group and correlates can be found in Everard and Calver (2014); Seymour and Vicary (2010) and Burns (1963; 1964).

2.0 BACKGROUND

Previously designated part of the Neoproterozoic Cleveland-Waratah association (Brown, 1986; Turner, 1989) the Luina Sheet is now recognised as an allochthonous thrust slice of Cambrian MORB-like basalt, chert and mudstone (Vicary, 2006; Seymour and Vicary, 2010; Everard and Calver, 2014). Remnants occur across western Tasmania (Figure 3), including the Luina type area near Cleveland Mine, the Penguin-Sheffield area of northern Tasmania, the Point Hibbs mélange belt and the Ragged Basin Complex near Adamsfield, southern Tasmania (Figure 3).

The Luina Group is defined and described by Everard and Calver (2014, p.110-120) as Early Cambrian allochthonous and parautochthonous sequences occurring as a

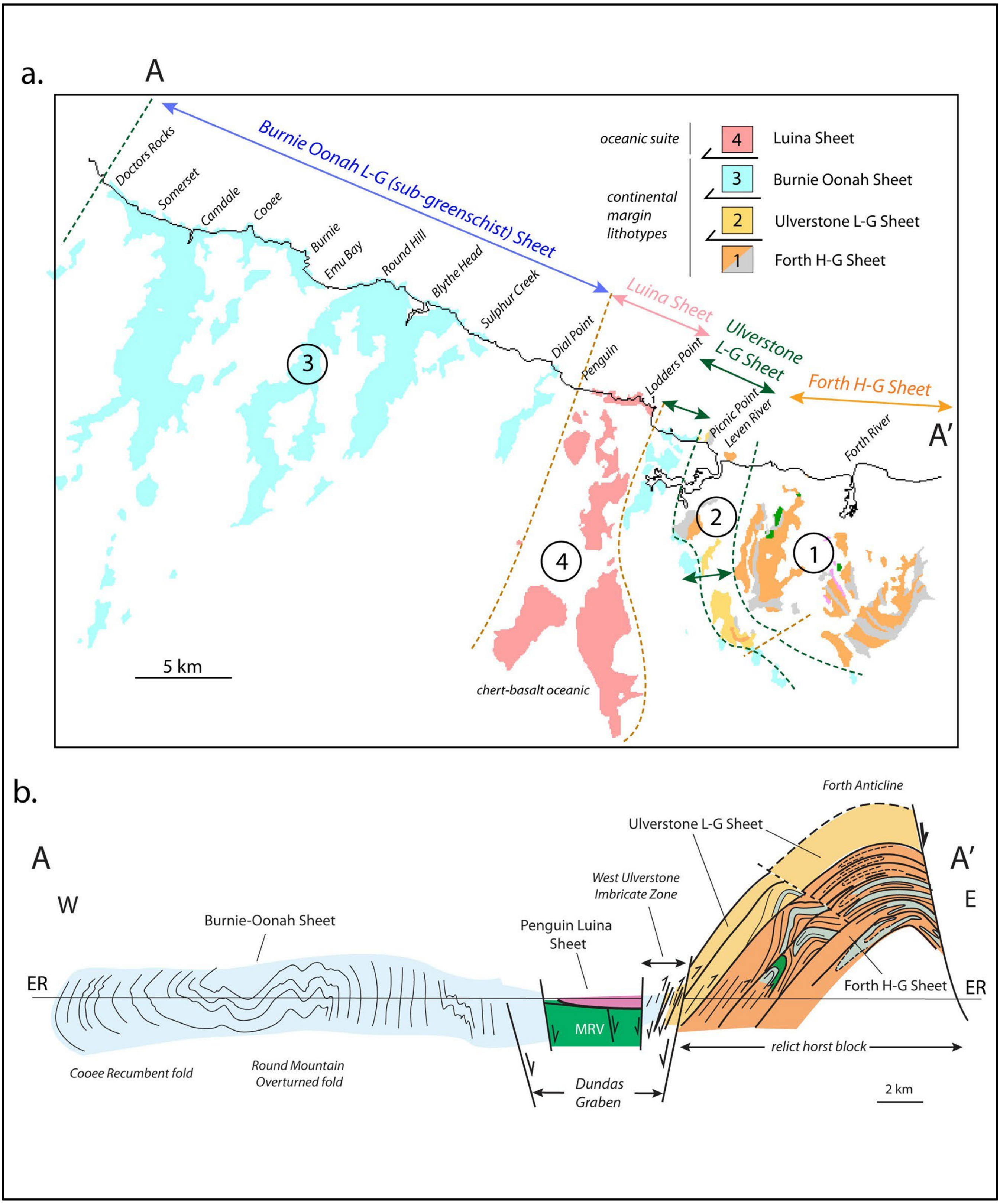


Figure 2. Simplified geological map of the north coast Proterozoic and Cambrian lithotectonic units (see Figure 1a for location). The north coast geology consists of stacked, subducted and exhumed continental margin segments including the Forth H-G Metamorphic Sheet, the greenschist facies L-G Ulverstone 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.

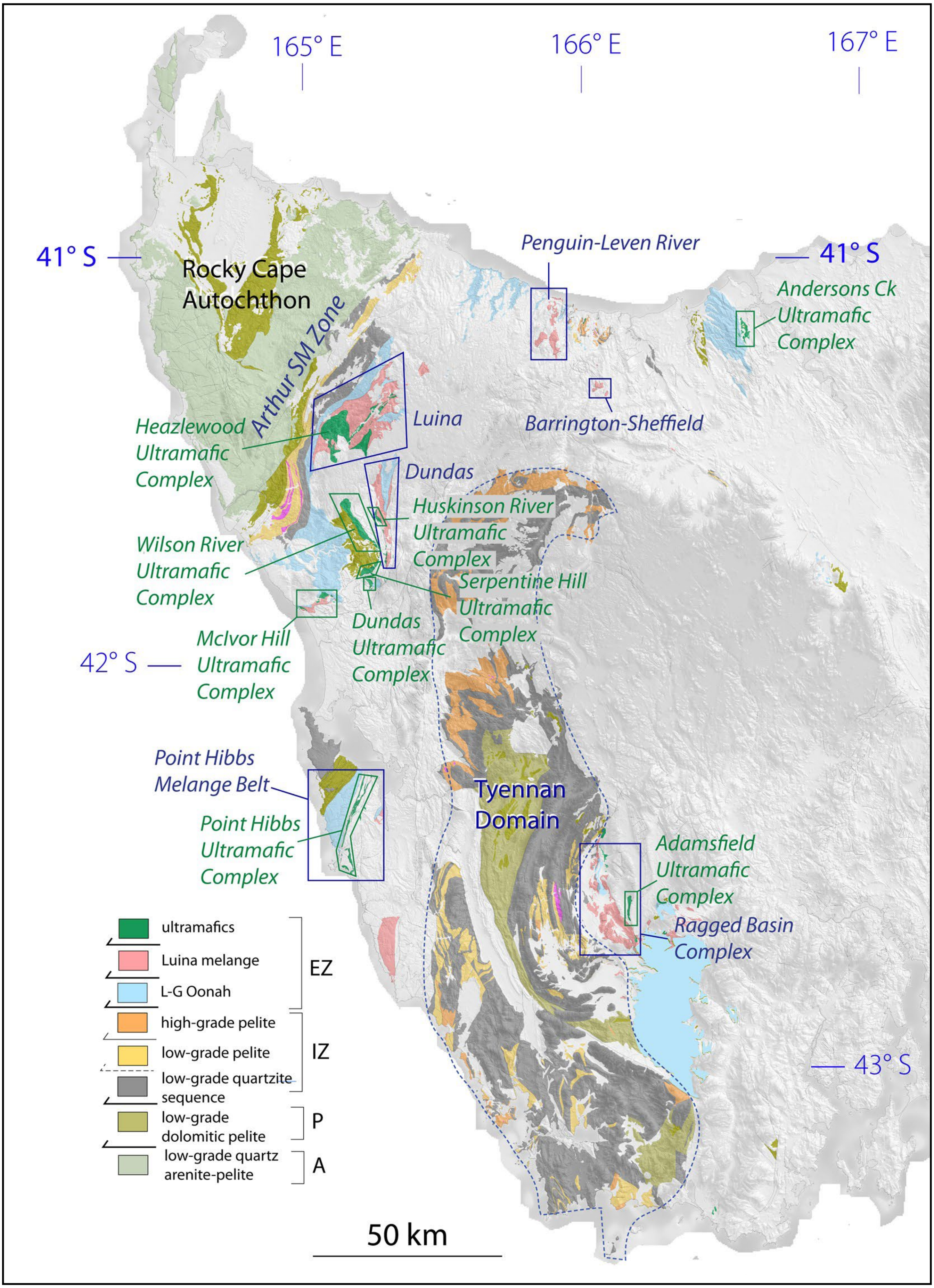


Figure 3. Simplified geological map of western Tasmania showing the fault-bound slices of the Cambrian Luina Group and correlates (blue text designations) and the associated Cambrian ultramafic complexes (green text designations). These are considered allochthonous relict slices of a once contiguous ophiolite sheet and the associated seafloor basalts and deep-water oceanic sedimentary facies, including chert, red mudstone and volcanic-lithic greywacke.

series of fault-bound blocks of sedimentary and basaltic rocks. The lithologies include: greywacke, mudstone and chert, as well as tholeiitic basalt lavas.

The Luina Group (and correlates) has been assigned a Cambrian age based on the following after Everard and Calver (2014, p.110-111):

1. intruded by feeder dykes for the boninitic and low Ti-tholeiitic lava cumulates of the Heazlewood River Ultramafic Complex that has a late igneous-phase tonalite dated at 513.6±5 Ma (late Early to Middle Cambrian; Black et al., 1997).
2. Luina Group correlate basalt (Guilfoyle Creek basalt) underlying the Middle Cambrian Yolande River sequence (Corbett, 1979, 2002).
3. the presence of Cambrian siliceous sponge spicules in the Barrington chert (Saito et al., 1989).

Pivotal elements in understanding the significance of the Luina Sheet include recognition of:

1. MORB geochemistry and the seafloor basalt affinity of the basaltic components (Sproule, 1994; Everard and Calver, 2014)), and
2. the allochthonous nature of the Luina slices with delineation of basal faults (Vicary, 2006), and the realisation it is part of the obducted seafloor-ophiolite assemblage (refs). In northern Tasmania the oceanic lithosphere (ultramafics) has been stripped off by erosion with the closest remnant ophiolite slices/fragments preserved as the Heazlewood Complex near Luina and the (Devonian-affected) Andersons Creek ultramafics near Beaconsfield (Figure 3).

Most of the erosional/structural remnants of the Luina Sheet occur from the Penguin coast southwards through Barren Knob (the Leven River–Penguin area), and are preserved within the northern part of the Middle Cambrian, Dial Range Trough (Burns, 1963 and 1964) (Figures 1 and 4). The Devils Gate–Sheffield area remnants occur within the east-west trending, Fossey Mountain Trough (Figures 1 and 4).

2.1 Lithology and Lithologic Associations

The Penguin-Sheffield remnants of the Luina Sheet consist of Barrington Chert conformably overlain by Motton Spilite (Everard and Calver, 2014). The remnants were originally considered part of, or occupied, the Dial Range "Trough" (Burns, 1964; Sproule, 1994).

The Barrington Chert is ~1000 m in thickness in the type area near Devils Gate and consists of variously coloured, well bedded or laminated chert (Jennings et al., 1979). The chert displays soft sediment slump folds, penecontemporaneous faulting, intraformational breccias and erosional interfaces. Intercalated with the chert are minor interbeds of mudstone, lithic wacke/sandstone and chert-derived conglomerate (Everard and Calver, 2014).

The Motton Spilite is generally a massive MORB-like, low-K tholeiitic basalt (Sproule, 1994; Everard and Calver, 2014). It has an estimated ~500 m thickness and has minor associated chert-derived breccia, occasional pillow lava and interbedded tuff, argillite and siltstone (Everard and Calver, 2014). The basalt is considered to have erupted in a pelagic setting either in the late stage of continental rifting or in the early stages of sea-floor spreading and was later obducted as part of the Tyennan Cambrian arc-continent collision (Everard and Calver, 2014). The geochemistry suggests there is no evidence of a subduction signature or interaction with continental crust.

2.2 Mesostructure and Kinematics

The mesostructure of the basalt and chert components of the Luina Sheet are characterised by brittle deformation, typified by slickensided fault surfaces and cataclasite breccia zones (Figure 6). The chert slices also show brittle fault-related kink bands and folds (Figure 7).

All the structural elements were used in kinematic analysis of the emplacement and internal deformation of the Luina Sheet (Figures 8 and 9).

2.3 Previous Mapping

An index map for mapping and structural data sources for the northern Tasmanian part of the Luina Sheet is shown in Figures 10 and 11.

The well-exposed, coastal section of the Luina Sheet between Penguin and Lodders Point was first mapped and described by Burns (1963 and 1964). Subsequent structural mapping of this coastline was undertaken by David Gray in the period 1988–1989, supported by an Australian Research Council (ARC) Grant (Gray, 2025).

The inland parts of the Luina Sheet have been incorporated into Geological Survey mapping undertaken by: 1) Michael Vicary in 2006 with a reinterpretation of the Castra-Kindred area (Vicary, 2006); 2) David Seymour in 2010 across the Penguin-Sheffield region as part of the MRT 1:25 000 mapping update; and 3) David Gray and Michael Vicary in 2013 as part of the Central North 3D Model Project (Gray, 2025).

David Seymour and Michael Vicary in 2010 reinvestigated the fault and broken formation zones from Penguin to Picnic Point as part of the TasExplore Project (Seymour and Vicary, 2010).

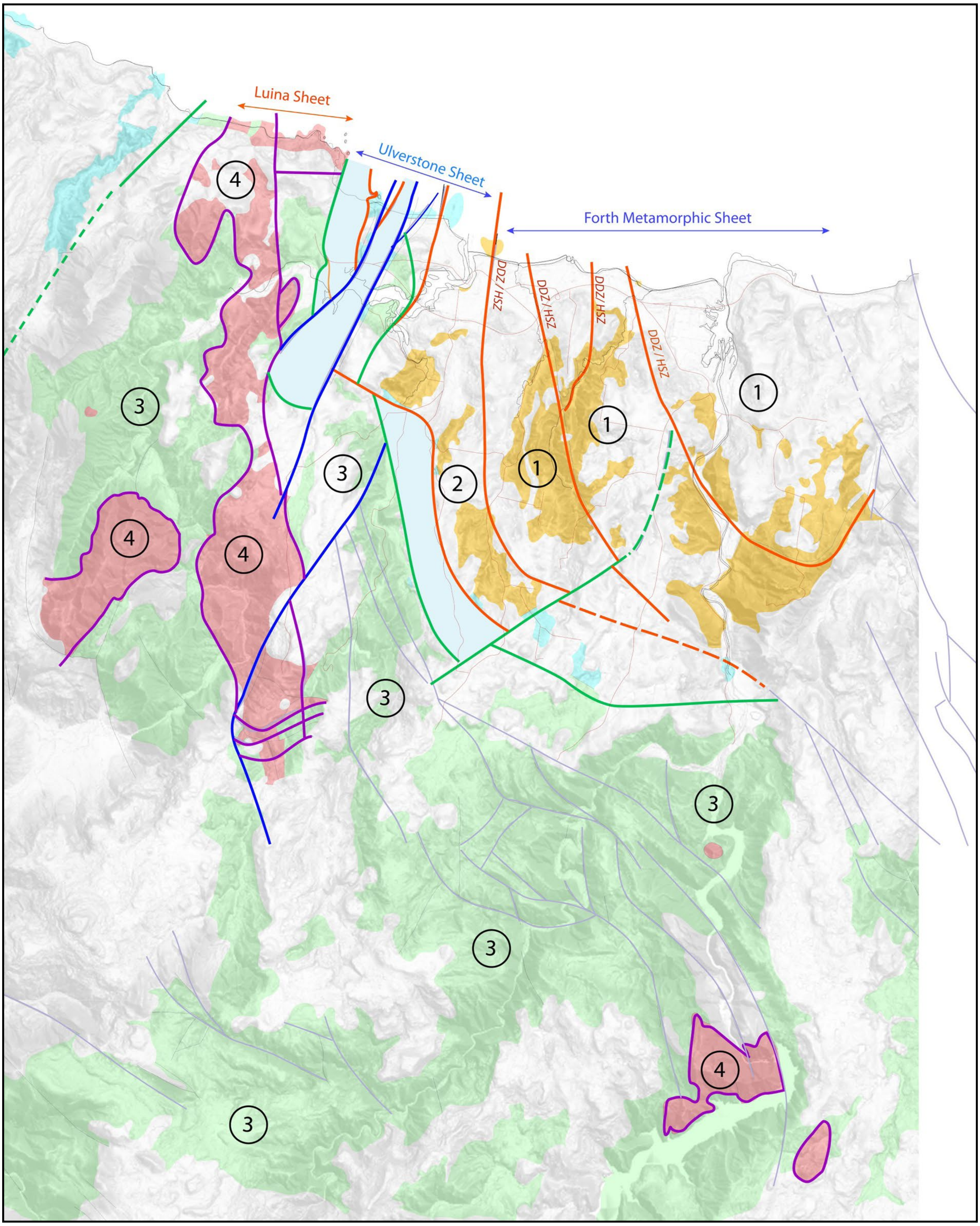


Figure 4. Lithotectonic sheet map of the Penguin-Forth-Sheffield region showing the four major lithotectonic units (black circled numbers) and the associated complex fault network. The lithotectonic units include: the structurally lowest, H-G Forth Metamorphic Sheet (pink sheet/ Unit 1), the overlying L-G Ulverstone Oonah Sheet (orange sheet/ Unit 2), the Middle Cambrian volcano-sedimentary rift sequence of the Dial Range-Fossey Mountain Troughs (pale green/ Unit 3) and the structurally highest Cambrian chert-basalt sequence of the obducted Penguin-Luina sheet (pink / Unit 4). The colour-coded fault traces include: 1) red line traces: Cambrian subduction-exhumation high strain zones (HSZ), 2) green line traces: Middle Cambrian extensional fault system, 3) purple line traces Luina sheet basal fault(s), and 4) blue line traces: Devonian reactivated Cambrian extensional faults.

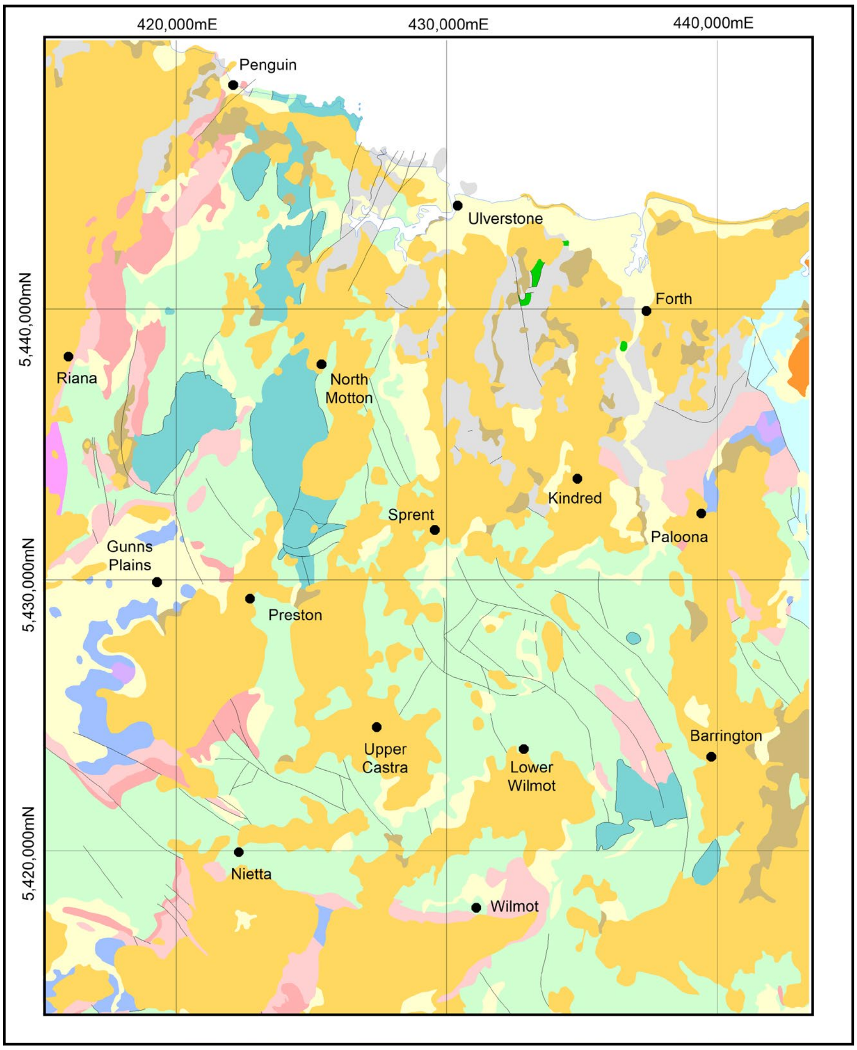


Figure 5. Geological map of the Castra Kindred area showing the distribution of Proterozoic basement rocks (grey colour units) and Early Cambrian chert and basalt remnants of the Luina Sheet (turquoise colour units). Minor Early Cambrian ultramafic rocks are shown in bright green. The lithological units of the underlying Middle to Late Cambrian Dundas-Fossey Graben system are highlighted by the pale green units and include: the Tyndall Group, andesitic and felsic lavas ± intrusives and the western volcano-sedimentary sequence. Late Cambrian to Devonian cove sequences include the Owen Group (in red), Moina Sandstone (pink), Gordon Limestone (blue) and Silurian to Devonian sedimentary rocks (pale purple). Devonian granite is shown in magenta. Tertiary basalt (orange unit) and Cainozoic sequences (yellow units) cover a large part of the region.

Figure 6. Typical brittle structural elements of the Luina Sheet. a) Brittle fault zone showing a complex, multilayered fault system with gouge and cataclasite zones. Symos Quarry, Barren Knob. b) Fault with groove type slickensides. Shackley Hill quarry. c) Folded cataclasite layering within basal fault system at Barren Knob.

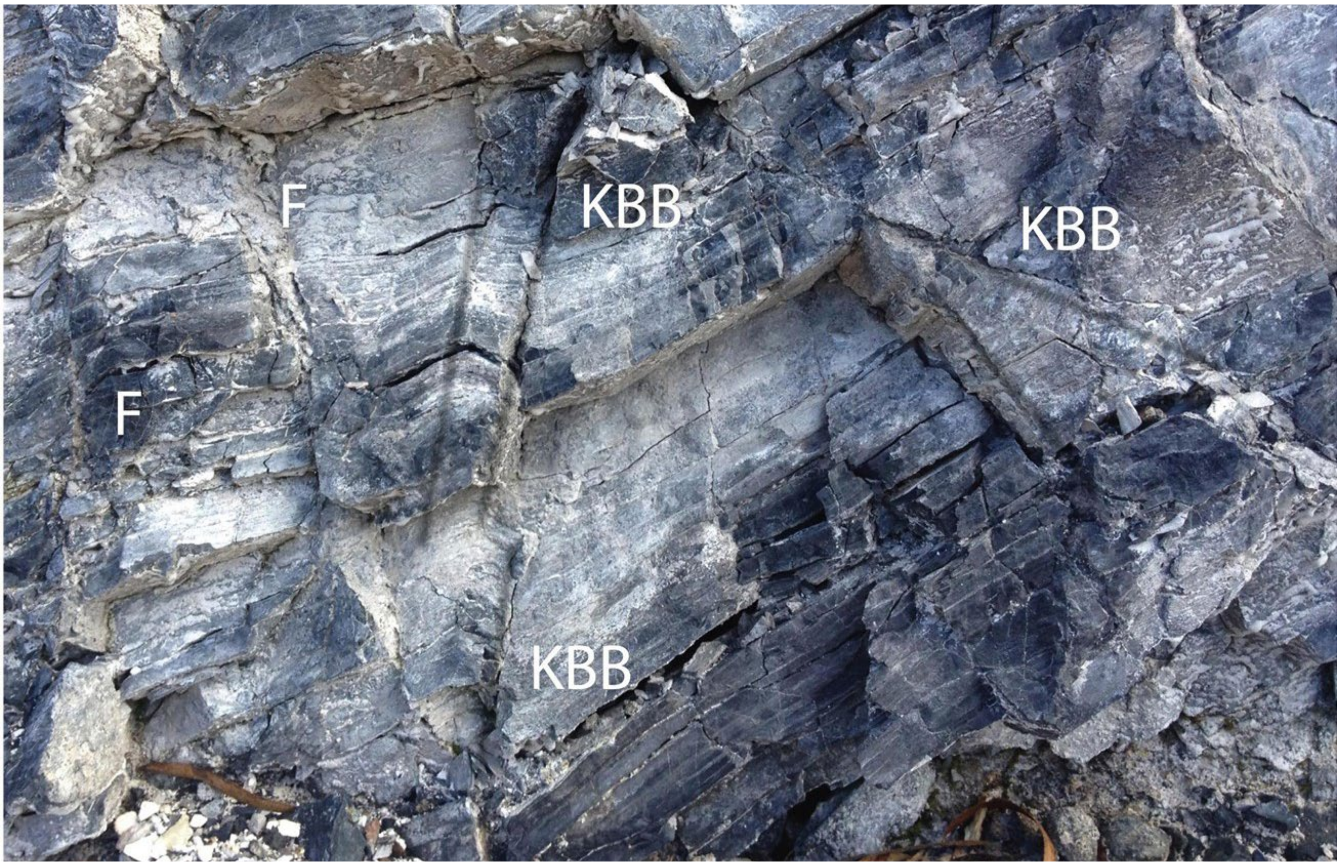


Figure 7. Typical brittle structural elements of the Luina Sheet. Brittle faults and associated conjugate kink bands. Barrington Chert exposure in Symos Quarry, Barren Knob area.

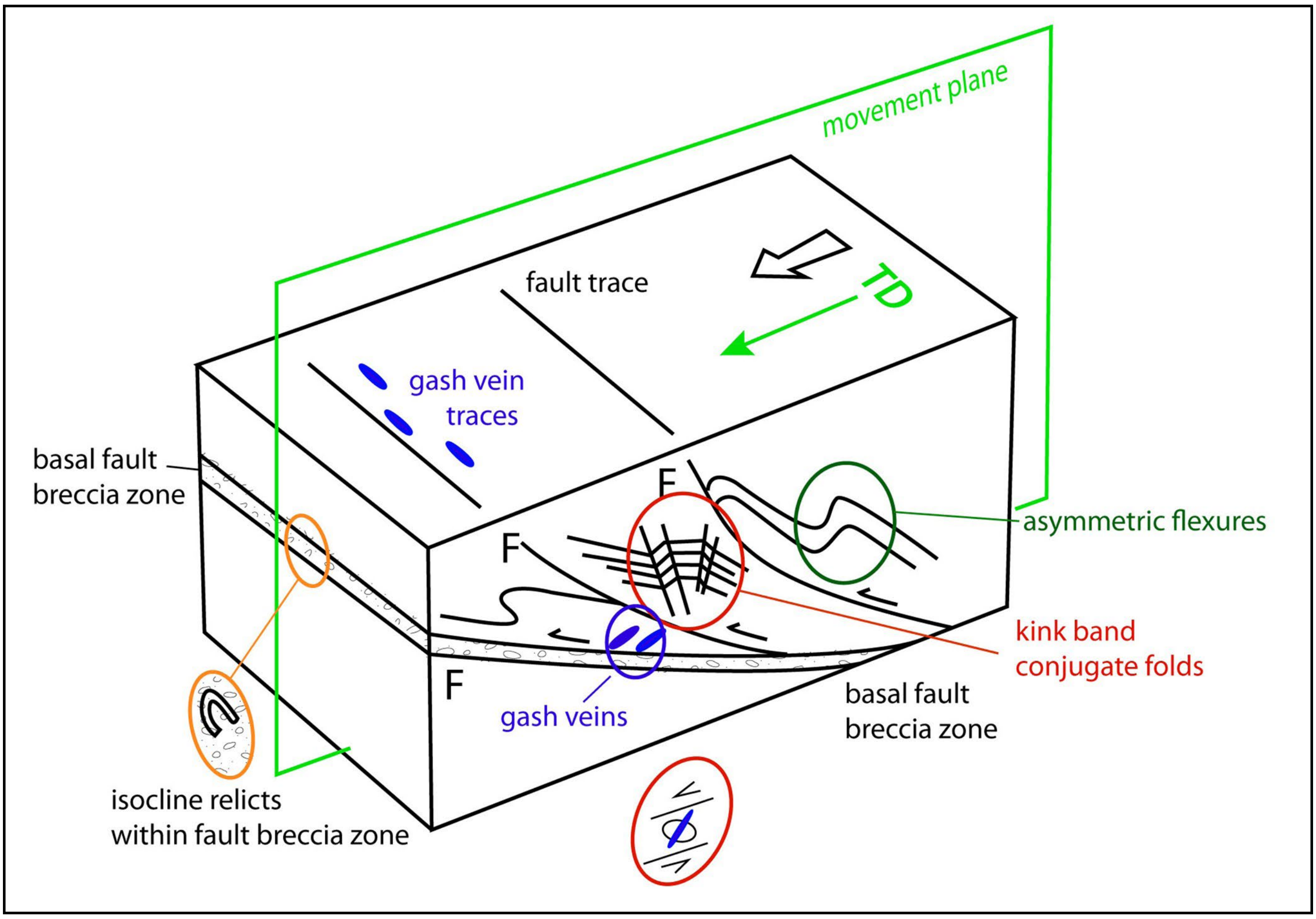


Figure 8. Schematic diagram of obduction-thrust sheet geometry and internal mesostructures, and the structural relationships used to establish the kinematics of thrust sheet transport and emplacement (see Figure 9).

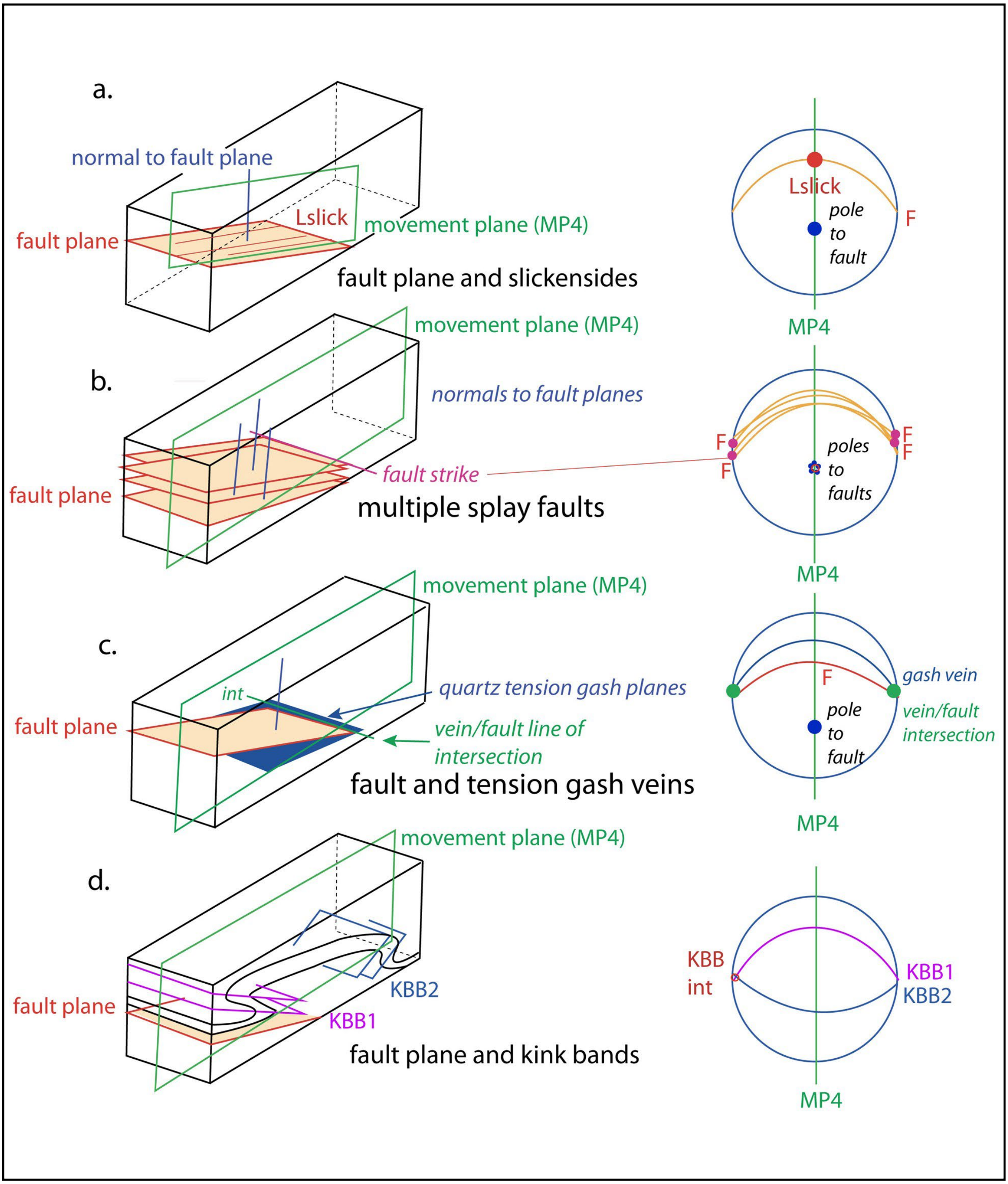


Figure 9. Kinematic Analysis of thrust sheet meso-structural elements including a) Fault and slickenside attitude data, b) fault splay population modes, c) fault and quartz tension gash veins, and d) kink band analysis. Left is block diagram of the structural element and attitude relationships. Right is stereonet of elements in the block diagram. Movement planes containing the slip direction are shown for each element. Movement planes designated as MP4 can be derived from 1) fault/slickenside data, 2) multiple faults (typically splay faults) using unimodal pole clusters, 3) vein and gash veins by determining the plane containing poles to the vein and fault, and 4) fault-related kink bands by determining the plane orthogonal to the kink band intersection are all TD vectors.

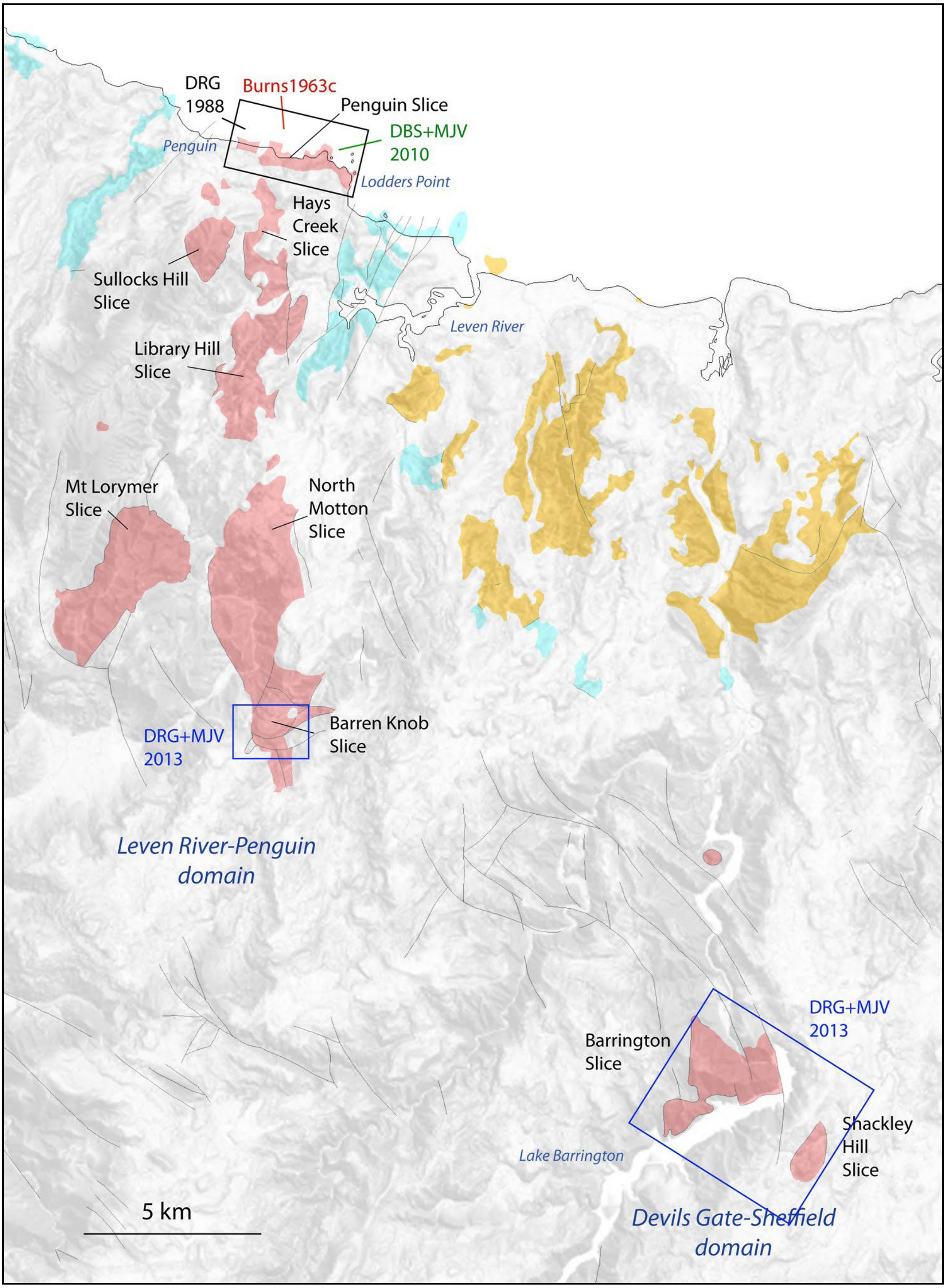


Figure 10. Structural contribution map for the northern part of the Luina Sheet (pink units) draped on a ListMap topographic base with simplified geology from the 1:25 000 digital atlas series. The Penguin-Lodders Point coastline (Penguin Slice) has been mapped by Burns (1963 and 1964), David Gray (DRG) in 1989 (see Gray, 2025), and Seymour and Vicary (2010) (DBS+MJV). Greater detail is shown in Figure 11. Vicary (2006) undertook fieldwork on the inland Luina slices in the Castra-Kindred area as part of updating the 1:25 000 digital atlas series. Further structural data and observations were collected by David Gray and Michael Vicary in 2013 (DRG+MJV) (Gray, 2025) as part of the MRT Central North 3D model construction.

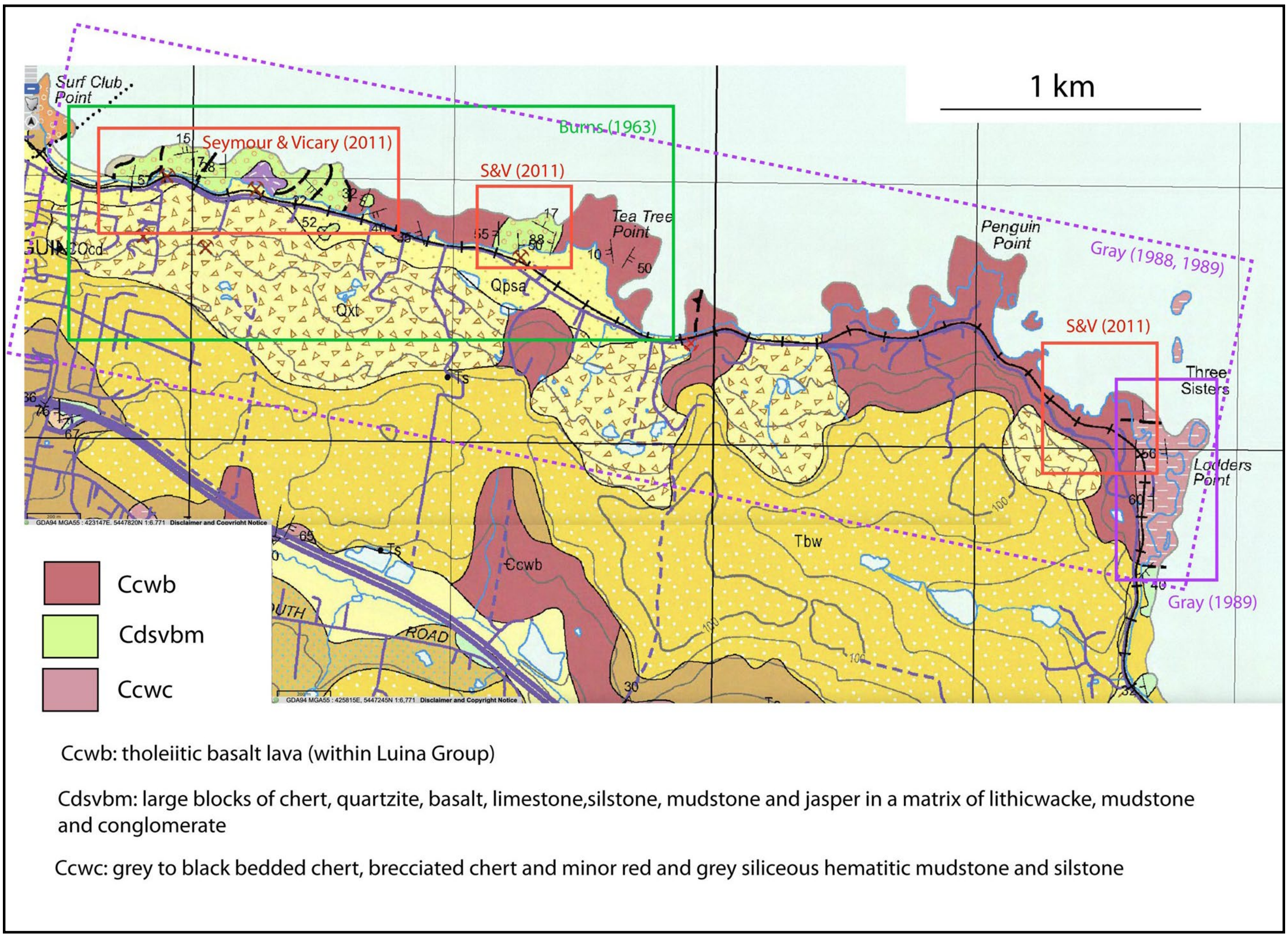


Figure 11. Mapping index for the Penguin slice of the Luina Sheet. Structural mapping by Burns (1963c) shown by the green rectangle, by Seymour and Vicary (2010) by the red rectangles and Gray in 1989 by the purple rectangle. Map units include: basalt/Motton Spilite (Ccwb), mega-breccia/melange (Cdsvbm) and Barrington Chert (Ccwc).

3.0 STRUCTURE OF THE LUINA SHEET

The Luina chert-basalt sheet occurs as a series of erosional remnants representing parts of a once continuous, allochthonous sheet (Figure 12). They are now preserved as klippe with a basal fault contact with the underlying units (Figure 13). The klippe are preserved within the down-dropped parts of the Dundas and Fossey Middle Cambrian grabens (Figure 2). The basal faults, recognised by Vicary (2006), are not always exposed.

The slices show elements typical of shallow level, brittle crustal deformation. Structures reflect the thrust-transport of the sheet along a basal fault, with internal deformation by brittle faulting, folding and kink band development. The folding and kink bands typify deformation within the chert and sedimentary facies, whereas the basalt shows faulting and inhomogeneous strain with cataclasite development.

Due to outcrop constraints, not all slices have been examined. The discussion of the Luina Sheet structure is based on observations and structural data from: 1) the Penguin slice in the Penguin-Lodders Point coastal exposure; and 2) quarry exposures for the the Barren Knob slice, the Barrington slice and the Shackley Hill slice (Figure 12).

3.1 PENGUIN SLICE

The Penguin slice is the northern-most part of the Luina Sheet. Like the Sheet proper it is a composite, largely made up of MORB-basalt (Motton Spilite) and chert (Barrington Chert) (Figure 14). Unlike other parts of the Luina Sheet, the Penguin slice also contains mega-breccia zones including the Beecraft Megabreccia, the Tea Tree Point Megabreccia (Burns, 1963) and the Lodders Point Mélange (Seymour and Vicary, 2010). The mega-breccias consist of relatively unsheared and nonfoliated, very coarse breccias not directly associated with fault zones (Burns, 1963; Seymour and Vicary, 2010).

These are variably deformed Cambrian coarse (boulder grade) blocky breccias hosted by a coarse clastic unit that varies from a bedded, commonly graded, polymict, lithic-wacke conglomerate to massive, disorganised polymict lithic breccia (Seymour and Vicary, 2010). The lithologies have a dominantly basalt and chert composition, with chert occurring as large blocks up to ~5 m in length scattered irregularly through the mega-breccias. A comprehensive description and analysis of these rocks is given in Burns (1963) and Seymour and Vicary (2010).

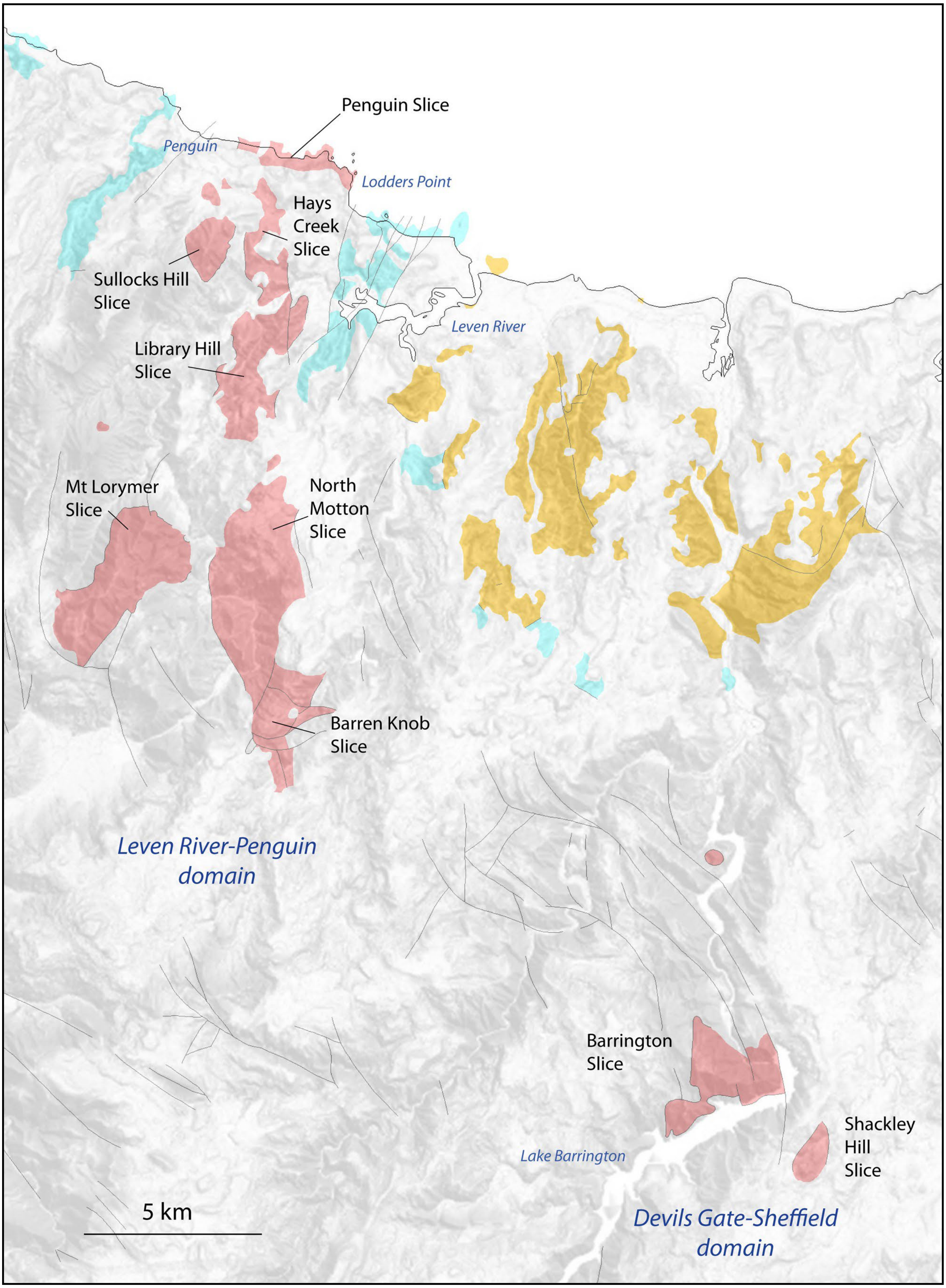


Figure 12. Northern Tasmania Cambrian basalt-chert obduction thrust sheet preserved as a series of erosional remnants (klippe) showing a northern Leven River-Penguin domain and a Devils Gate-Sheffield domain to the southeast. Map base is from the MRT 1:250 000 and 1:25 000 digital atlas series.

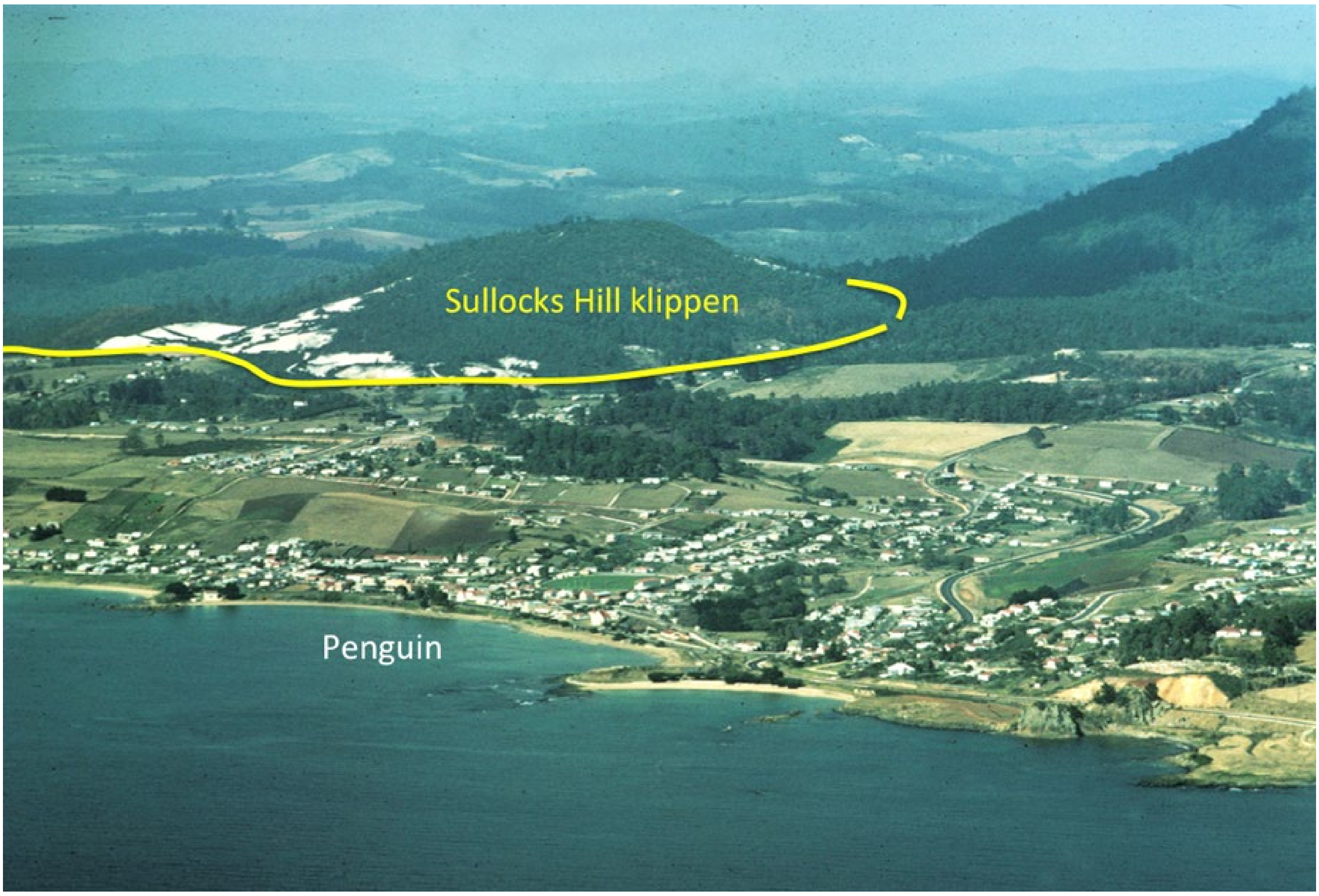


Figure 13. Photograph of the Sullocks Hill klippen of Barrington Chert taken from a helicopter in 1972. A flat lying or gently dipping thrust underlies the chert. The town of Penguin is shown in the foreground. The yellow line indicates the approximate position of the now largely hidden basal fault contact on the northern and western sides of Sullocks Hill. The basal fault has an elevation of ~100 m (see Figure 63).

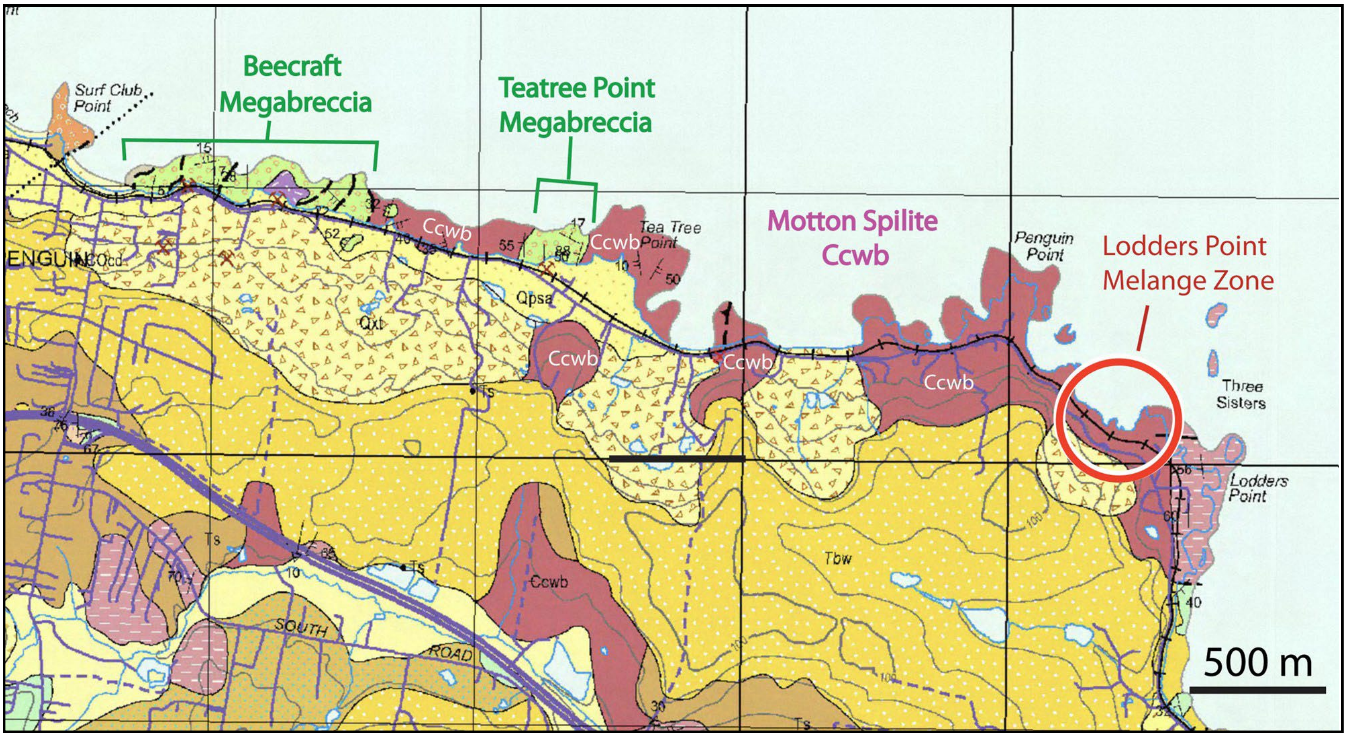


Figure 14. Penguin Luina slice lithological components exposed in coastal outcrops between Penguin and Lodders Point. Map Base is from the MRT digital atlas 1:25 000 series. The slice largely consists of basalt (Ccwb/Motton Spilite) with zones of sedimentary megabreccias and a large block of chert at Lodders Point. The megabreccias include: the Beecraft Megabreccia and the Teatree Point Megabreccia. The Lodders Point mélange is a foliated interface between the basalt and the large chert block.

3.1.1 Beecraft Megabreccia

The Beecraft Megabreccia (Burns, 1963; 1964) occupies an ~900 m zone on the western side of the Penguin Slice (Figures 14 and 15). It is a made up of lithic-wacke breccia hosting large blocks of basalt, chert, chert-breccia blocks, laminated, silicified cherty siltstone and mudstone (Figures 15, 16, 17 and 18). The megabreccia is intruded by a small (~160 m wide) felsic intrusive stock with contact aureole and dyke-like apophyses.

This intrusion is a correlate of the Lobster Creek Volcanics, dated at 495.5+/-0.6 Ma. (Vicary et al., 2015). Both contacts of the megabreccia zone are faults (Figure 15). The western part of the megabreccia, near the fault contact with the L-G Oonah Sheet, is bedded with a moderate (~40°) west dip and is west facing (Seymour and Vicary, 2010). The western boundary fault (designated the Penguin Fault) is gently (~25°–30°), east-dipping with occasional steep (~60°) dipping, potentially reactivated, segments (Figure 19).

Minor faulting occurs within the breccia as a series of ~30–100 m spaced northeast-trending steeply dipping faults (black line traces Figure 15) and cataclasite zones (Figure 18).

3.1.2 Tea Tree Point Megabreccia

The Teatree Point Megabreccia is an ~225 m wide zone (Figure 20) of blocky, coarse-grained clastic rocks dominated by chert-rich lithic wacke (Figure 21a, c), commonly graded (Figure 21b), and lithic conglomerate-breccia wacke (Burns, 1963; Seymour and Vicary, 2010). The mega-breccia zone is enclosed by basalt (Motton Spilite) on both the west and east along irregular "non-faulted" contacts, although the eastern contact is partially faulted (Figure 20).

The megabreccia contains large (~10–23 m size) blocks of dolomite, limestone and banded jasper-chert occupying the western, less bedded part and an ~10 m block of basalt in the eastern part (Figure 20). Slump folding (Figure 22), crumpling and brecciation are common within the zone and are considered evidence of soft-sediment deformation (see discussion in Seymour and Vicary, 2010, p.15).

Conjugate gash-vein array kinematics within the greywacke host of the Teatree Point megabreccia reflect an ~068°-248° (magnetic) shortening within the breccia zone (Figure 23).

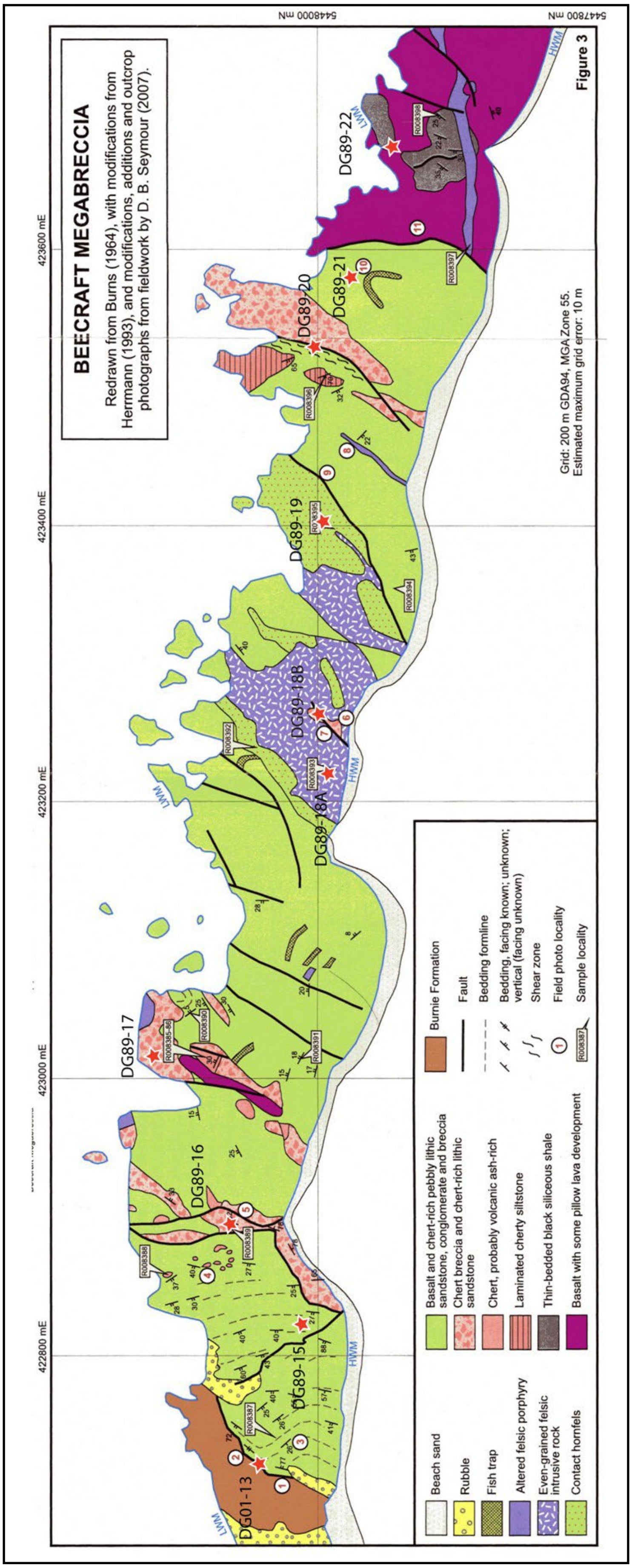


Figure 15. Map of the Beecraft Megabreccia (pea green colour unit) dominated by basalt and chert-rich pebbly lithic wacke, conglomerate and breccia (from Seymour and Vicary, 2010, fig.3). The mauve area represents the felsic intrusive hosting the historic Penguin Mine. The locations of DG89 and DG01 field stations are shown by the red stars.

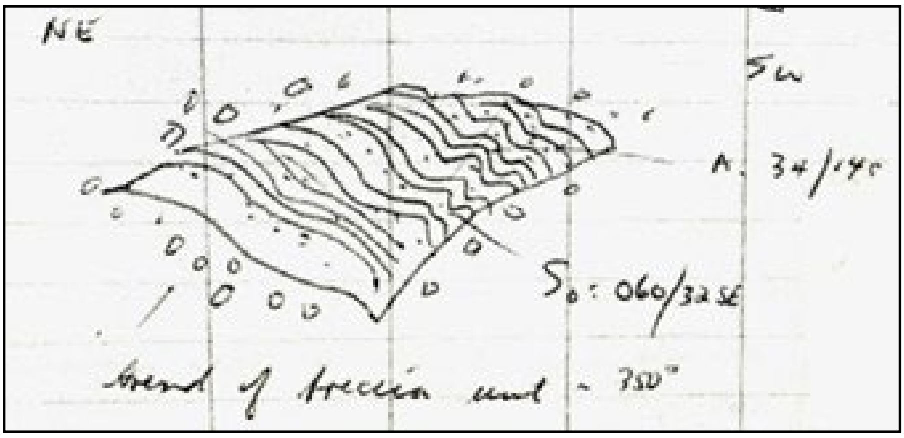


Figure 16. Sketch map of large silicified sandstone (orthoquartzite) block within the Beecraft Megabreccia. Station DG89-16 (see Figure 15 above for location). The block has internal bedding trending 060°/32°SE (magnetic) that is folded about southeast-plunging open folds (34°/140° magnetic).

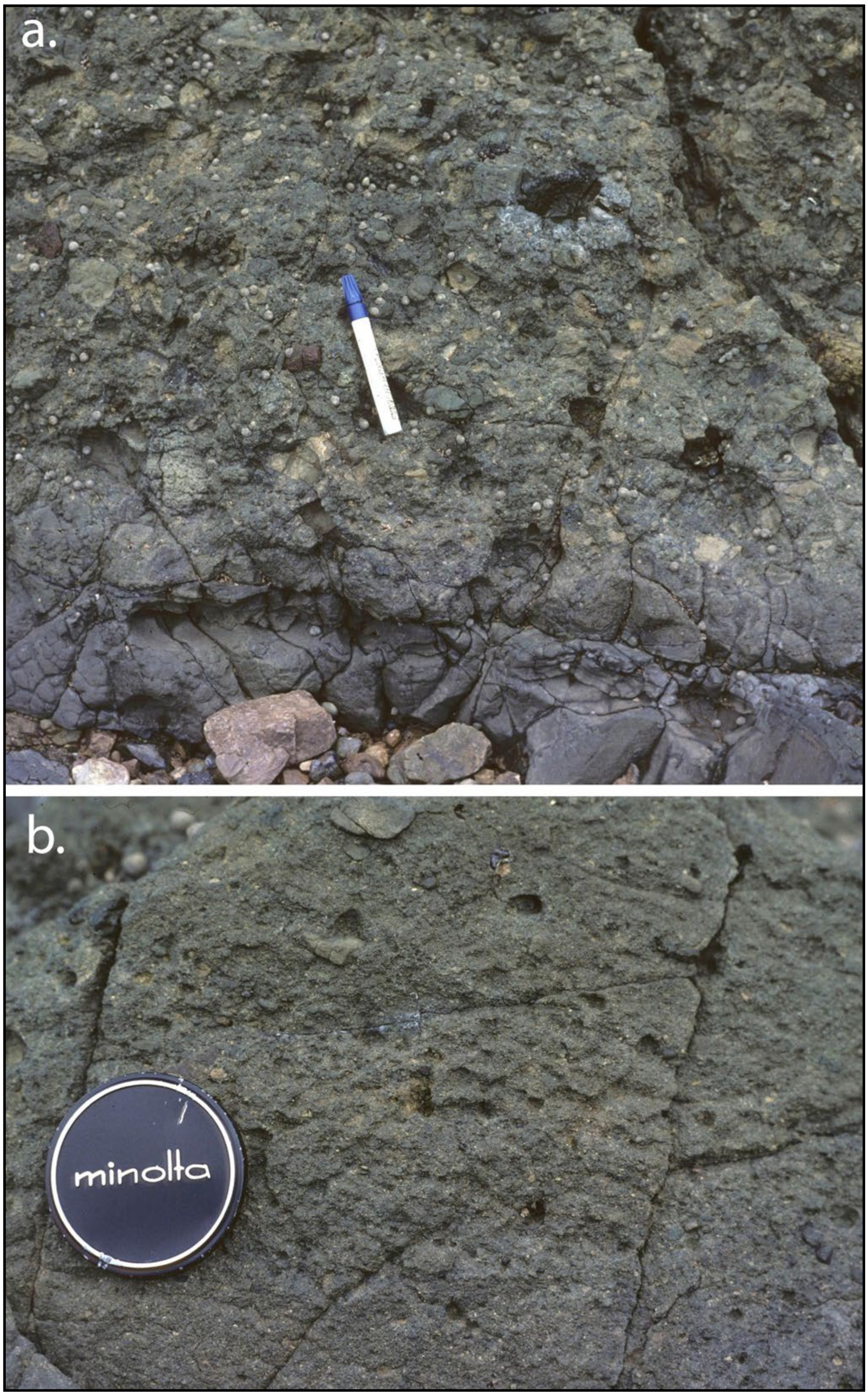


Figure 17. Mudstone and lithic wacke lithologies of the Beecraft Megabreccia, Penguin foreshore. a) Mudstone-matrix-supported conglomerate (sedimentary "breccia") transitional into bedded mudstone. b) Coarse, sandy lithic wacke with occasional, small pebble-sized clasts/ fragments.

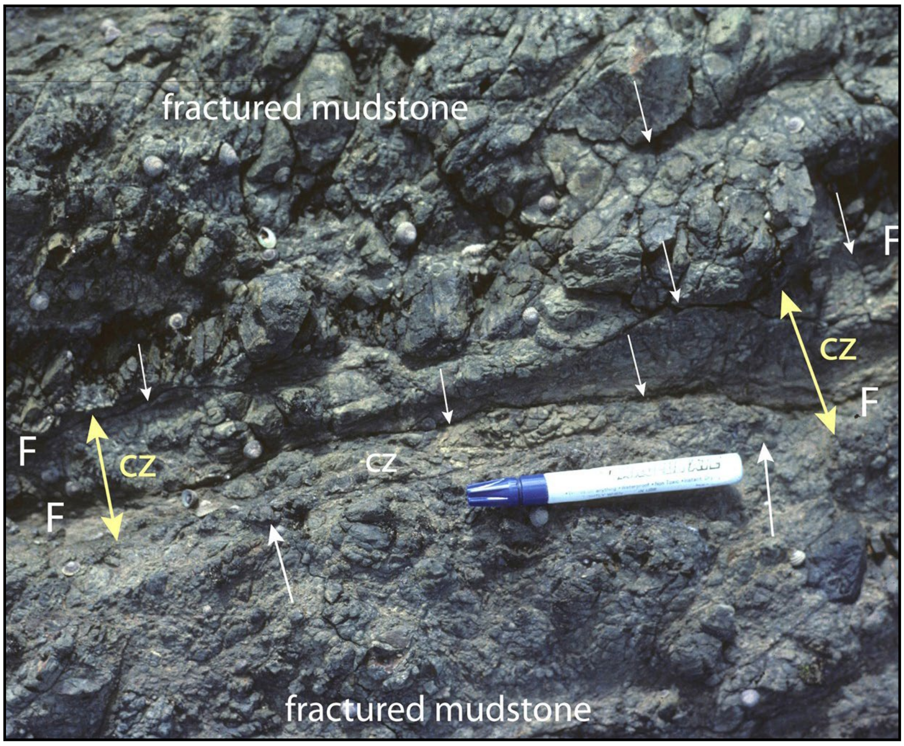


Figure 18. Brittle faulting within the Beecraft Megabreccia on the Penguin foreshore. Cataclasite zone and bounding brittle faults within fractured mudstone. F: fault. CZ: cataclasite zone.

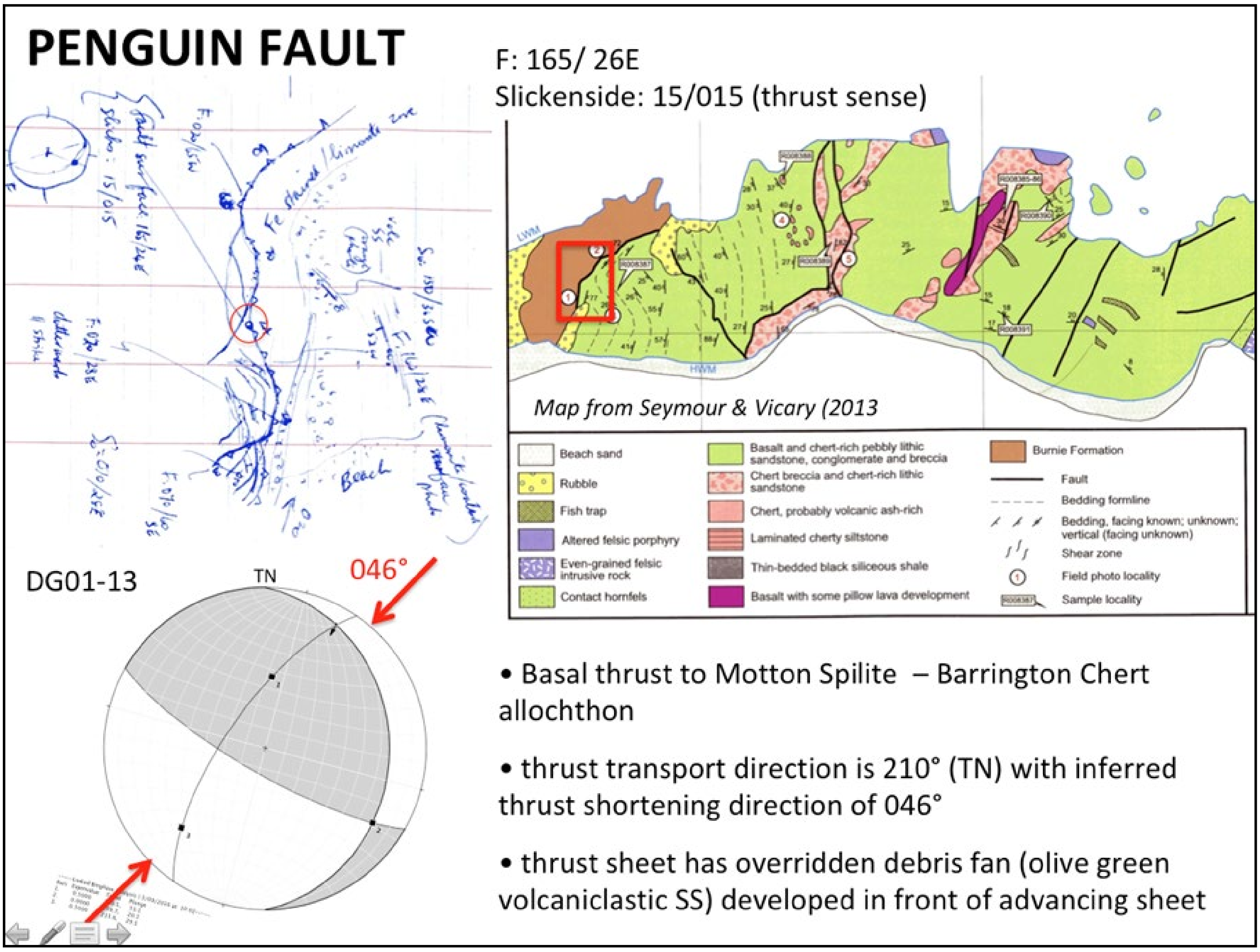


Figure 19. Upper left: Field sketch map of the Penguin Fault (blue barbed trace) showing curved or scallop-shaped fault segments on the wave-cut platform. The red circle position is the location of the fault plane with slickenside data (F: 165°/24° E with slick: 10°/015° magnetic). Station DG01-13. Upper right: Portion of the Seymour and Vicary (2010, fig.3) map with the red rectangle showing the location of the sketch map. Lower left: Faultkin[TM] stereonet of the fault data from the position designated by the red circle. The fault kinematics give a movement plane MP3 of ~046° (TN).

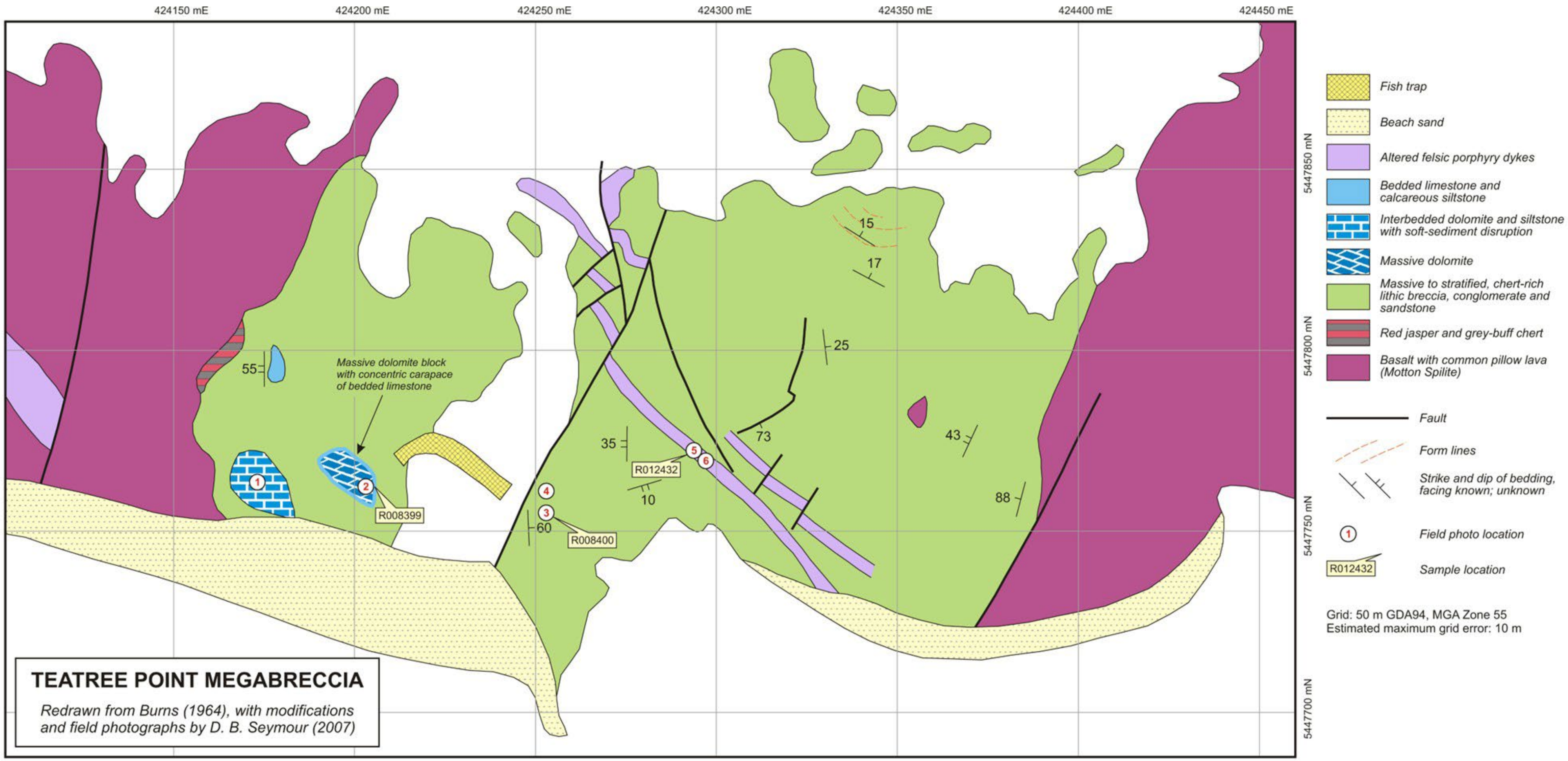


Figure 20. Map of the Teatree Point Megabreccia showing large blocks of limestone, dolomite, chert and basalt (fig.6 from Seymour and Vicary, 2010). Black lines are brittle faults and/or thin (<50 m) cataclastic zones. The nature of the western and eastern contacts with basalt have irregular form and do not appear substantially faulted. Bedding where present in the eastern part of the zone has variable dip and dip direction.

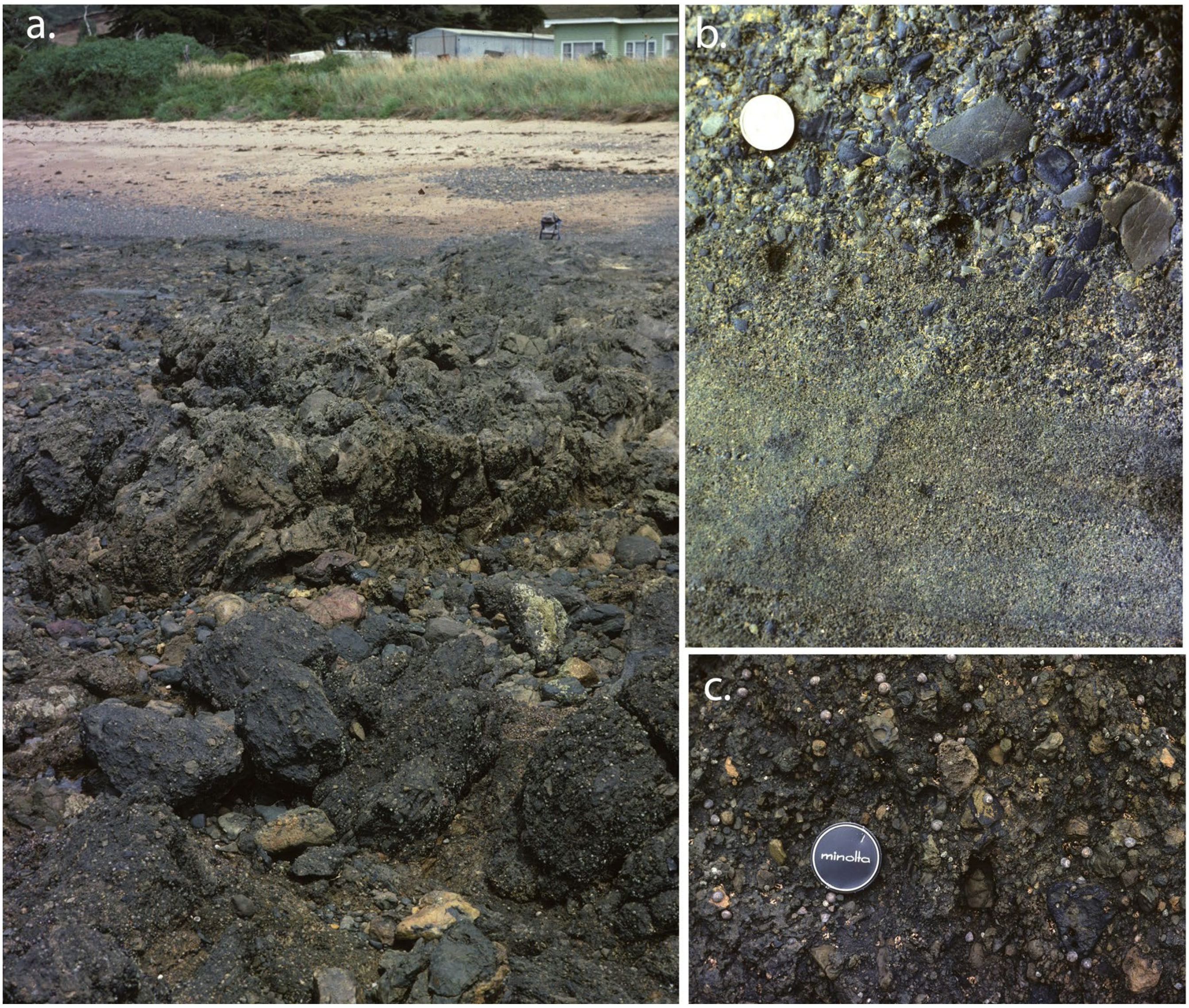


Figure 21. Teatree Point Megabreccia (photos taken in 1989). a) Fault or cataclasite zone (middle of photo) within the intermixed lithic wacke and lithic wacke conglomerate host. b) Graded bedding with lithic wacke sandstone transitional into lithic wacke conglomerate. c) Poorly sorted conglomerate and/or breccia rich in chert clasts.

Figure 22. Slump fold within thin-bedded siltstone within the lithic wacke host of the Teatree Point Megabreccia with discrete or separate blocks separated by apparent fault-like discontinuities. The hinge of the slump folds is 37°/255° (magnetic) and the lower limb attitude is 020°/69°NW. Within the slump fold hinge there is a weak axial surface reticulate cleavage.

3.1.3 Basalt (Motton Spilite)

The Motton Spilite (Burns, 1963; 1964) has generally massive character with associated volcanic breccia and local pillows (Scott, 1952; Sproule, 1994; Seymour and Vicary, 2010). It has an ~500 m thickness and contains rafts of chert, maroon mudstone and siliceous shale as large blocks within the basalt (Figure 14). It shows an apparent foliation in parts (Figure 24a) and contains ferruginised chert zones (Figure 24b). Fault surfaces within the basalt are commonly chlorite-coated and reflect east-west shortening (Figure 25).

3.1.4 Lodders Point Mélange

The eastern boundary of the Motton Spilite, within the Penguin-Luina slice, is the Lodders Point Mélange, an ~190 m wide contact zone of coarse blocky mélange (Figure 26). The mélange separates the Motton Spilite from a large block (380 m, but up to 1 km in length including Three Sisters Islands) of Barrington Chert (Figures 26, 27 and 28). The mélange consists of large (20 m to 50 m scale), fault-bound blocks of basalt, basaltic volcaniclastic rocks, black siliceous shale, green to maroon mudstone and chert in a foliated, largely scaly mudstone matrix (Figures 29, 30 and 31). Overall the bedding within the mélange -blocks, and within the Barrington Chert is moderately to steeply, west-dipping (Figures 28 and 29).

3.1.5 Lodders Point Chert Block

The easternmost extent of the Penguin slice of the Luina Sheet coincides with the ~380 m long, north-northeast-trending Lodders Point Chert block (Figures 26 and 27). The chert body is predominantly west-dipping (DG89-50B stereonet, Figure 27), but is broadly folded (DG89-50A upper right stereonets, Figure 27). The folding is dominated by a south-plunging, polyclinal fold set (Fold FA_AS stereonet, DG89-50A, Figure 28). Rare, early, tight to isoclinal folds within the bedding of the chert (Figure 33a) are also folded by these folds (Figure 32 and 33b). Polyclinal conjugate folds in the southern part of the chert block (Fold FA-As stereonet, DG89-46, Figure 28) show northwest and west-southwest fold plunges and indicate an 050°-230° shortening component.

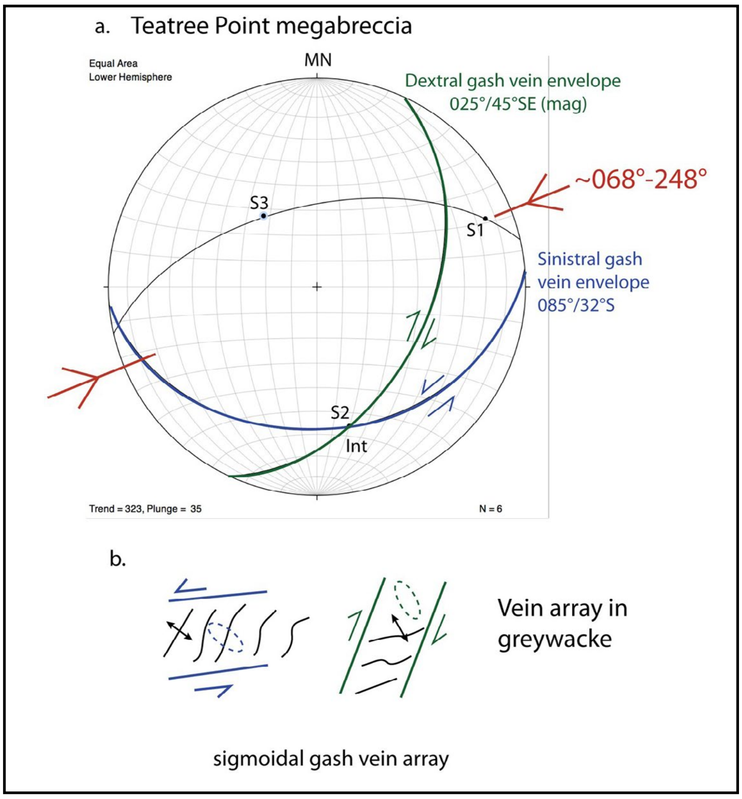
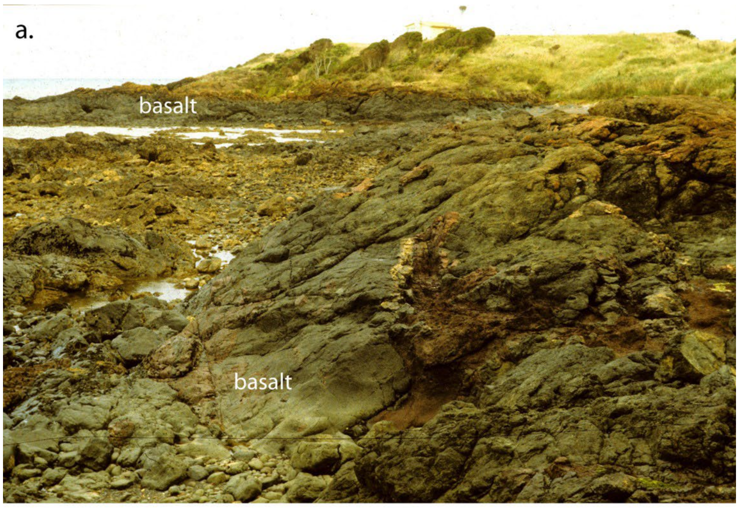


Figure 23. Conjugate gash-vein array kinematics within greywacke host of the Teatree Point megabreccia. Station DG89-28. a) Stereonet showing great circle traces of the envelopes to the dextral (green trace) and sinistral (blue trace) gash-vein arrays shown in (b). The envelope intersection represents the pole to the S1-S3 plane. The sigma1 (S1) direction is ~068°-248° (magnetic). b) Field sketch of the vein arrays showing shear sense and vein opening directions (black arrows) for each gash vein set.



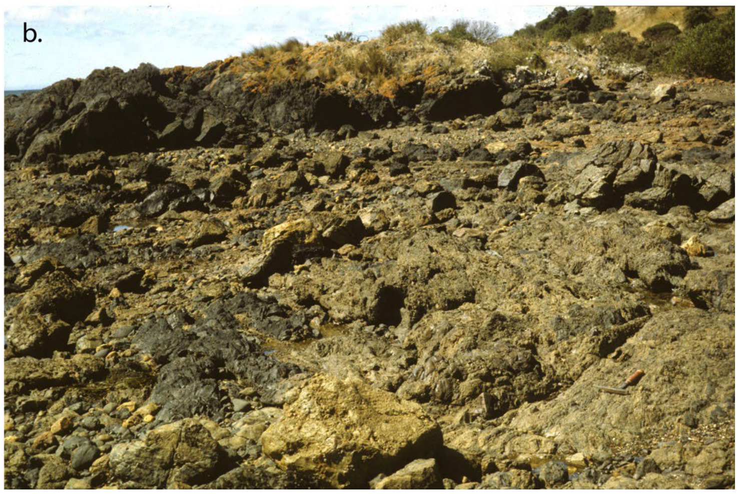


Figure 24 (Right). Photographs of basalt within the eastern part of the Penguin slice of the Luina Sheet. Penguin Point is in the background. a) Typical basalt (Motton Spilite) with ferruginised cherty zones and an apparent gently north-dipping, flaser-like foliation. View is to the east, west of Lodders Point. b) Contact between massive basalt (top of photo) and basalt breccia (lower part of photo) on the western side of the Lodders Point Mélange zone (see Figure 26).

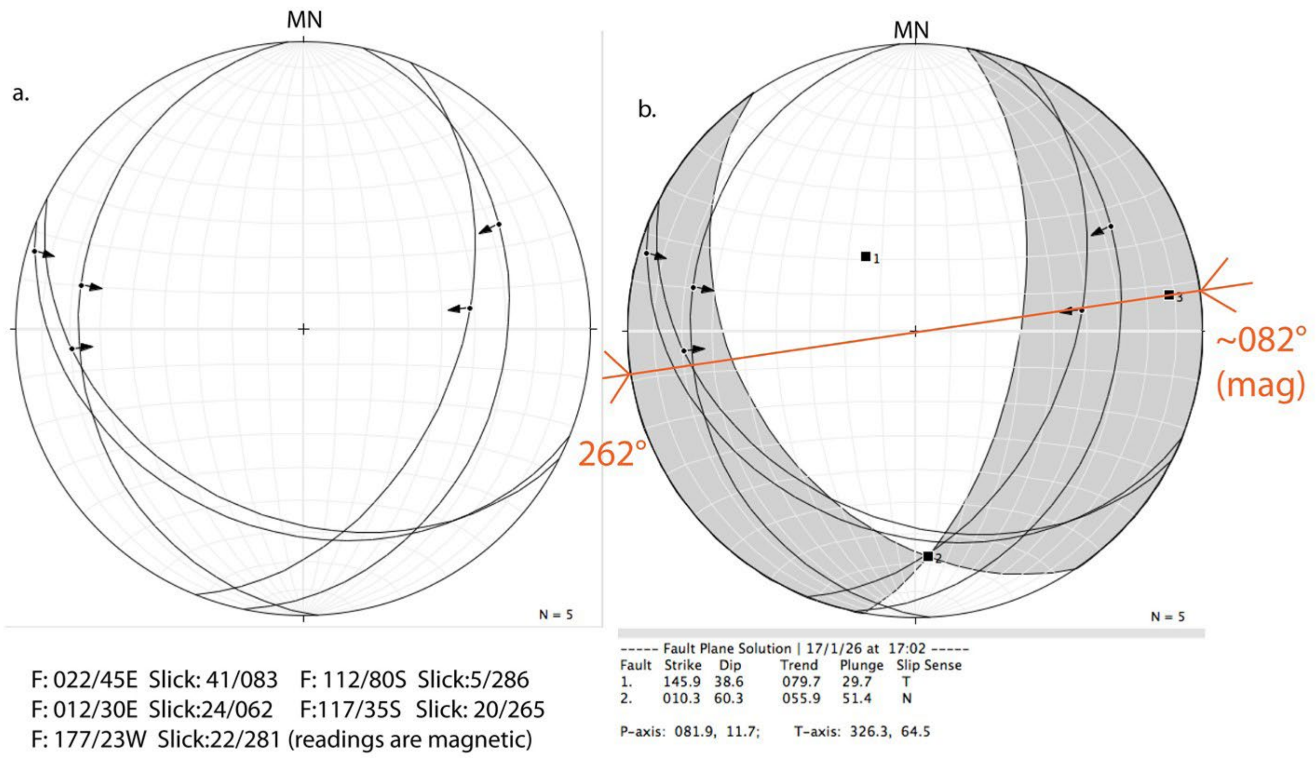


Figure 25. Fault and slickenside data for chlorite coated fault surfaces within the basalt (Motton Spilite). a) Stereonet of fault great circle traces with slickenside attitudes. b) Faultkin™ stereonet showing an 082°-262° bulk rock shortening within the basalt.

North-, northwest- and east-west-trending brittle faults (Fault stereonet, DG89-50A; Figure 28) cut and segment the chert block (Figure 32). Kinematic analysis of faults from the DG89-50A area, including the Lodders Point Mélange zone (Figure 28), indicate two episodes of faulting. Some faults show an ~080°–260° shortening direction reflecting the Cambrian emplacement event, whereas other faults show an ~345°–155° shortening typical of the younger Devonian, overprinting event (compare with Figure 159, Gray and Vicary, 2026b).

3.2 Barren Knob Slice

The Barren Knob slice of Barrington Chert is fault-bound, with a tongue-shaped body of chert (Ccwc in Figure 34). It is cut by four, low-angle, moderately to gently north-dipping faults with the basal fault requiring chert thrust southwards over, or emplaced over, basalt (Ccwb) of the Motton Spilite, thrust over the Cambrian volcano-sedimentary sequence (pale green unit in Figure 34). Some of the thrust faults within the chert truncate and offset the basal fault of the Barren Knob slice. They therefore cause structural repetition within the footwall to the Barren Knob slice, including basalt of the underlying North Motton slice (maroon Cwcb) and the structurally lower Cambrian volcano-sedimentary sequence (pale green Cdsvgs and Cdsvgg) of the southern part of the Dial Range Trough (Figure 34). The western contact between the chert of the Barren Knob slice and the basalt of the North Motton slice (Cwcb) is a sub-vertical, north-northeast-trending lateral ramp, or transfer fault. Structural data and observations were collected in three quarries located in the southern or frontal part of the chert slice (Figure 34).

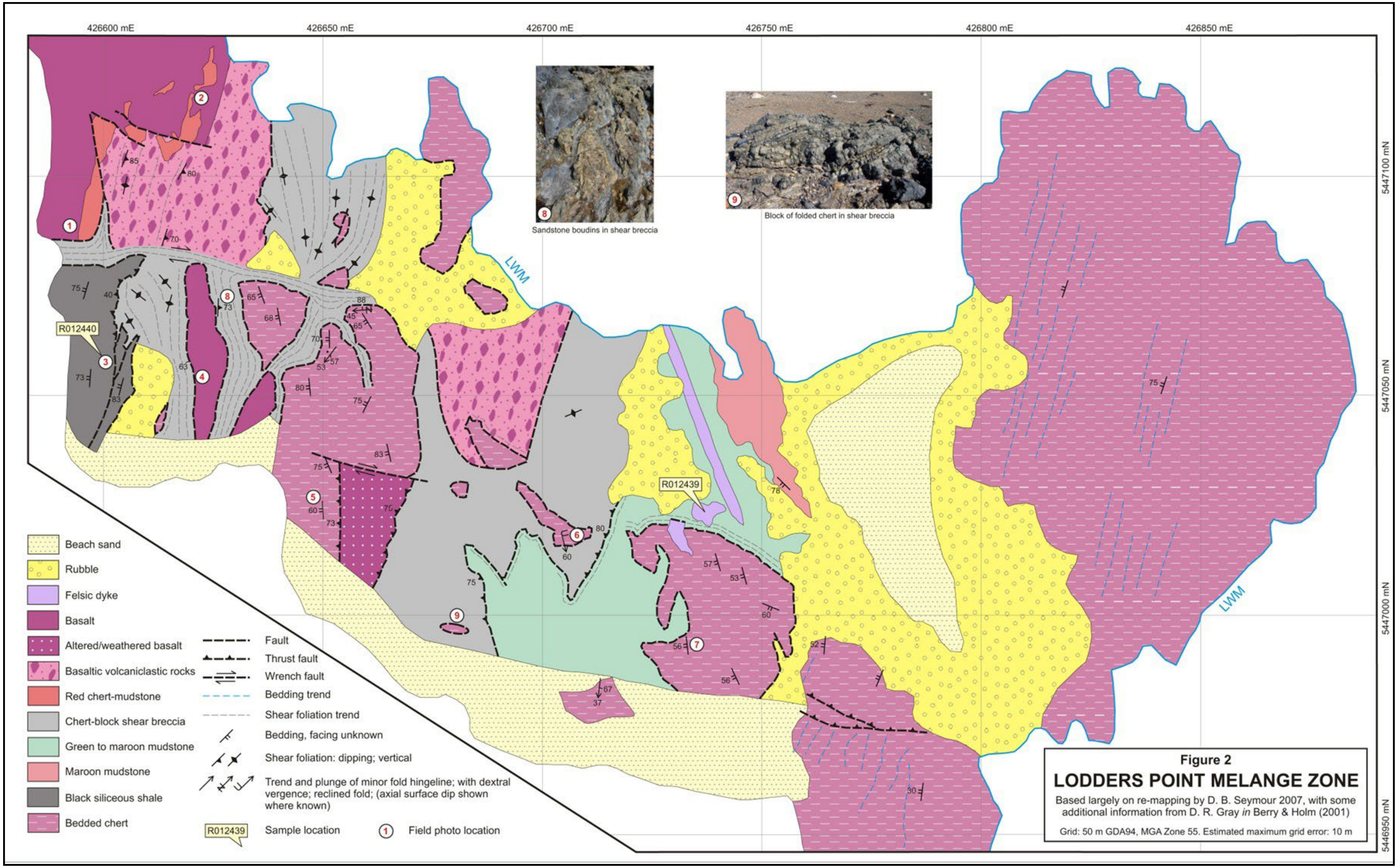


Figure 26. Map of the Lodders Point Mélange zone (from Seymour and Vicary, 2010, fig. 2). Compare with sketch map shown in Figure 29b.

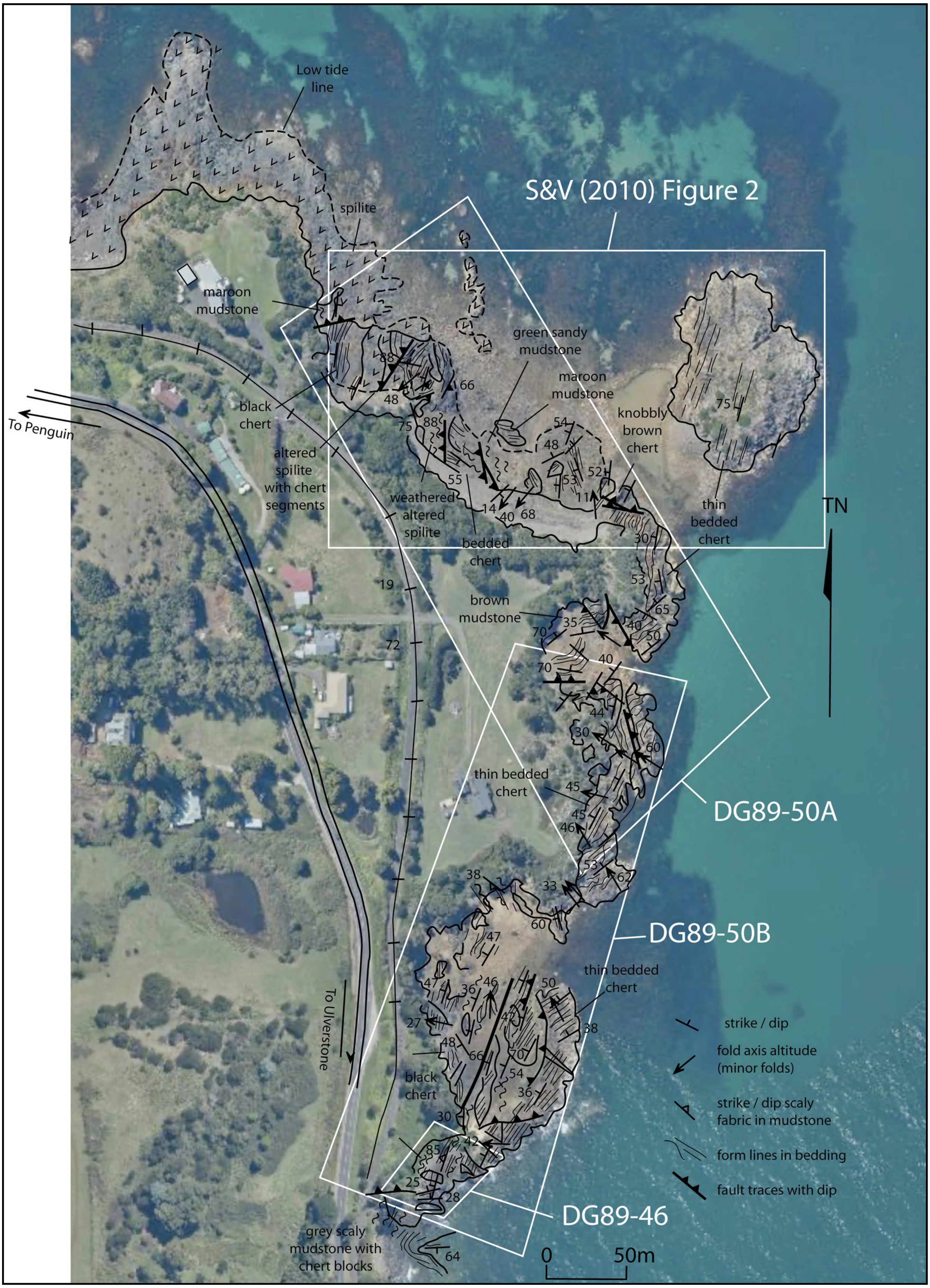


Figure 27. Structural form line map of Lodders Point superimposed on Google satellite image. Formlines in bedding So are shown by the black line traces. Mapped areas are shown by the white rectangular polygons including the detailed mélange map of Seymour and Vicary (2010, fig. 2), and detailed field sketch maps labelled DG89-46, DG89-50A and DG89-50B (see Appendix 2).

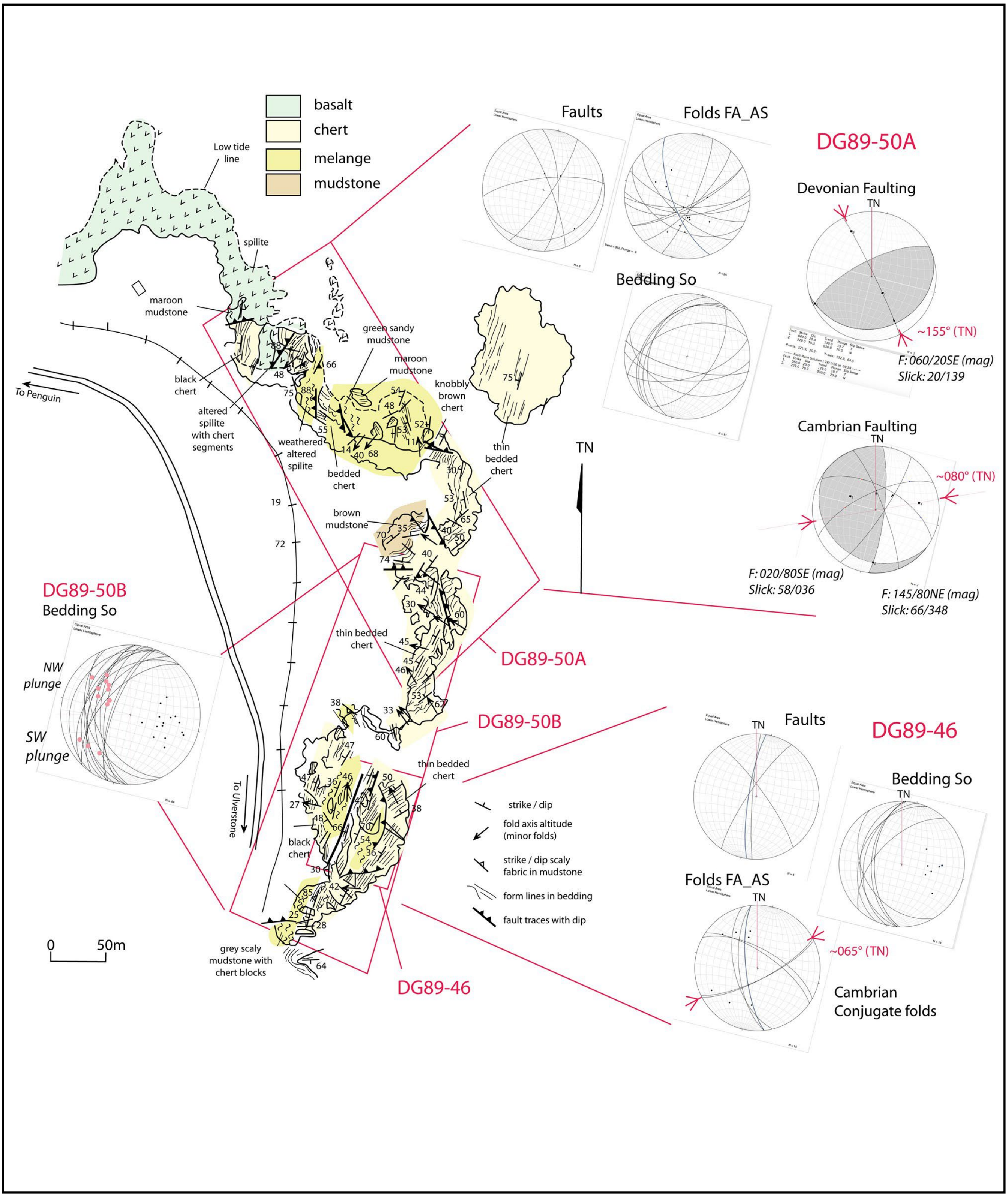


Figure 28. Structural map of the Lodders Point Mélange Zone (yellow coloured unit) between basalt (pale green unit) chert (buff coloured unit). Formlines in bedding are shown by the black lines traces in the chert and melange. Stereonets of structural data collected in subareas DG89-50A, DG89-50B and DG89-46 show the attitudes of bedding So, faults and fold axes and axial surfaces. The domains are highlighted by the red rectangular polygons.

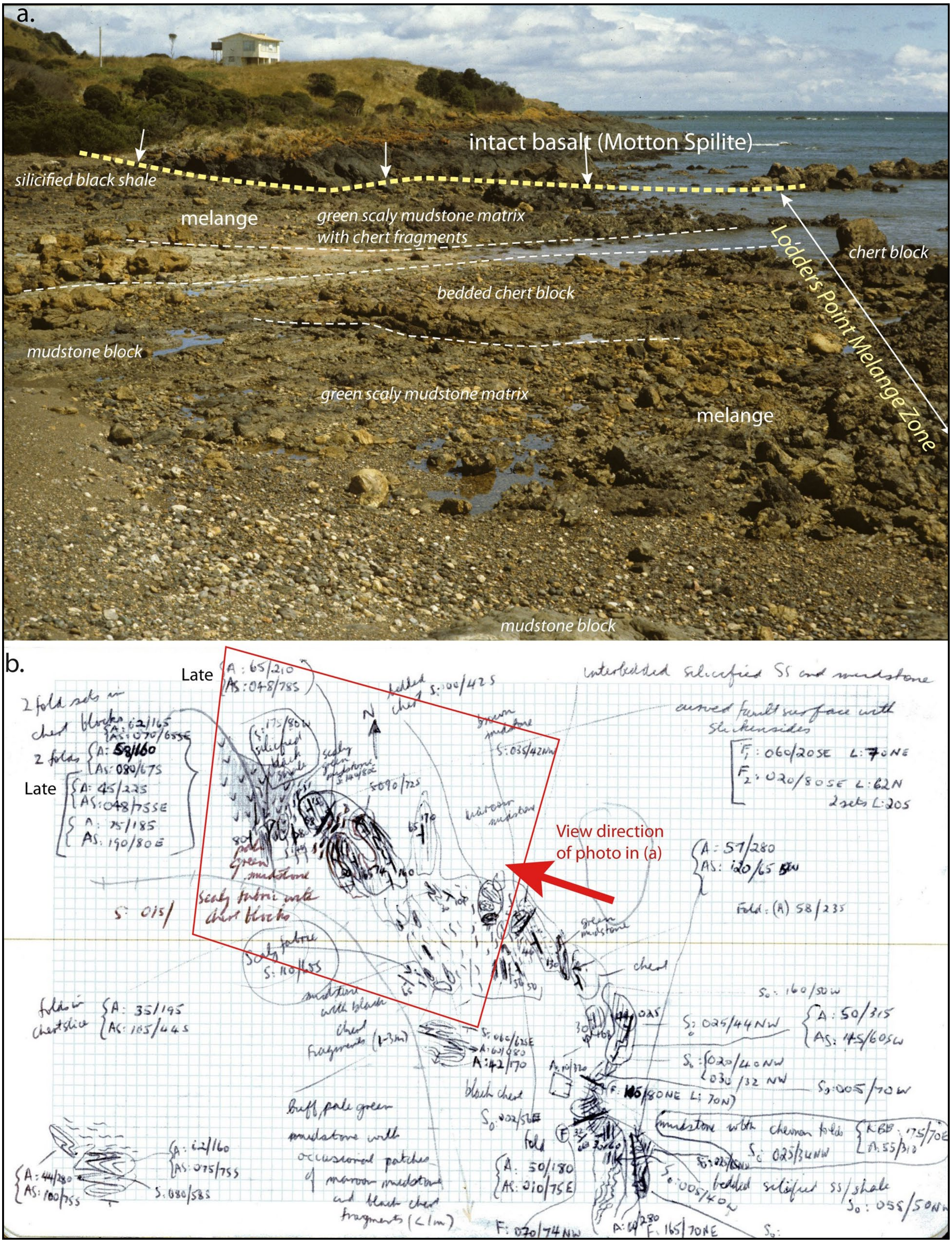


Figure 29. Lodders Point Mélange Zone. a) View of the western contact of the Mélange Zone showing intact spilite (top of photo) in contact with mélange and blocks of mudstone and chert. The photo is looking to the west. b) Sketch field-structural map of the Lodders Point mélange zone and the northern end of the Lodders Point Chert block. The red polygon denotes the region of the photo in (a) above. The red arrow indicates the view direction of the photograph.

Figure 30 (Left). Contact between altered, foliated basalt and fissile , foliated mudstone with chert clasts at the western end of the mélange.

Figure 31 (Below). Scaly mudstone with chert fragments from the Lodders Point mélange close to the contact with the intact basalt (spilite).

Figure 32 (Right). Folded and homoclinally west-dipping, thin-bedded chert within the Barrington Chert block along the east side of Lodders Point (see Figures 26 and 27 for structural map). View is looking south from Lodders Point. The chert is broadly folded about south-plunging axes but also contains rare, apparent, tight to isoclinal fold closures. The chert block is also cut and segmented by a strong ~east-west trending faults (dashed white line traces).

Figure 33. Folds within Barrington Chert at Lodders Point. a) Early tight to isoclinal folds in black chert block within the melange at northern end of the Lodders Point chert block. Isocline axis 60°/080° (magnetic). b) Late stage conjugate folds within fault-bounded blocks within the Lodders Point chert block.

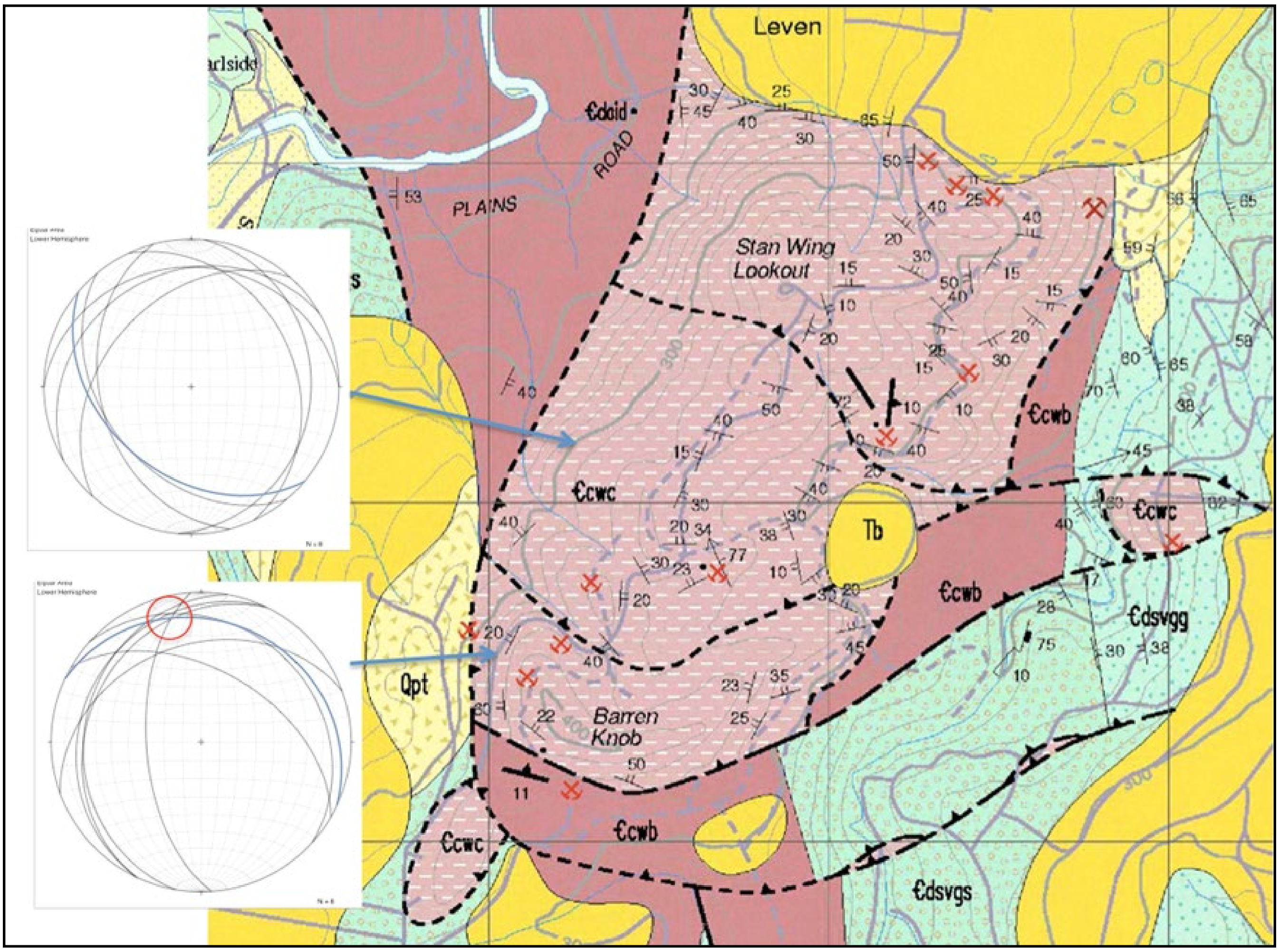


Figure 34. Geological map of the Barren Knob part of the Barrington Chert slice. The map is from the MRT 1:25 000 and 1:250 000 digital Atlas series. The stereonets show bedding great circle traces for the two lower parts of the tri-partite sheet Barren Knob slice. The red shovel symbols indicate the positions of the quarries visited in the lower slices (compare with Google satellite image in Figure 35 below).

3.2.1 Barren Knob Quarry

The Barren Knob Quarry is located in the structurally lowest thrust sheet of the Barren Knob slice (Figures 34 and 35). The quarry exposes a series of sub-parallel, north-dipping thrust faults at the apparent leading edge, or frontal part, of the slice (Figures 36, 37 and 38). The thrusts are brittle faults and fault zones made up of cataclastic, gouge-breccia zones up to 60 cm in thickness (Figures 38 and 39). Some of the zones contain disrupted and segmented, small-scale isoclinal folds in cataclasite layering (Figures 40 and 41). These folds – combined with the general dip/strike of the faults – indicate north-over-south transport of the sheet (Figures 36 and 41).

3.2.2 Symos Quarry

The northern wall of the Symos quarry (Figure 42) provides an ~40 m profile through part of the Luina Sheet. The quarry wall exposes gently south-dipping, thin-bedded chert, with internal folds and kink bands, cut by moderately to steeply north-dipping reverse faults (Figure 43). The structures in the chert require NE–SW shortening (stereonets in Figures 43 and 44).

3.2.3 Northern Unnamed Quarry

The northern quarry shown Figure 35 provides two structural profiles in the northeast corner of the quarry (red and blue arrowed line traces, Figure 45). The profiles show interaction between steeply west-dipping strike slip faults (F:75/270, Lslick: subhorizontal with west block north sense) (north wall, Figures 45 and 46) and northeast-dipping faults with associated kink bands. Both sets of structures indicate northeast-southwest shortening within this part of the Luina Sheet (Figures 46 and 47).

3.3 Structure of the Cambrian Volcano-Sedimentary Sequence, footwall to the Luina Sheet

The Cambrian sequence underlying the Mt Lorymer and North Motton slices of the Luina Sheet are also locally offset by small-scale reverse faults, part of the fault system responsible for Luina Sheet emplacement, suggesting footwall involvement as observed at Barren Knob (Figure 48).

Figure 35 (Left). Quarry location map of the quarries within the Barren Knob slice of Barrington Chert. These include: the Barren Knob Quarry, Symos Quarry and an unnamed quarry in the north.

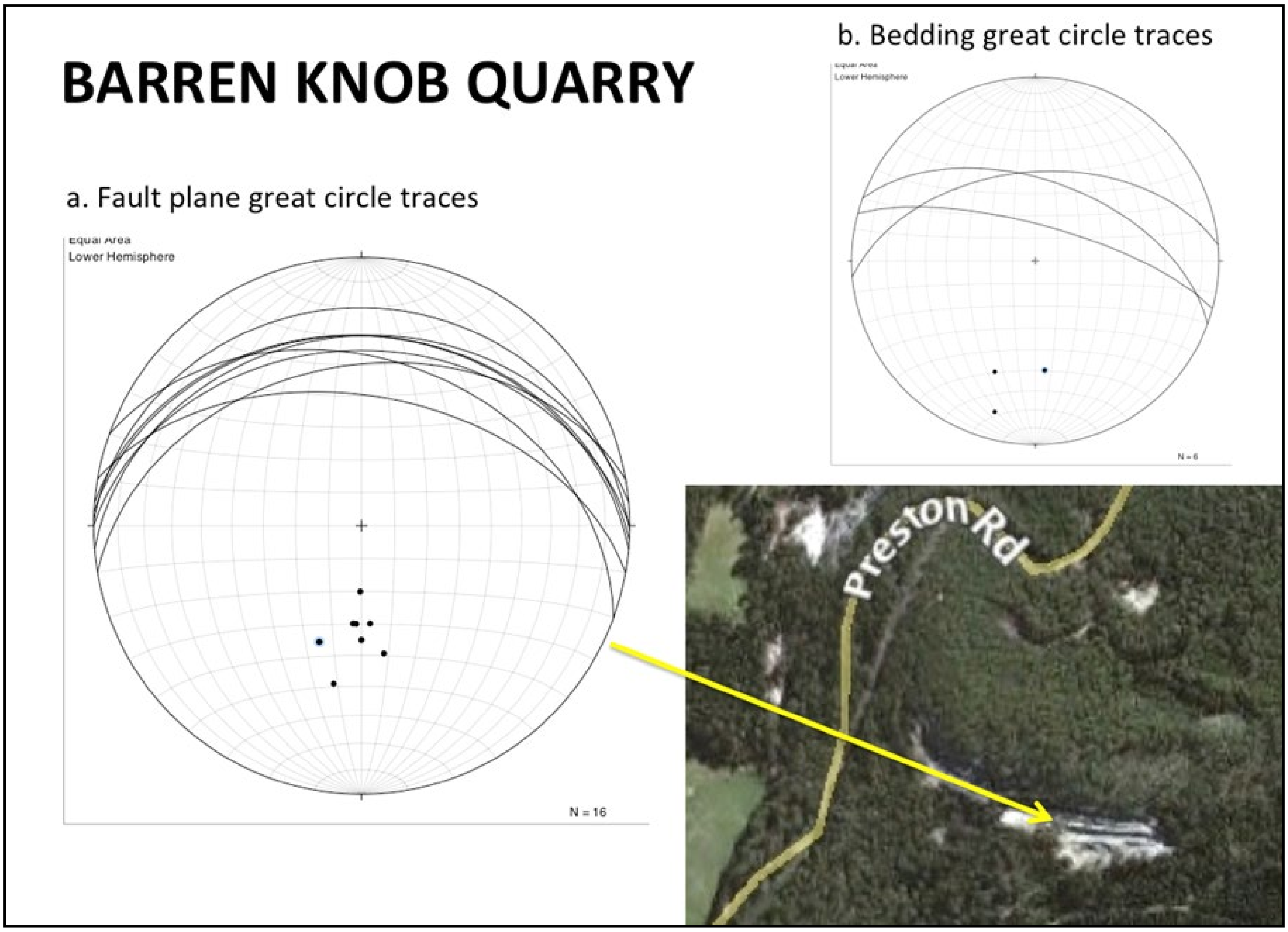


Figure 36. Structural data from the Barren Knob quarry off Preston Road (see Google image on lower right). A close-up of the wall of the quarry is shown in Figure 35. a) Stereonet showing fault plane great circle traces. b) Stereonet of bedding great circle traces. Note the bedding and fault planes are both gently north dipping.

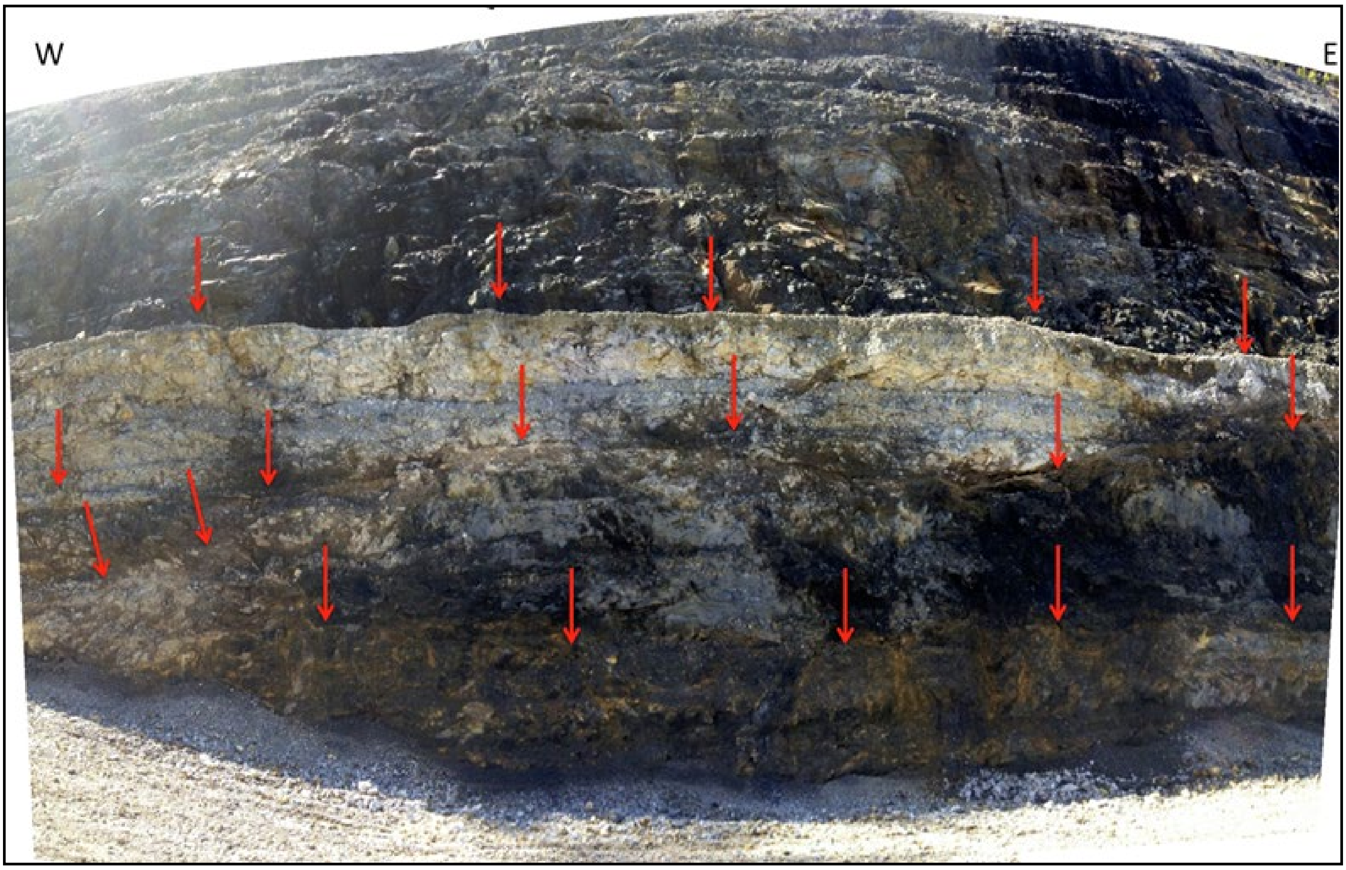


Figure 37. A series of gently, north-dipping décollement zone faults exposed in south-facing quarry wall of the Barren Knob quarry (see Figure 36 above). The fault traces are highlighted by the red arrows.

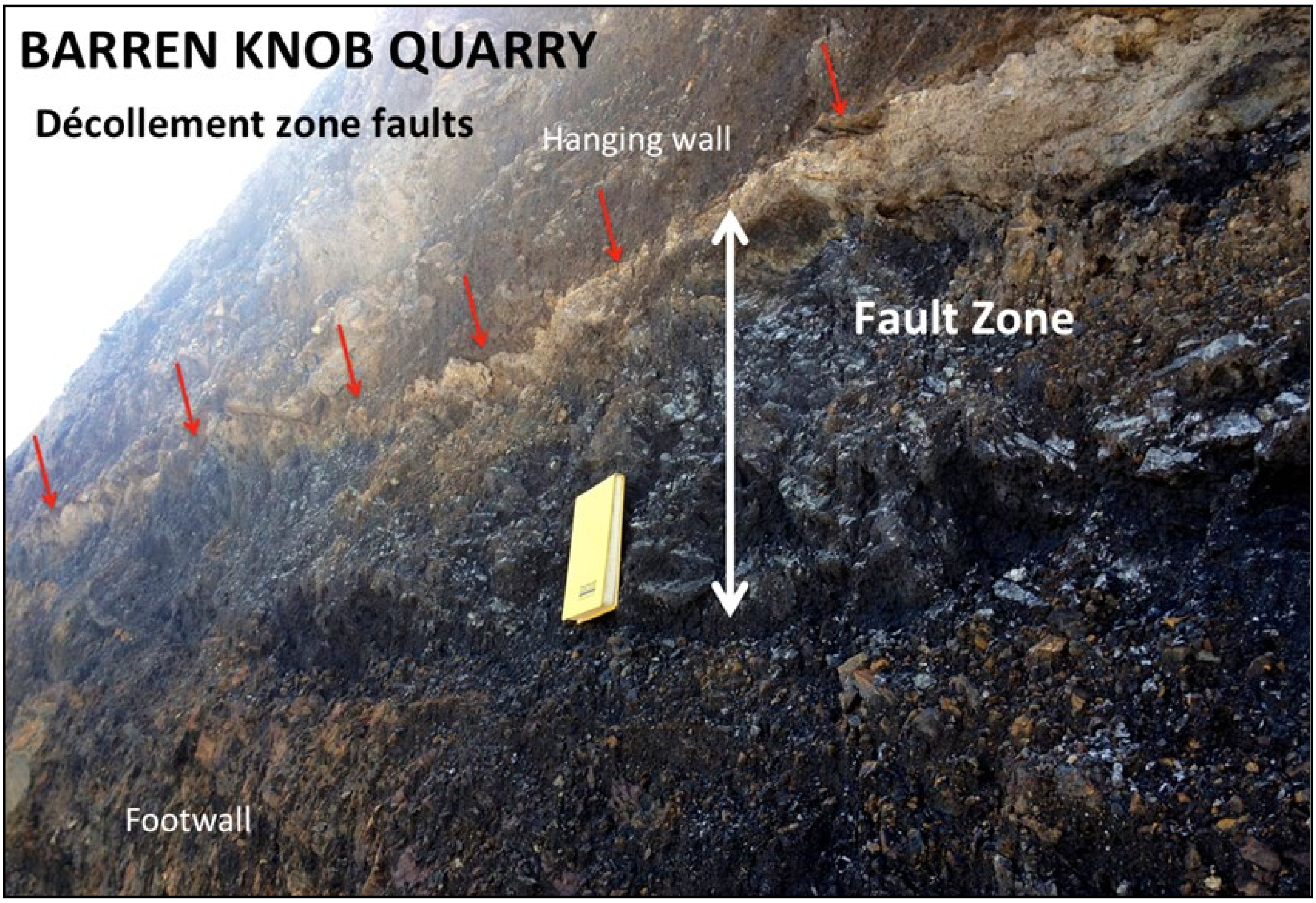


Figure 38. Oblique view of the Barren Knob quarry wall (looking to the west) showing a brecciated zone as part of the basal fault system.

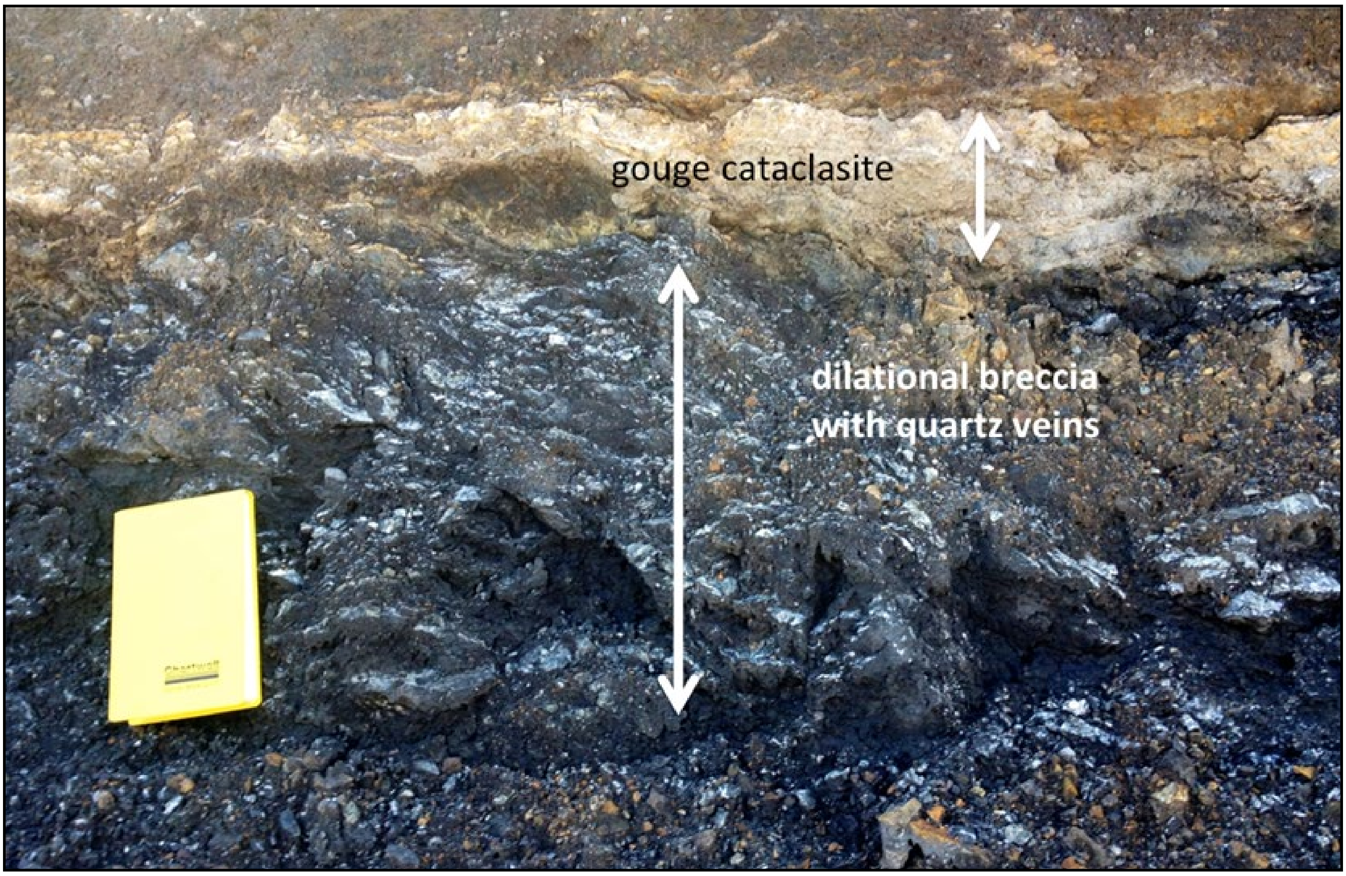


Figure 39. Strike-parallel view of the cataclasite fault zone shown in Figure 38 above. The view is looking north parallel to the transport direction (TD).

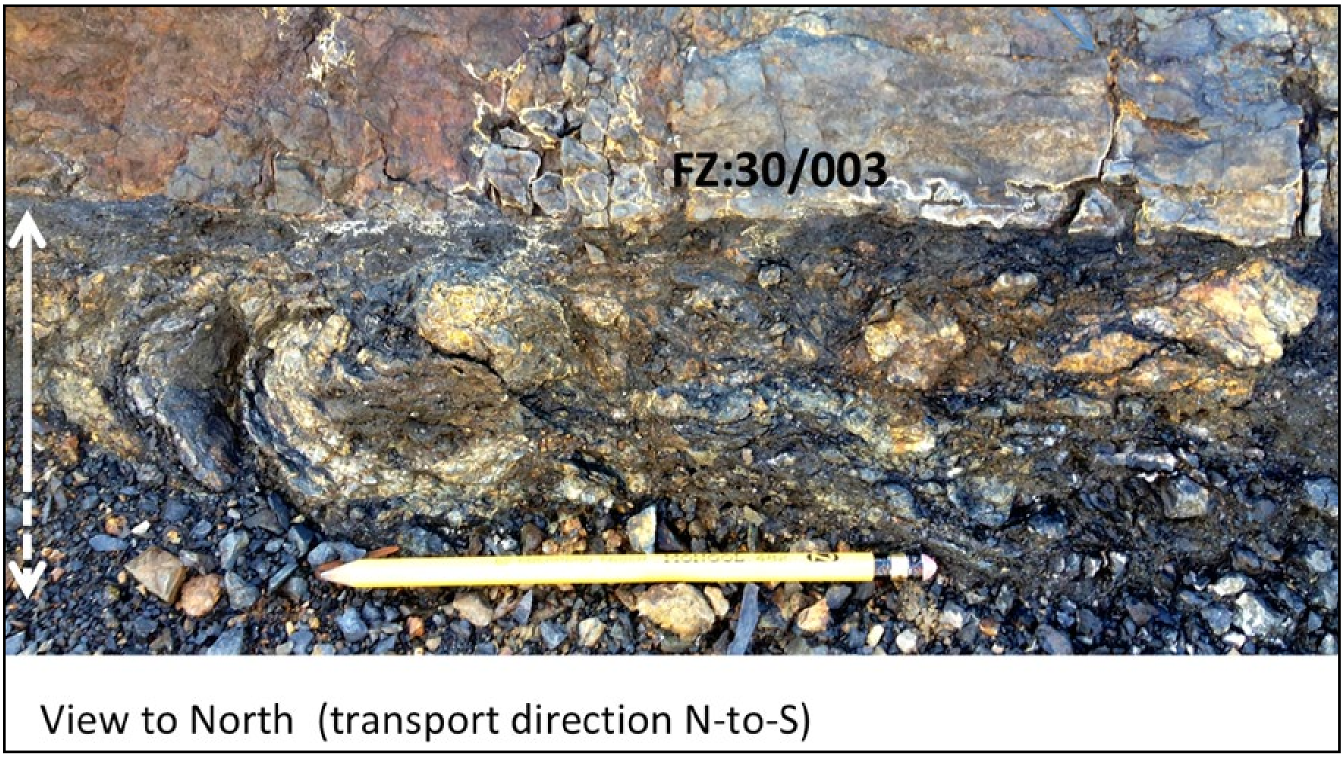


Figure 40. Mesoscopic fold in gouge breccia zone of décollement zone fault, Barren Knob Quarry. The fault has an attitude of 30°/003° (magnetic). Note partially continunous layering defining the fold hinge is truncated segmented with development of a fault breccia (right side of fault zone in photo).

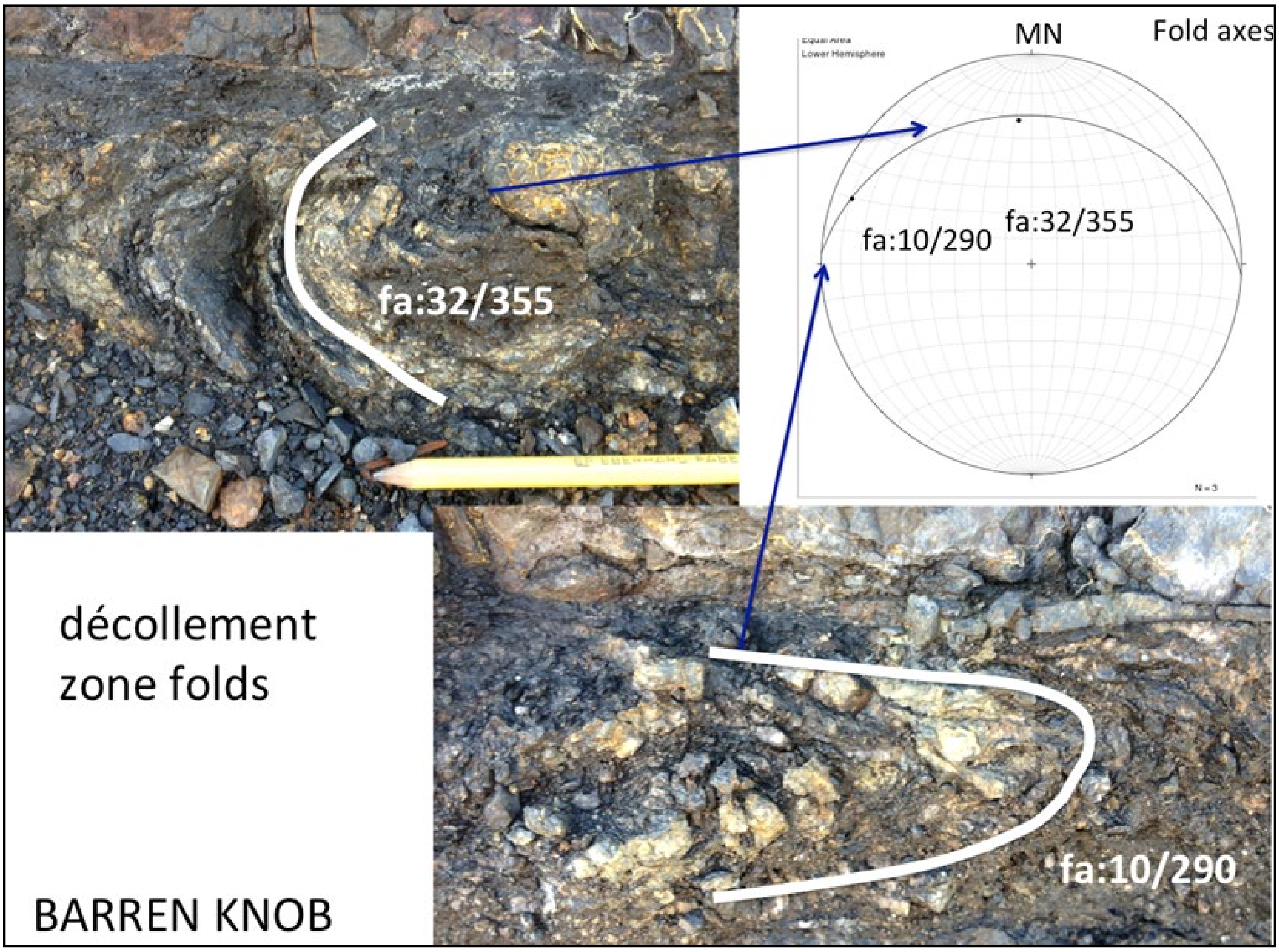


Figure 41 (Above). Variable fold axis orientation in gouge breccia zone of décollement zone fault at the leading edge of the Barren Knob fault klippen. Fold axes in the fault zone form at high angles to the thrust transport direction (i.e. parallel to the fault strike) and rotate with high shear strain into the transport direction (approximated by the blue arrow superimposed on the stereonet upper right).

Figure 42 (Right). Satellite image of the Symos Quarry in the Barren Knob slice (see Figure 35 for location). The purple arrowed-line trace indicates the position of the sketch structural profile shown in Figure 43.

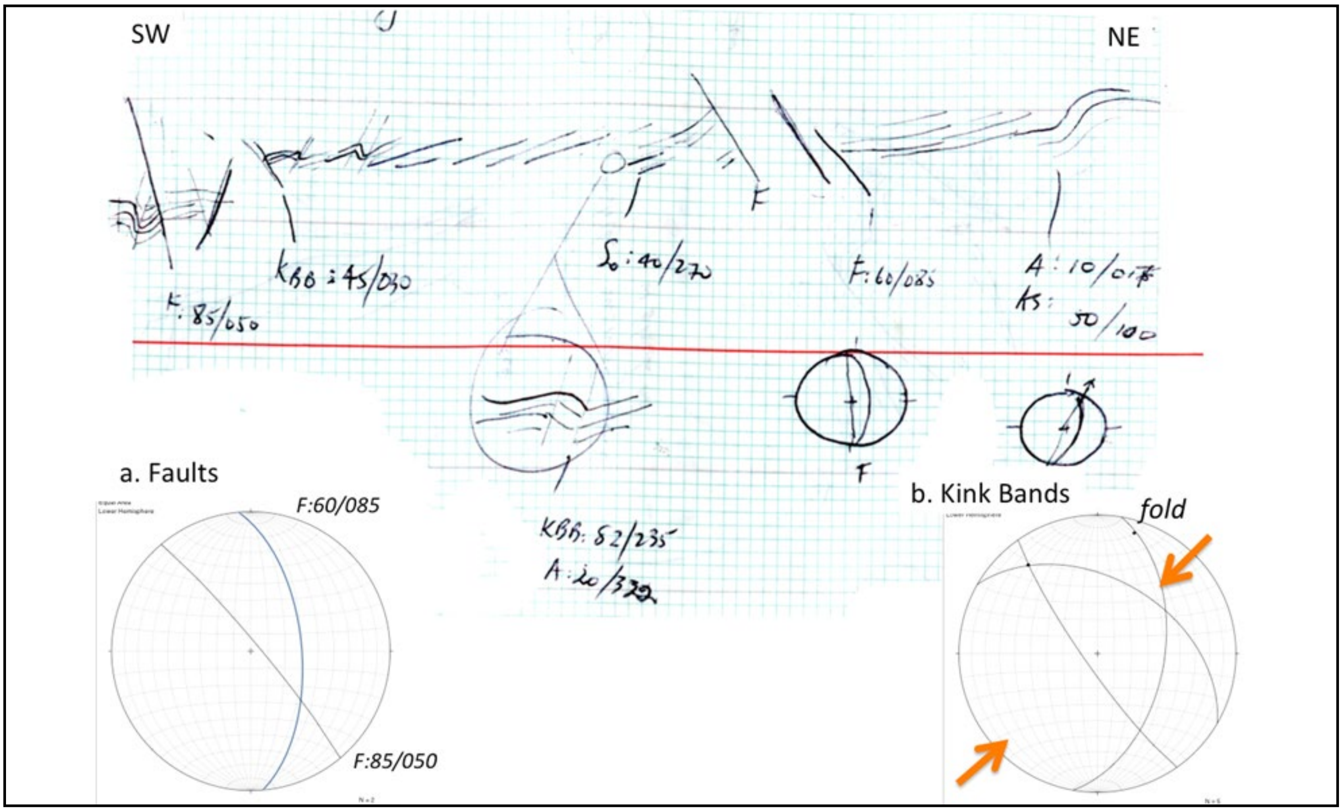


Figure 43. Structure of Symos Quarry in Barrington Chert, near Barren Knob. Sketch structural profile in the north wall of Symos Quarry (see Figure 42 above for location). a) Stereonet of fault great circle traces (magnetic). b) Stereonet of conjugate kink band boundaries as great circle traces (magnetic). The orange arrows indicate the shortening direction contained within the plane perpendicular to the band intersection.

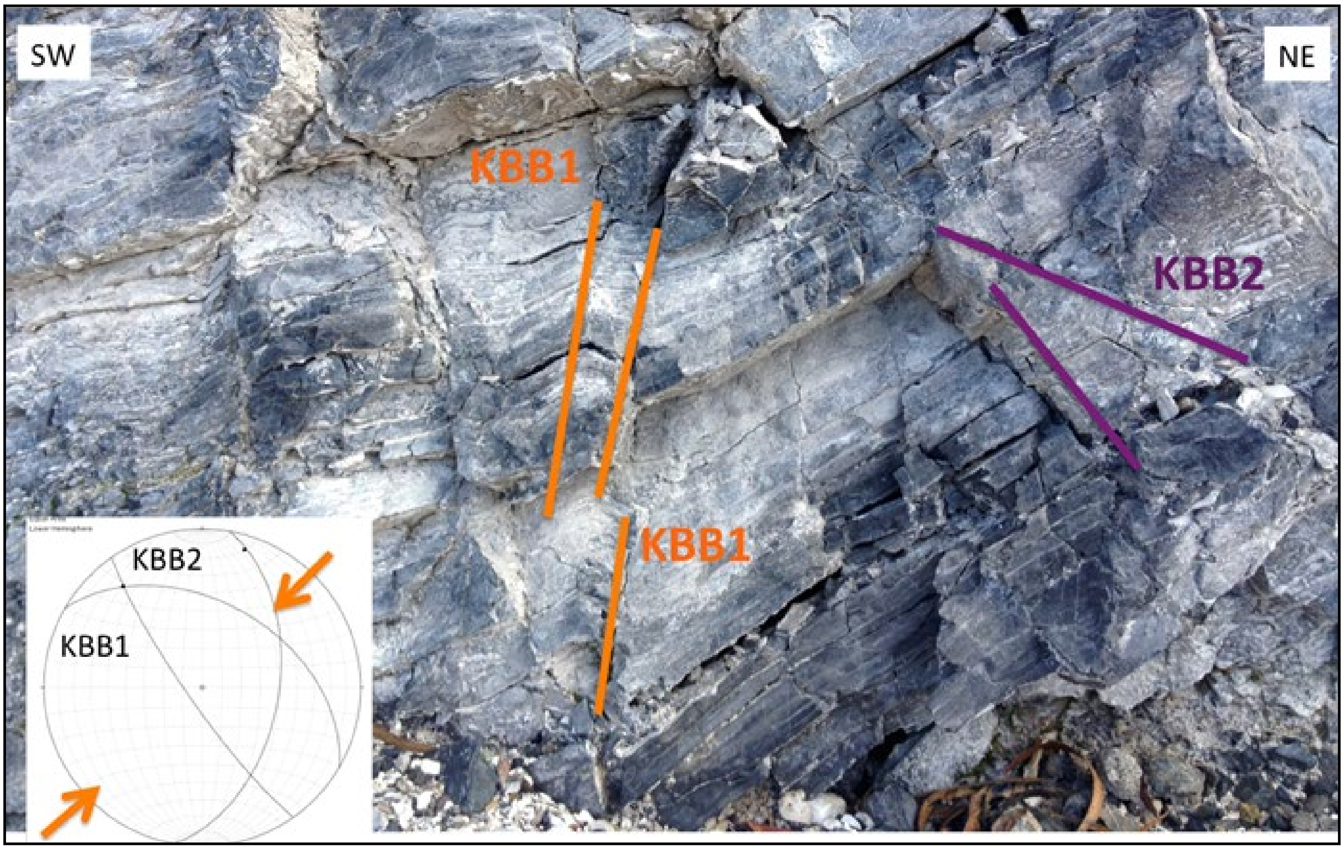


Figure 44. Kink band sets KBB1 (orange line traces) and KBB2 (purple line traces) in bedded Barrington Chert in Symos Quarry (see sketch profile, Figure 43 above). Plotted data with respect to magnetic north.

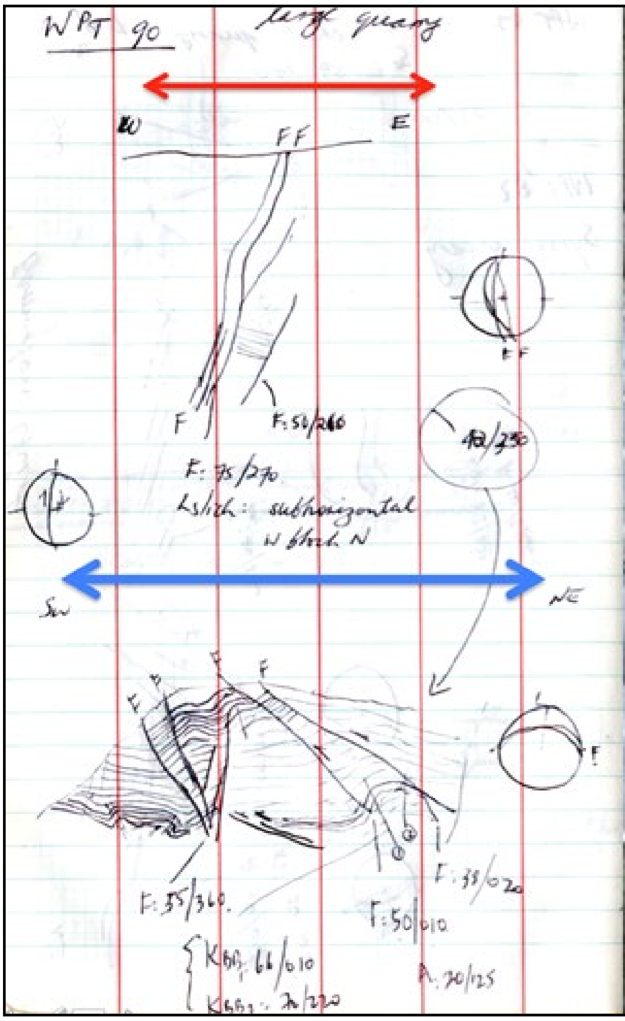
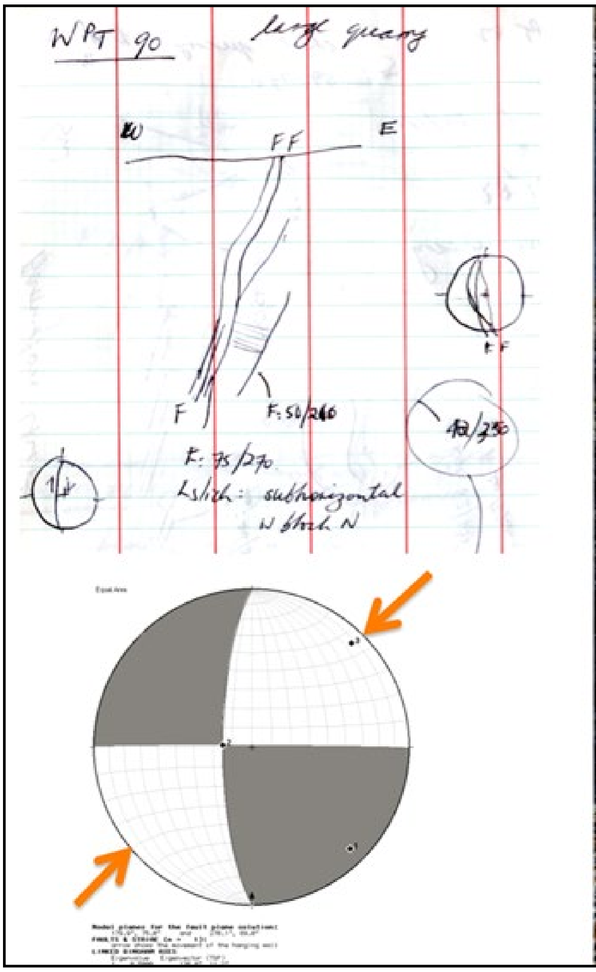


Figure 45. Structure of northern unnamed quarry in Barrington Chert (see Figure 35 for location). Profile sections are shown for the north wall (red arrow trend) in Figure 46 and the east wall (blue arrow trend) in Figure 47.



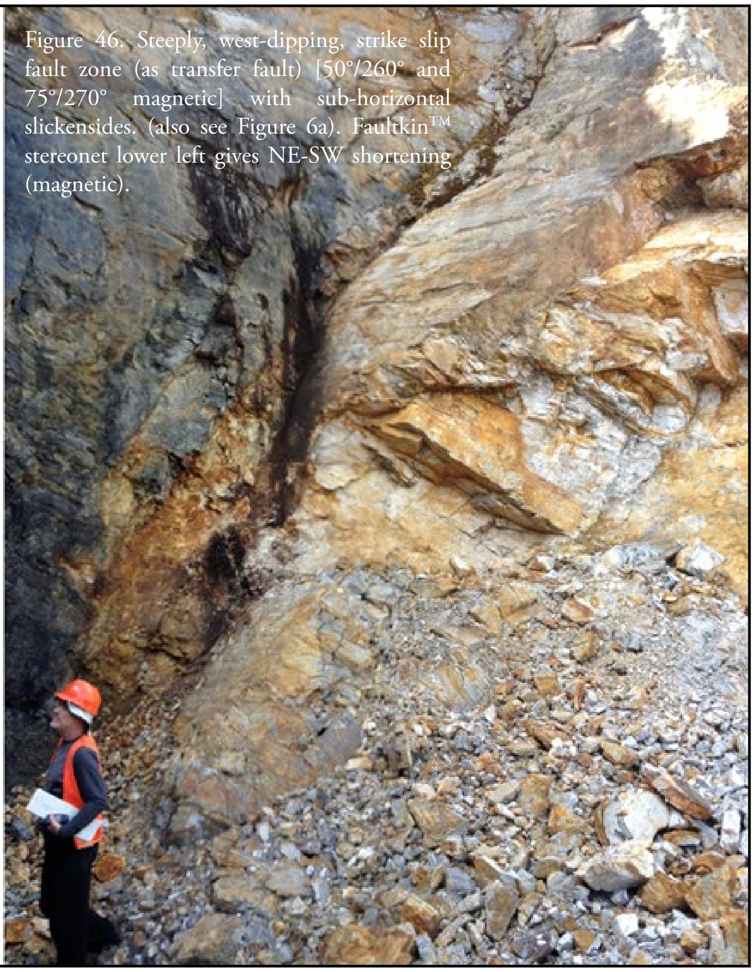


Figure 46. Steeply, west-dipping, strike slip fault zone (as transfer fault) [50°/260° and 75°/270° magnetic] with sub-horizontal slickensides. (also see Figure 6a). Faultkin™ stereonet lower left gives NE-SW shortening (magnetic).

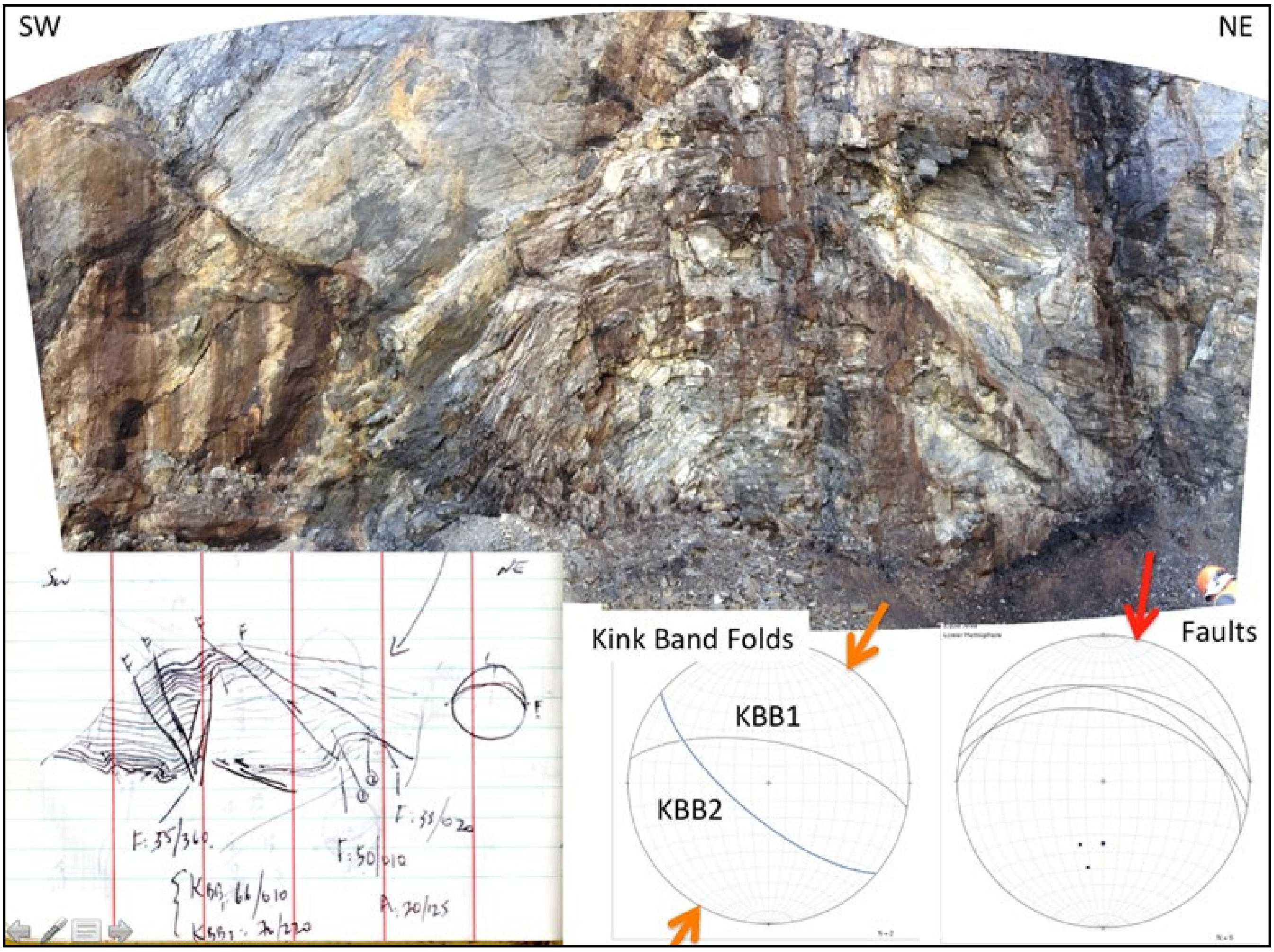


Figure 47. Complex fold-fault association with a conjugate box-like fold truncated by a series of moderately north- and northeast-dipping faults [35°/360°, 42°/020° and 50°/010° (magnetic)]. A conjugate fold associated with kink bands KBB1 [66°/010° magnetic] and KBB2 [70°/220° magnetic] sketched in the lower right of the sketch profile gives a NE-SW shortening direction. The fault data suggest a more NNE-SSW shortening direction.

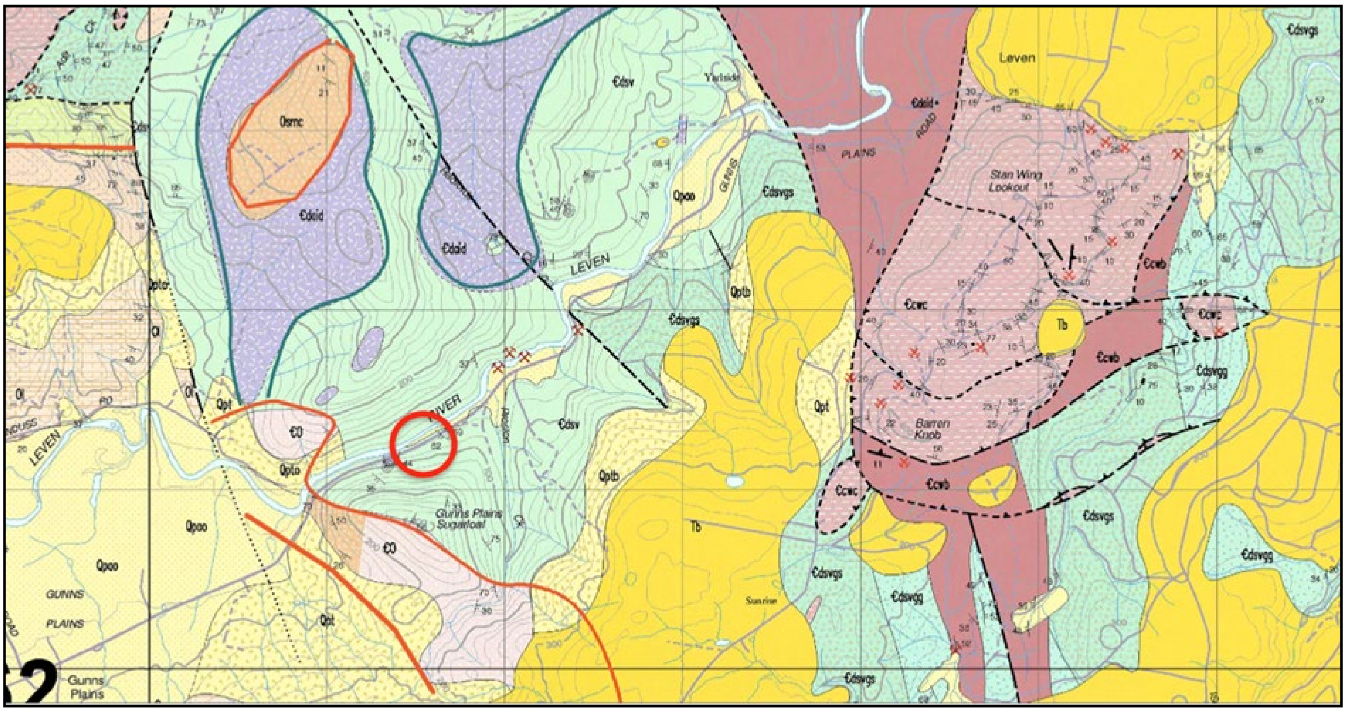


Figure 48. Geological map of the Leven River-Barren Knob area after the MRT 1:25 000 digital atlas series. The red circle indicates the location of Gunns Plains road section through Sugarloaf Gorge . Stations DG13-56 to DG13-58. The pale green units are the Cambrian Western Volcanosedimentary Sequence Formation (Cdsv) and the overlying Sprent Formation (Cdsvgs). The Cambrian sequence and locally the Early Cambrian Motton Spilte is intruded by the Lobster Creek Volcanics (Cdaid), dated at appropriately 495.5 Ma. The white-stippled pale pink unit is the Barrington Chert and the dark pink is the Motton Spilite (basalt).

Some of these faults are also exposed within the Leven Valley, in particular in Sugarloaf Gorge along the Gunns Plains Road (red circled location, Figure 48). The road section shows fault repetition of the unconformity with Owen Conglomerate on the Cambrian Western Volcano-sedimentary Sequence (pale green unit/Cdsv) (Figure 49). Faultkin™ kinematic analysis of fault slickenside data from the cutting show northeast-southwest shortening associated with complex fault movement along southwest dipping faults (Figure 50). These faults have similar shortening and fault kinematics to that the Barren Knob fault system (Figure 51). Geometrically they are localised back-thrusts developed in the footwall to the major Luina Sheet.

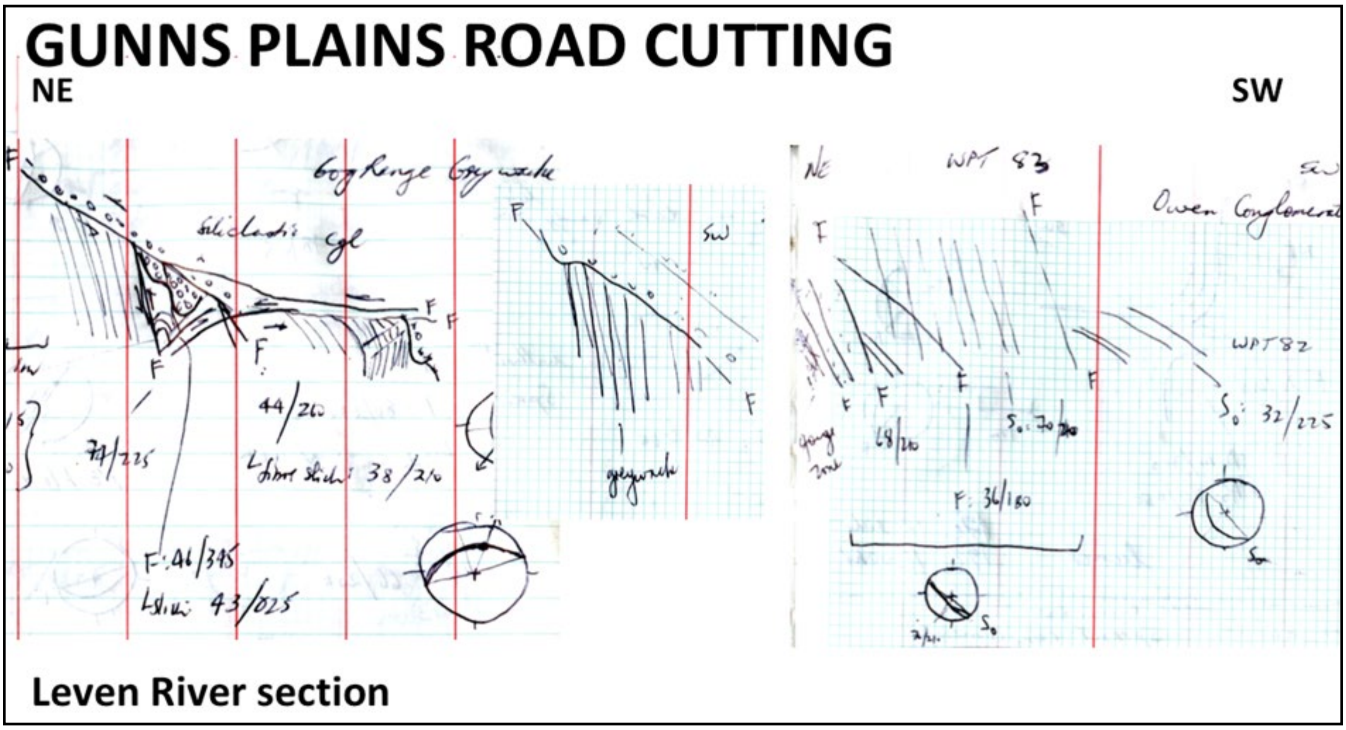


Figure 49. Sketch structural profile from the Gunns Plains road cutting in Sugarloaf Gorge on the Leven River. The section shows fault repetition of the unconformity with Owen Conglomerate on the Cambrian Western Volcano-sedimentary Sequence, possibly Gog Range Greywacke correlate (Cdsv). Stitched outcrop sketches from DG13-56, DG13-58 and DG13-57.

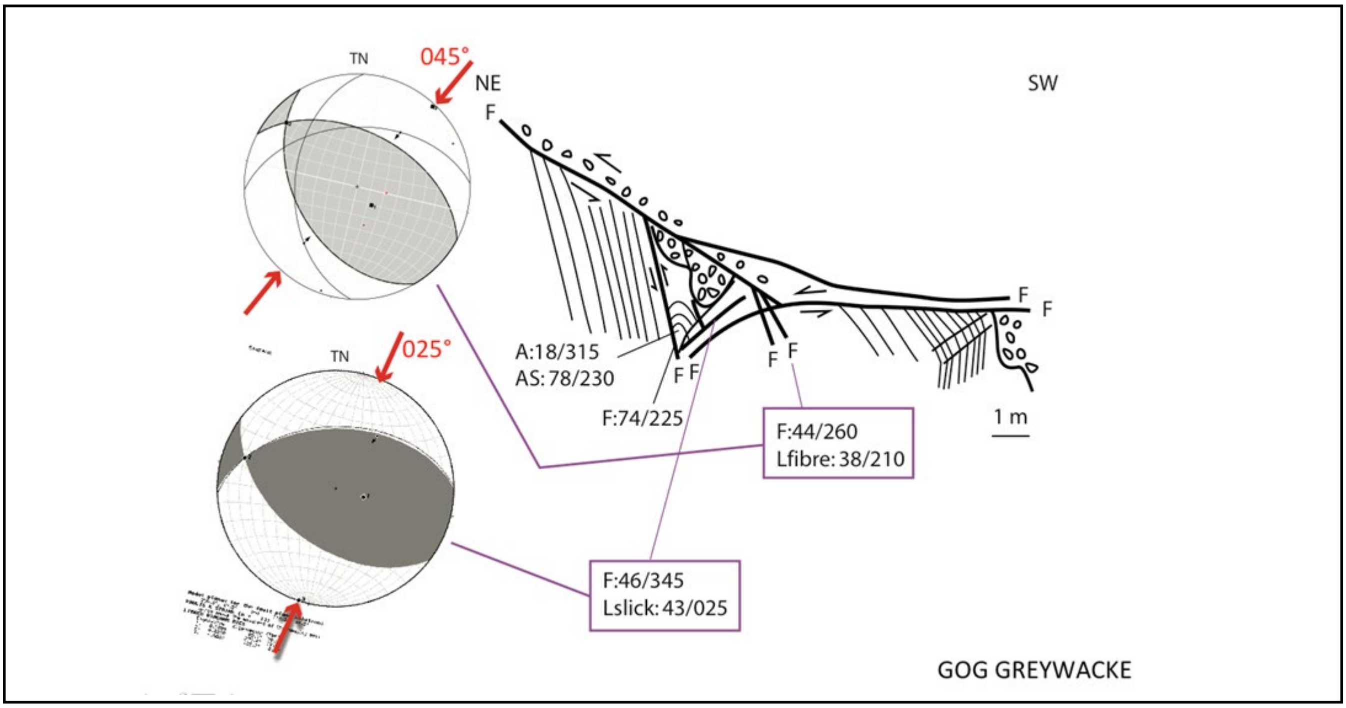


Figure 50. Fault structure at Station DG13-56 shown in profile section from Gunns Plains road cutting at Sugarloaf Gorge on the Leven River (NE end of Figure 49). Structural measurements are shown. The stereonets (Figure left) show Faultkin™ analysis of the two faults designated by the purple lines. All structural data are magnetic.

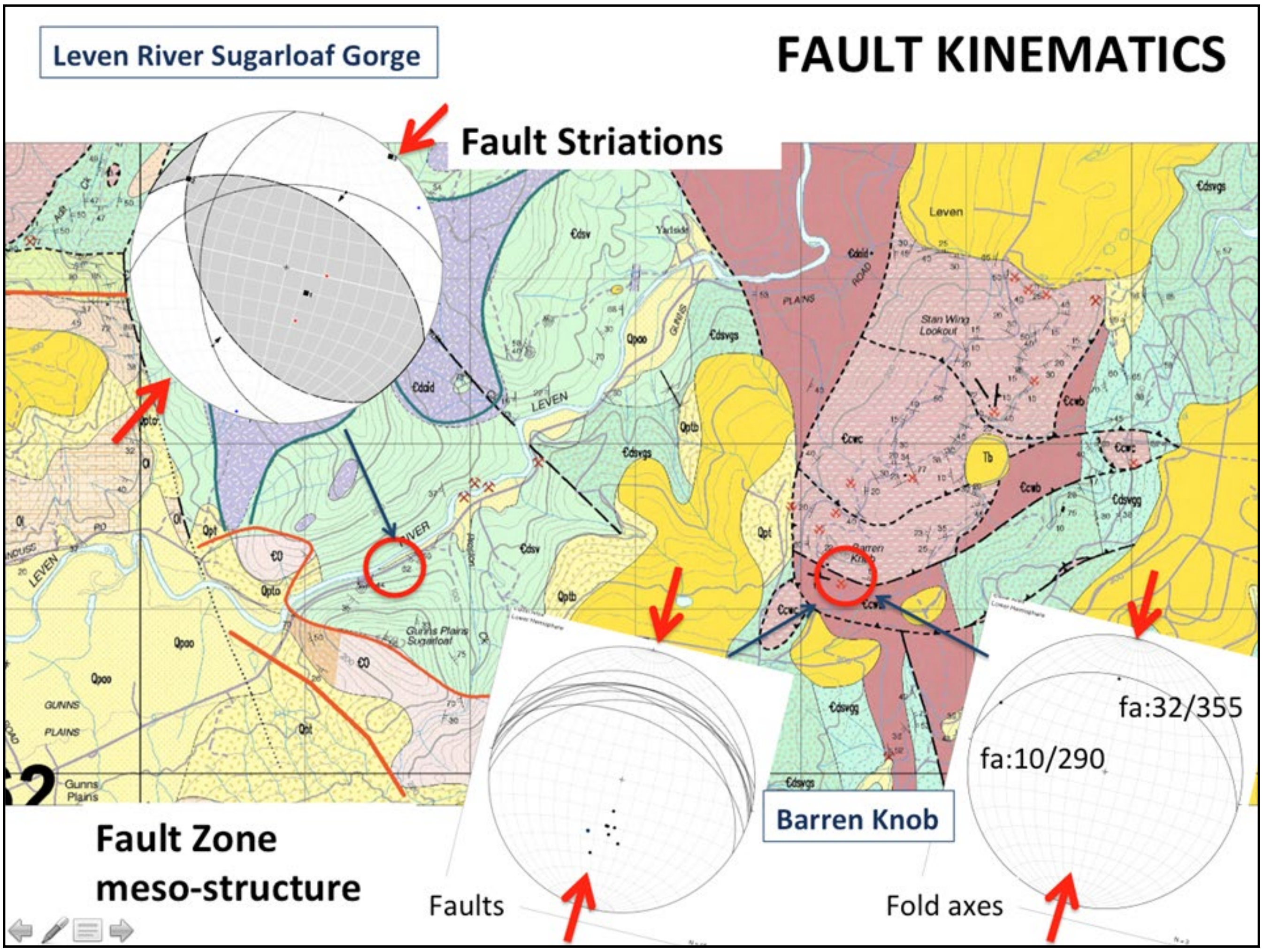


Figure 51. Stereonet plots of structural data from the Leven River-Sugarloaf Gorge. Gunns Plains road (Faultkin™ stereonet, upper left) and Barren Knob Quarry (stereonets of fault and fold axis attitudes within the fault zone, stereonets lower right).

3.4 Shackley Hill Slice

The Shackley Hill slice is the southeasternmost klippen of the southeastern Devils Gate–Sheffield region of the Luina Sheet (Figure 52). The internal structure of the slice can be seen in the Shackley Hill Quarry (Figures 52 and 53), located within Barrington Chert in the southern part of the slice. Structural observations within the quarry include:

1. Bedding within chert is steeply dipping with west northwest-east southeast strike (see green trend lines, Figure 54);
2. Three major fault groupings dominate the chert (Figures 55, 56, 57, 58 and 59), including a NNW-SSE set (bright green line traces), an E-W set (purple line traces) and a N-S set (blue line traces);
3. Quartz gash vein sets (red strike/dip symbols) tend to have a NW-strike and a moderate to gentle NE-dip (Figures 60 and 61); and
4. The fault and quartz vein data support SW-directed transport (Figure 62).

4.0 IMPLICATIONS OF THE STRUCTURE AND GEOMETRY OF THE LUINA SHEET

4.1 The Basal Contact

The basal fault contact of the Luina Sheet is sub-parallel to topographic contours, indicating the basal faults of the individual klippen are sub-horizontal to gently dipping (Figure 63). The basal fault contact occurs at different levels across the Penguin–Sheffield area (Figure 64). This includes sea level at the coast, 100 m base elevation for the Sullocks Hill, Hays Creek, Library Hill and North Motton slices, 200 m for the Lake Paloona and Barrington slices, and 300 m for the Barren Knob and Shackley Hill slices. These levels represent different detachment levels and can be explained by:

1. Development of a splay thrust system within the Luina Sheet, resulting in two separate and distinct thrust sheets (Figures 65 and 66). The base of the inferred upper sheet is at ~300 m. The base of the lower sheet is at ~100 m (Leven River area) increasing to 200 m towards the south in the Sheffield area in the transport direction (Figures 64 and 65).

2. Luina Sheet transport/displacement was partitioned by transfer faults (steep lateral ramps) sub-parallel to the transport direction, with ramps in the basal fault occurring at different levels in the separate or distinct sheets (see Section 4.4).

Further modification of the basal fault levels occurred via younger Devonian reactivation of the earlier Early Cambrian thrust system and the extensional fault architecture of the Middle Cambrian of the Dial Range-Fossey Mountains Troughs (grabens).

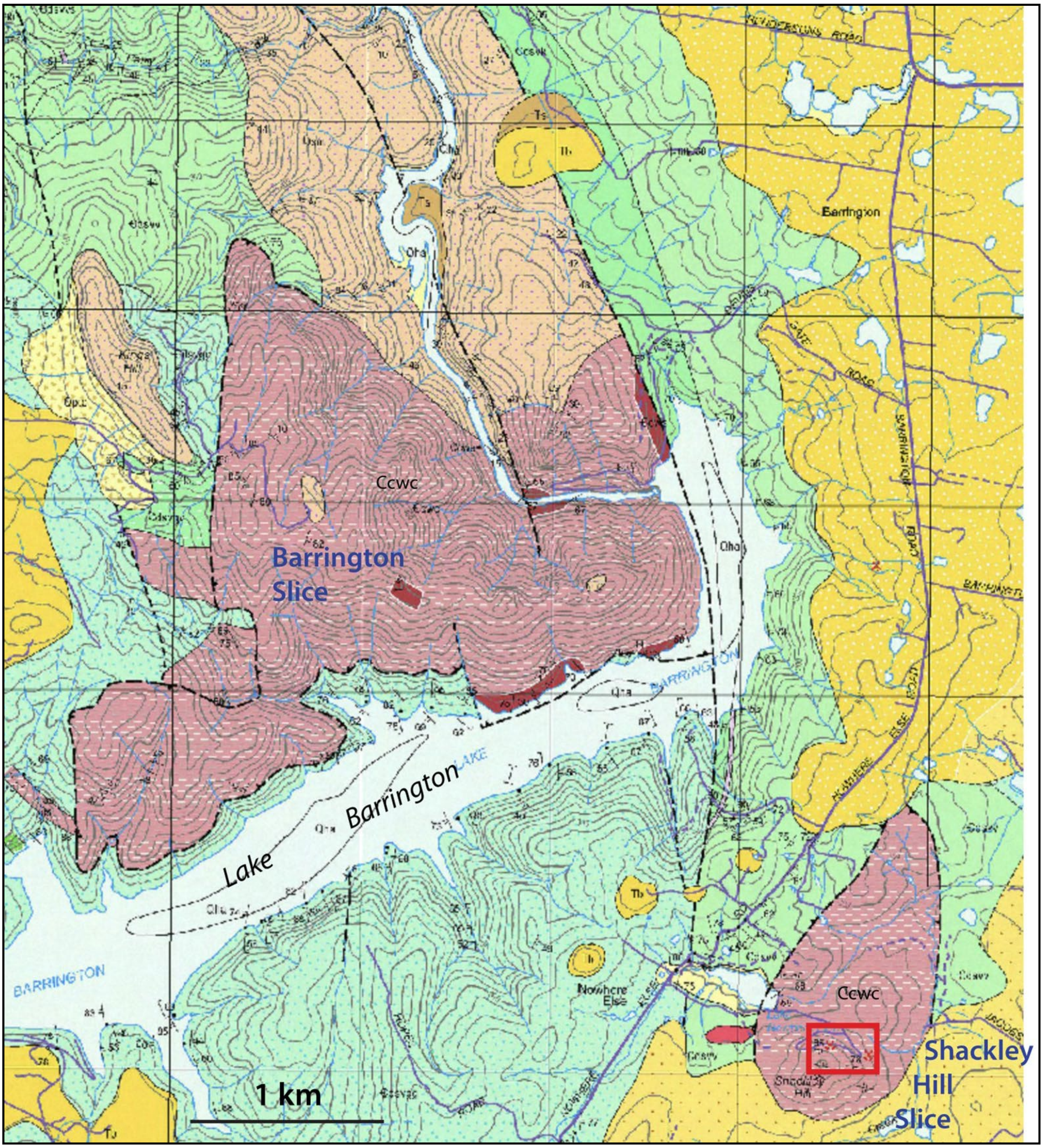


Figure 52. Geological map of the Barrington and Shackley Hill slices of the Luina Sheet, based on the MRT 1:25 000 digital atlas series. The slices are shown in pink (Ccwc), are bounded by faults and overlie the Cambrian volcano-sedimentary sequences of the Fossey Mountain Trough (teal coloured unit). Both are overlain in part by Tertiary basalt: orange coloured unit. The location of the Shackley Hill Quarry is shown by the red rectangle at the bottom right.

Figure 53. Google satellite image of Shackley Hill quarry in 2013. DG13 station locations are shown.

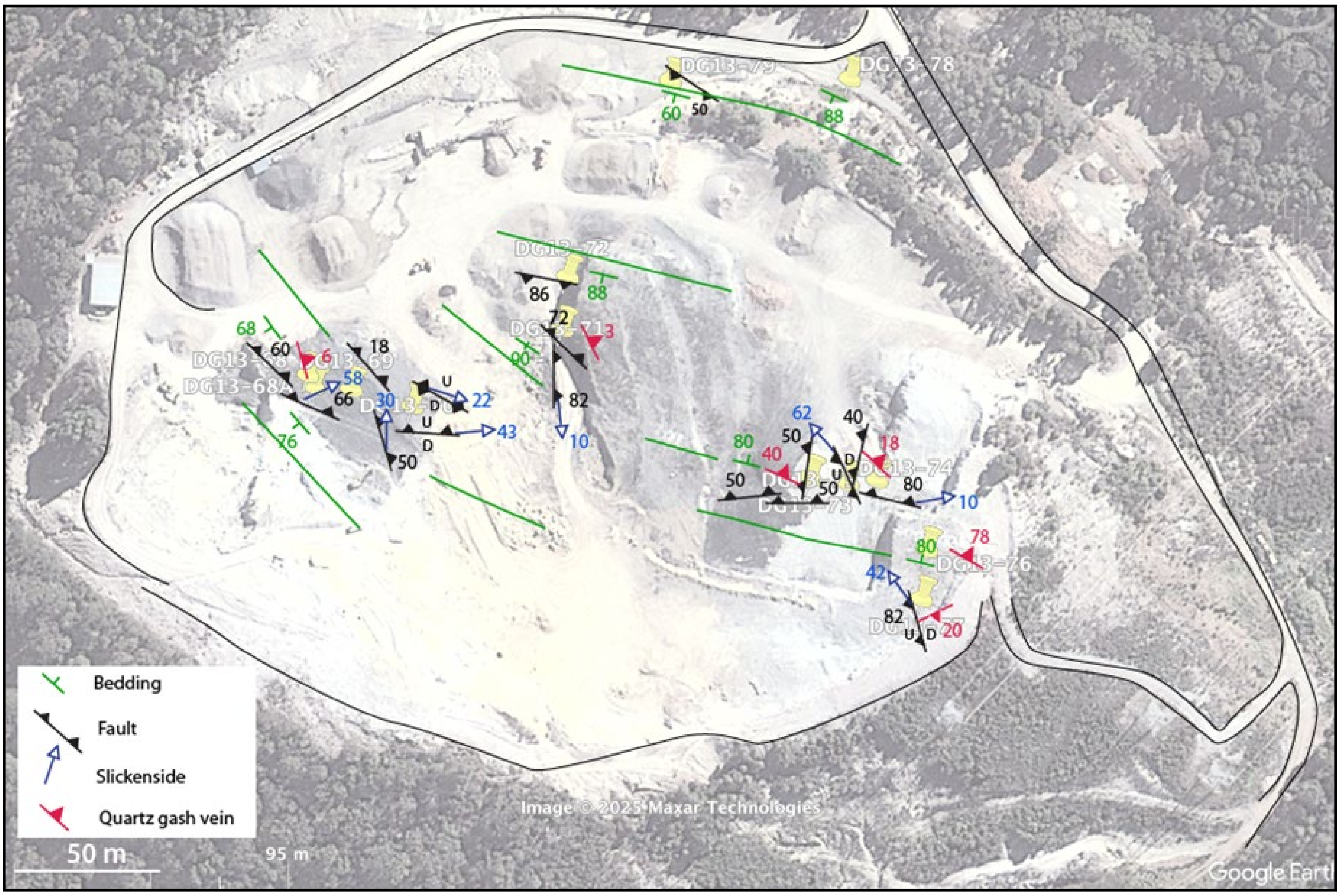


Figure 54. Structural map of the Shackley Hill quarry on Google satellite image base. Form lines in bedding are shown by the green line traces. Quartz gash vein sets (red strike/dip symbols) tend to have a NW-strike and a moderate to gentle NE-dip. Compare the fault traces with the sketch-mapped faults in Figure 57.

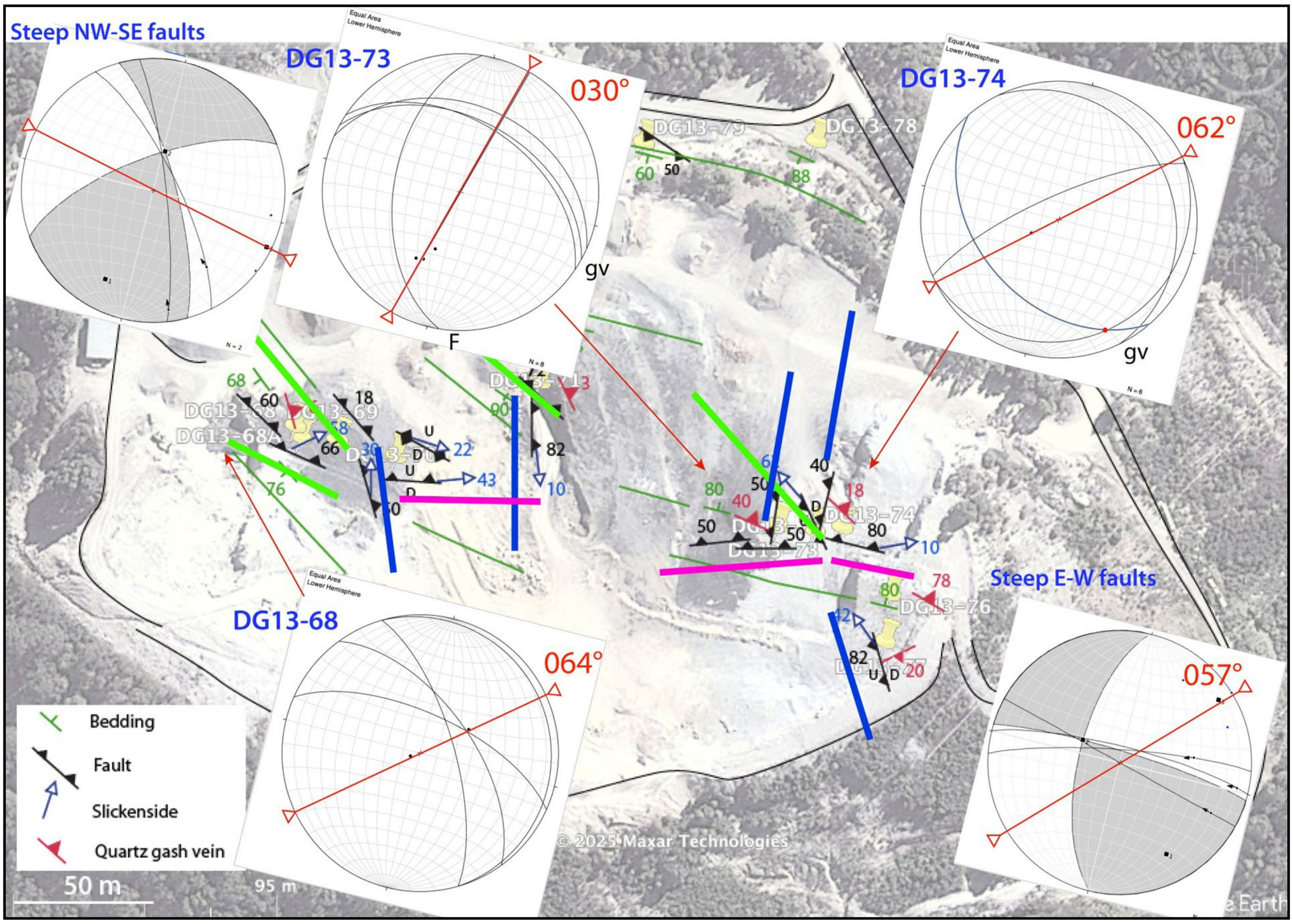


Figure 55. Fault trend line map of Shackley Hill quarry. The quarry is dominated by three fault sets: 1) NNW-SSE set (bright green line traces), 2) and E-W set (purple line traces) and a N-S set (blue line traces). The Faultkin™ beach ball stereonets show the shortening direction (red line traces) for steep NW-SE faults (top left) and steep E-W faults (bottom right). The stereonets show the attitudes of faults (F) and gash veins (gv) and the determined shortening direction (red line traces) for outcrop stations DG13-68, DG13-73 and DG13-74.

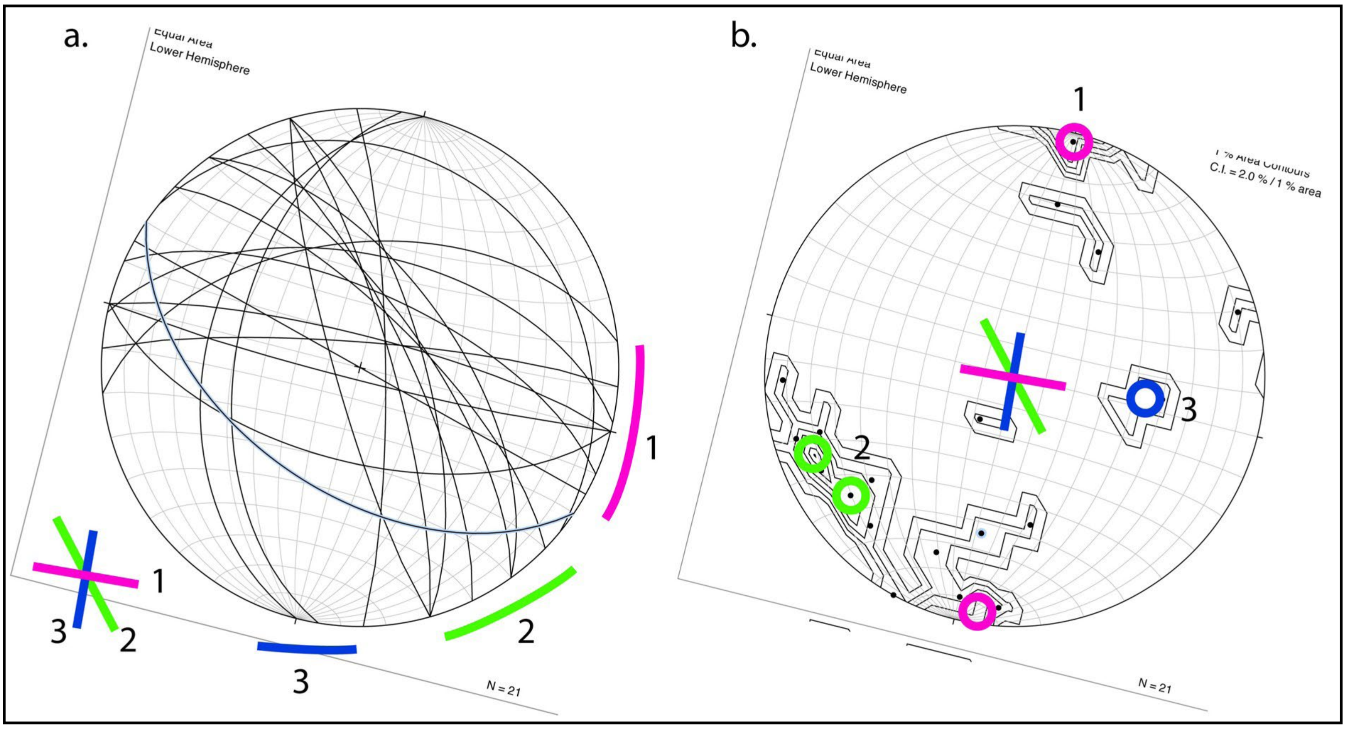


Figure 56. Stereonets of Shackley Hill Quarry Faults. a) Great circle traces showing 3 fault groupings. Compare with Figure 55 above. b) Contoured stereonet pole plot showing the pole distribution of the 3 fault groupings.

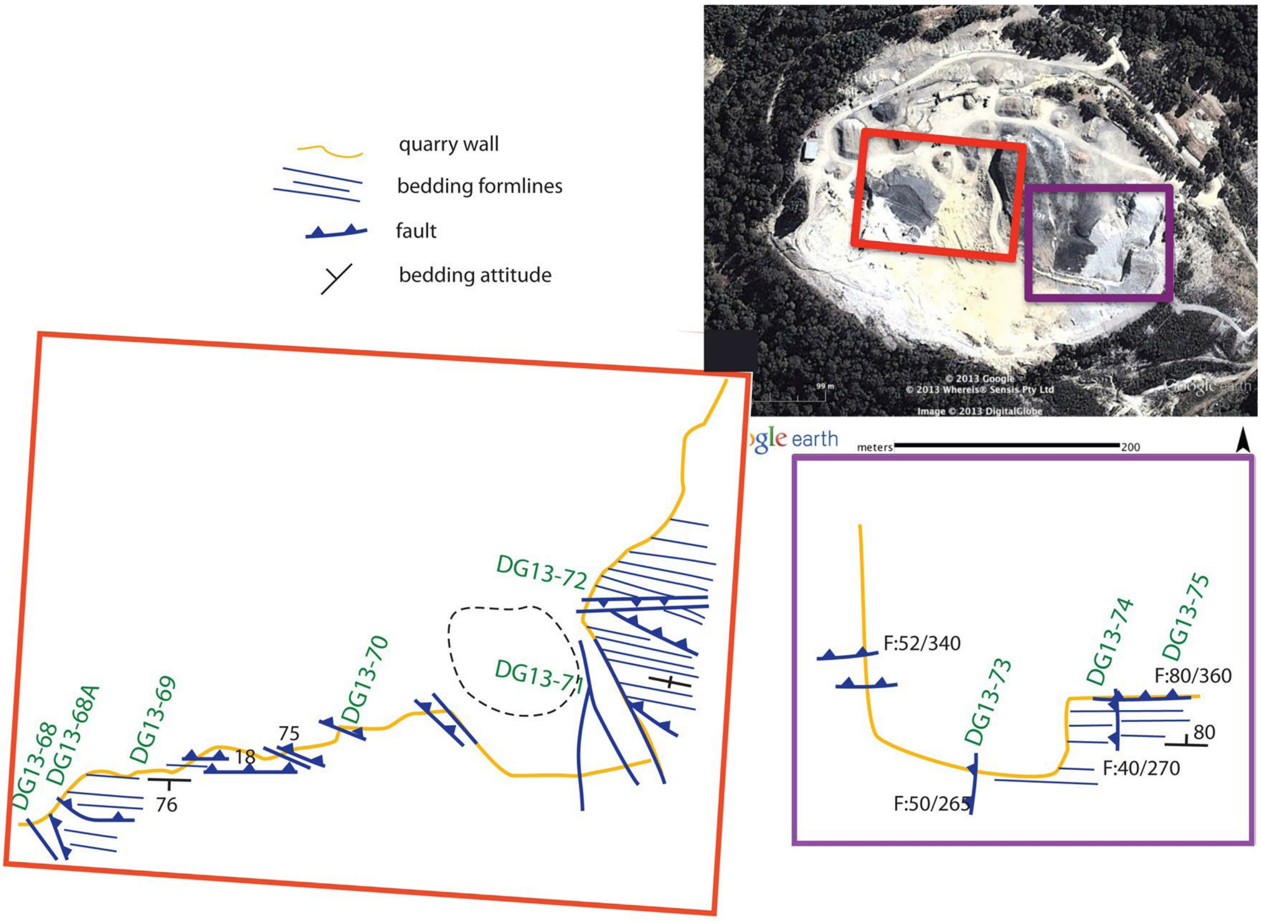
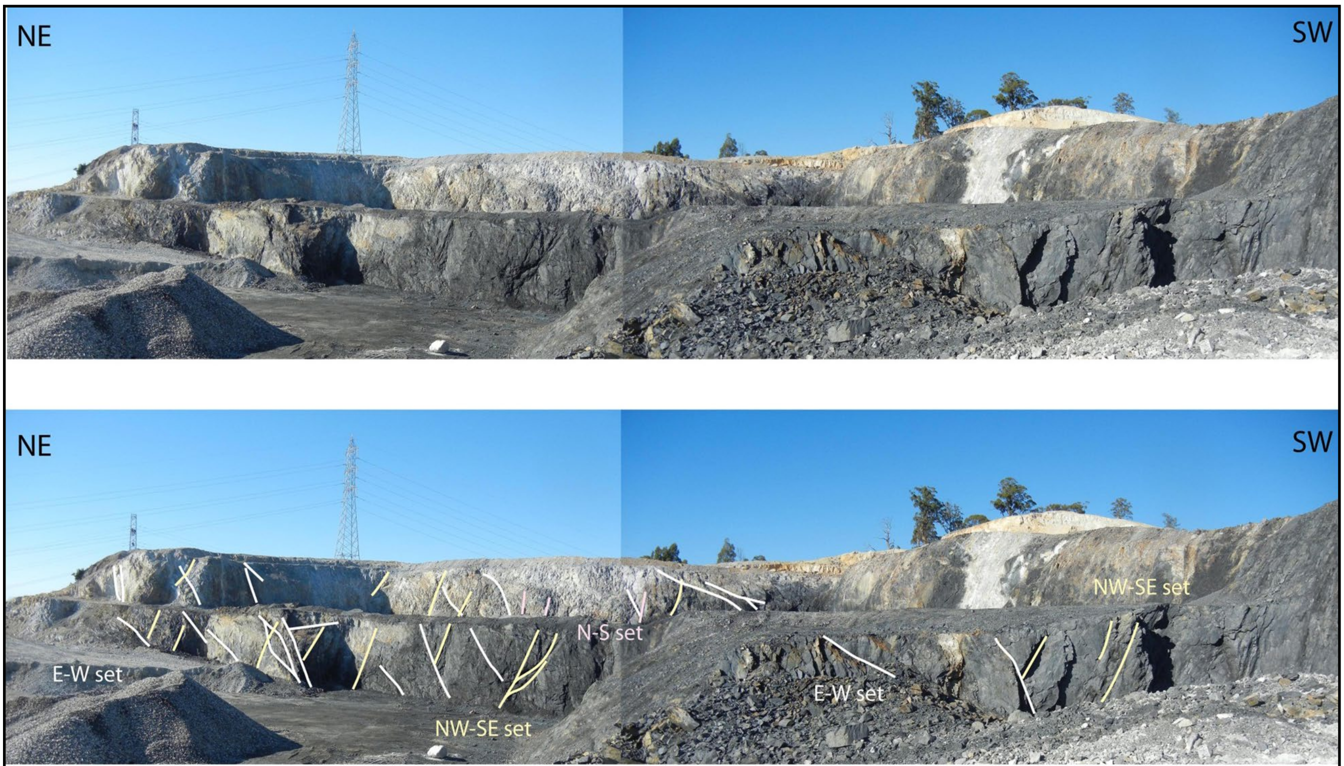


Figure 57. Structural sketch maps of the southern quarry walls in 2013. The coloured rectangles correspond to the coloured rectangles on the Google satellite image (top right). The bedding trends shown by the blue formlines are either east-west trending of west northwest trending.



View towards the SE corner of Shackley Hill Quarry in March, 2013

Figure 58. Shackley Quarry view of quarry walls showing intersection traces of the 3 fault sets. The dominant set is the E-W set (white line traces) followed by the NE-SW set (yellow line traces) and the minor N-S set (pale pink line traces). Compare with the structural maps in Figures 55 and 57 above.

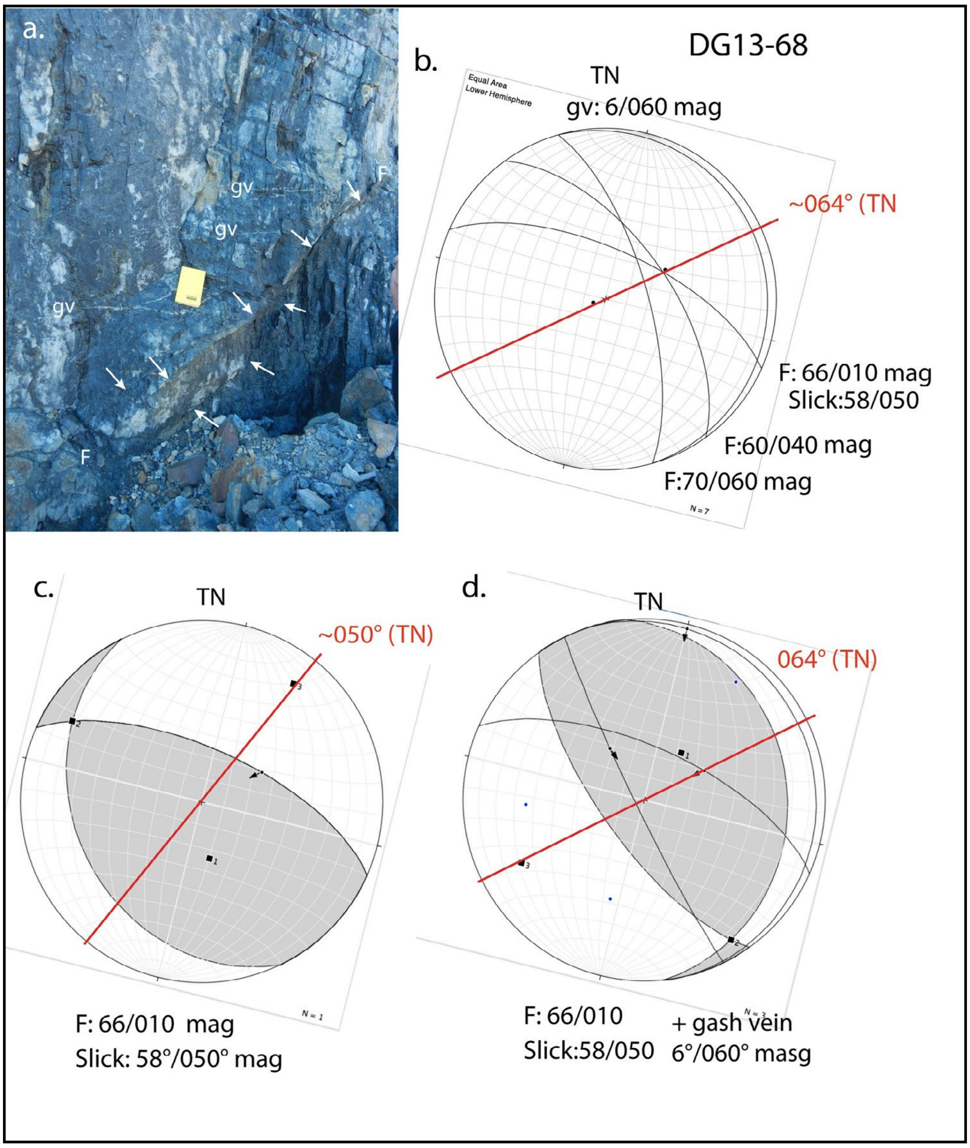


Figure 59 (Left). Reverse fault with sub-horizontal quartz gash veins. Shackley Hill Quarry Station DG13-68. a) Quarry face showing fault, fault splays and gash veins. b) Stereonet of fault and gash vein attitudes. Structural attitude data are all magnetic. The red line denotes the vertical movement plane based on the gash vein attitude. c) Faultkin™ kinematic analysis of fault plane with slickenside showing a 035° movement plane. d) Faultkin™ kinematic analysis of fault plane and gash vein combined. The combined data give an ~050°-230° movement plane.

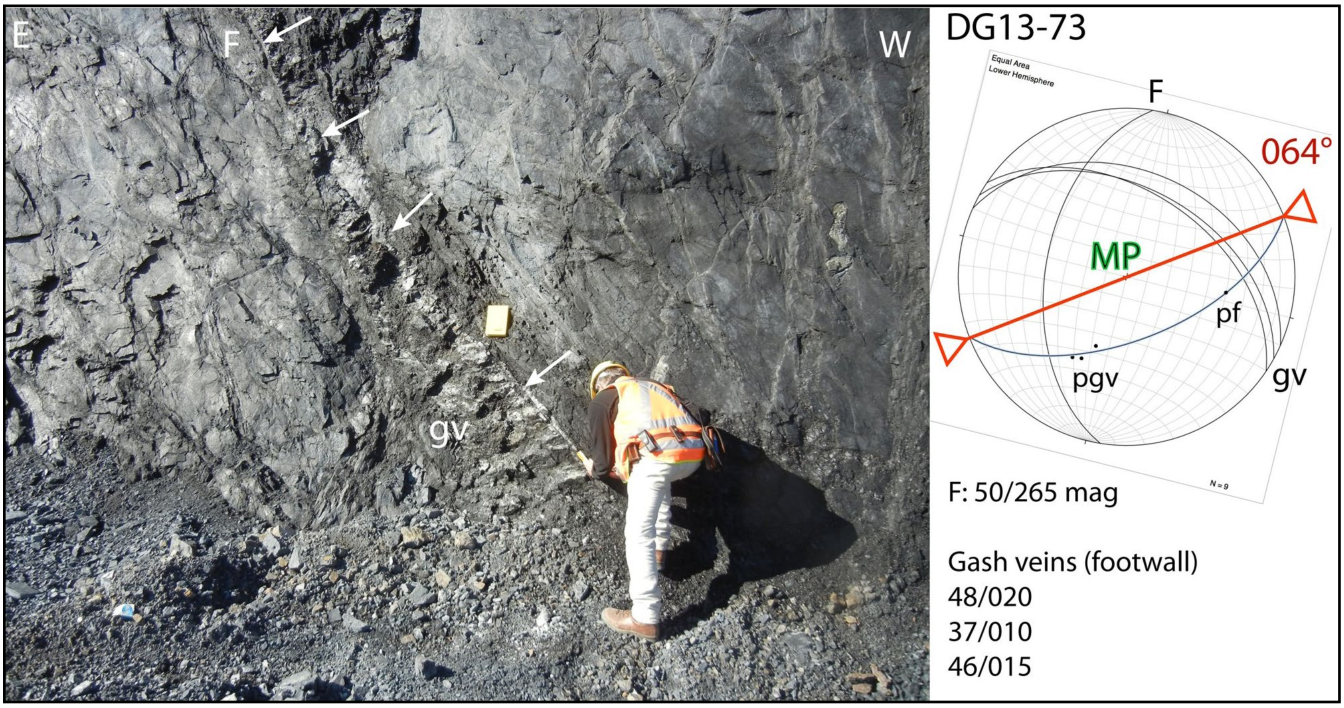


Figure 60. West-dipping, north-striking brittle fault with thin cataclasite gouge along the fault and chalky quartz gash veins in the fault footwall. The movement plane (MP) is the plane containing the pole to the fault (pf) and the poles to the gash veins (pgv). The shortening direction is 064°-244°.

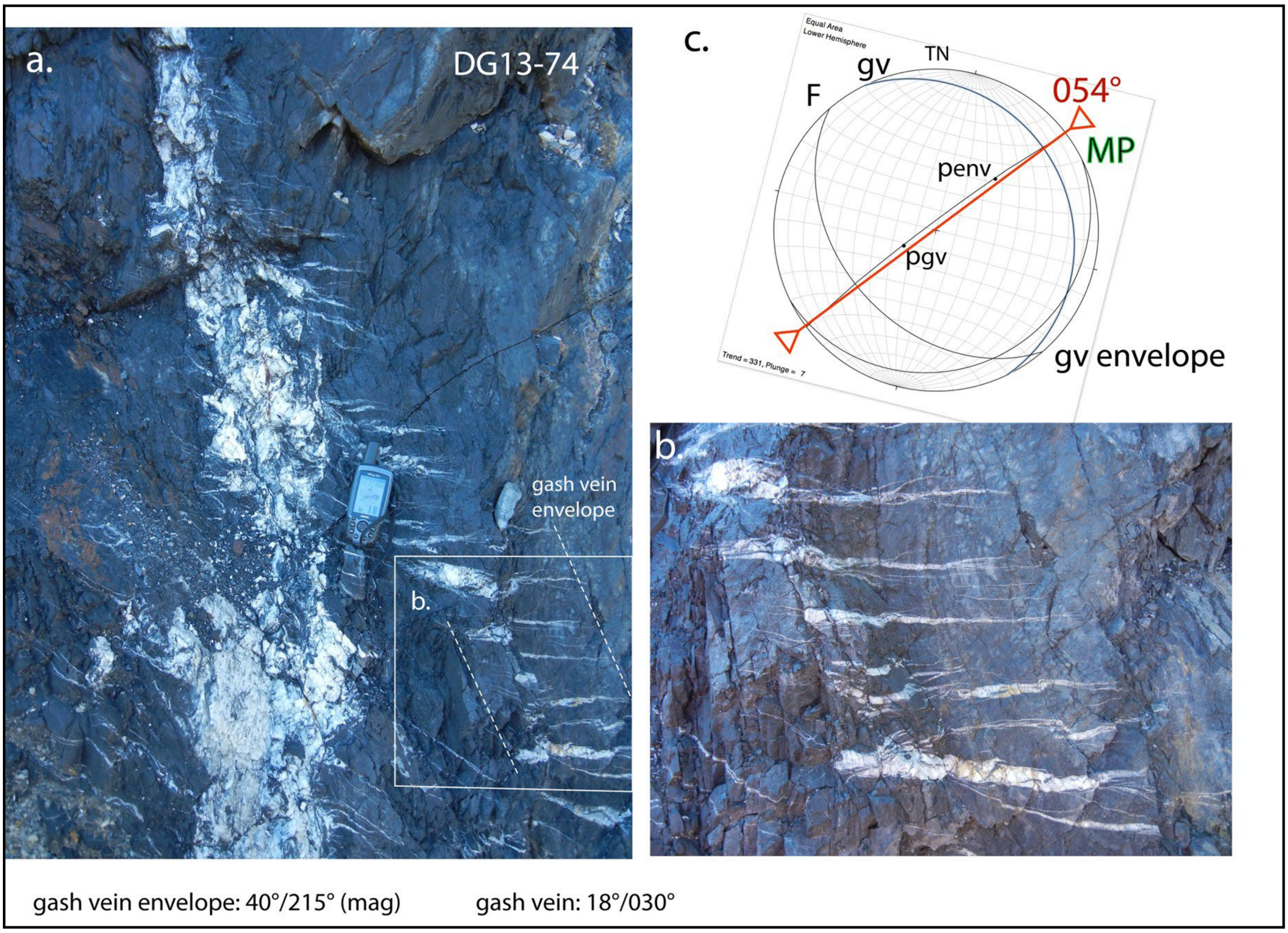


Figure 61 (Above). Irregular, quartz-filled, vein-fault (40°/270° mag attitude) with sub-horizontal, subsidiary quartz gash vein systems. Station DG13-74, Shackley Hill quarry. a) The dominant sinistral gash vein set within a 40°/215° (mag) envelope shown by the white dashed lines. The white rectangle shows the location (b). b) Enlarged portion of the gash vein set shown in (a). c) Stereonet showing the gash vein (gv), the gash vein envelope and the movement plane (MP) determined as the plane containing the pole to the gash vein (Pgv) and the pole to the gash vein envelope (Penv). The shortening direction is 054°-234°.

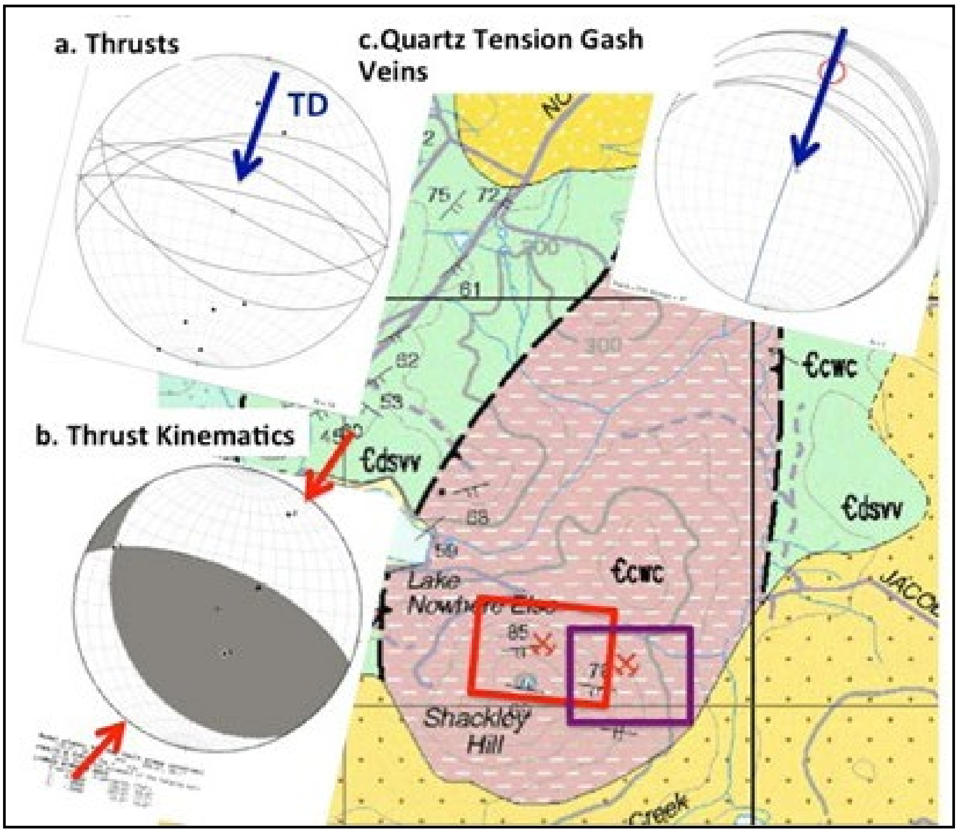


Figure 62 (Right). Fault and quartz vein data from Shackley Hill quarry just west of Sheffield. a) thrust and reverse fault great circle traces with transport direction (TD) shown by the blue arrow. Note the TD is contained within the plane normal to the fault intersections. b) Beach ball diagram for steeply dipping reverse fault plane with slickenside. The fault slip shortening direction is shown by the red arrows. c) Flat quartz tension gash veins as great circle traces with red circle indicating σ1 position and the blue arrow the relative shortening direction from the veins. Note the tension gash veins equate to the σ1 σ3 plane. The areas mapped in the quarry are shown by the red and purple boxes (see Figure 57).

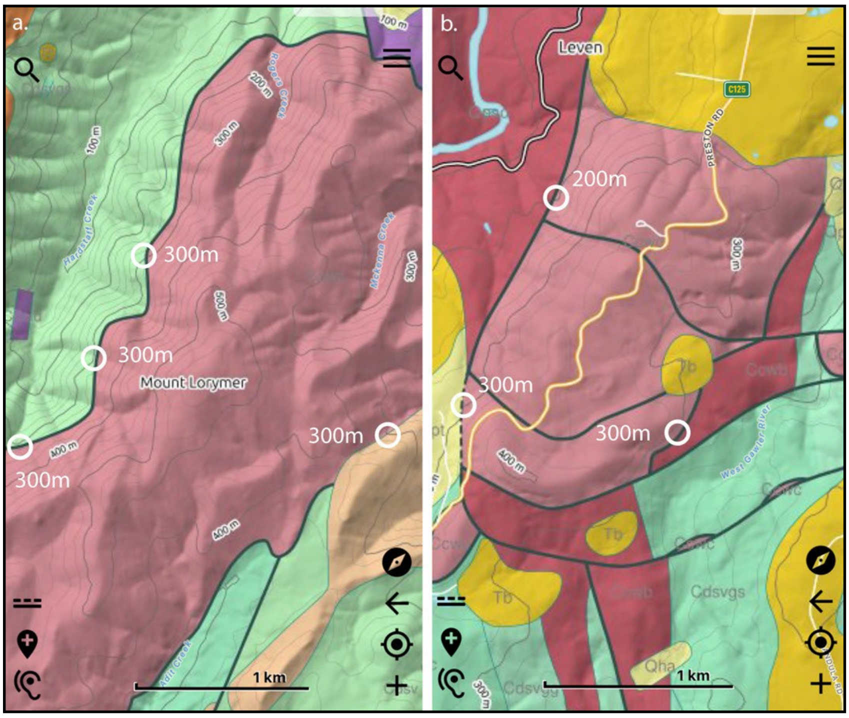
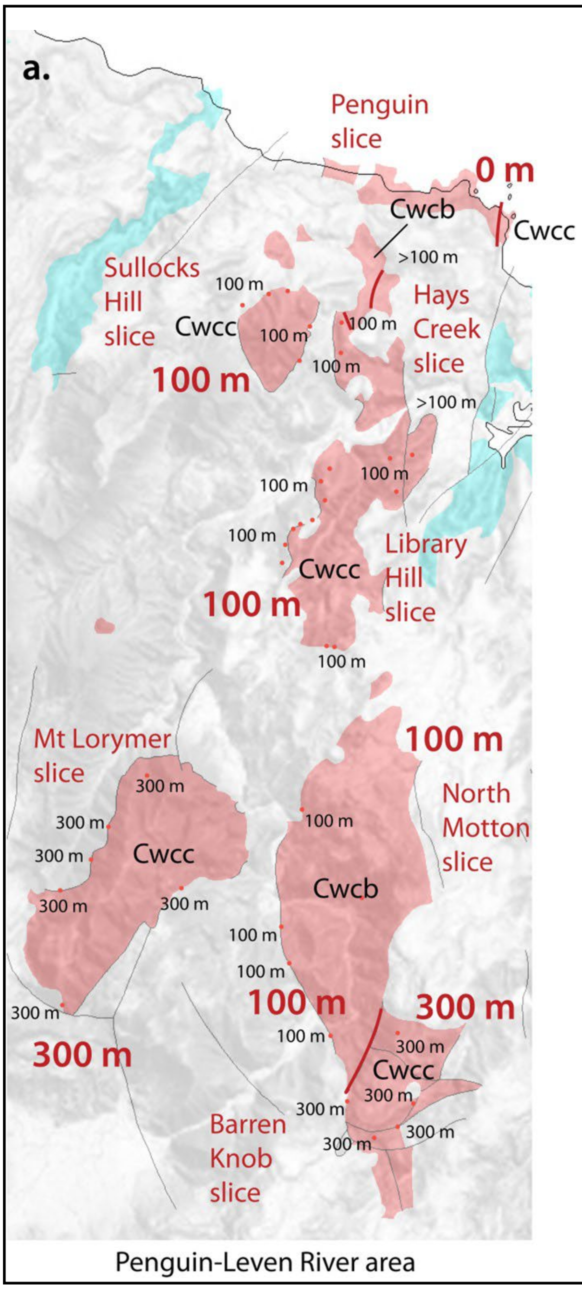
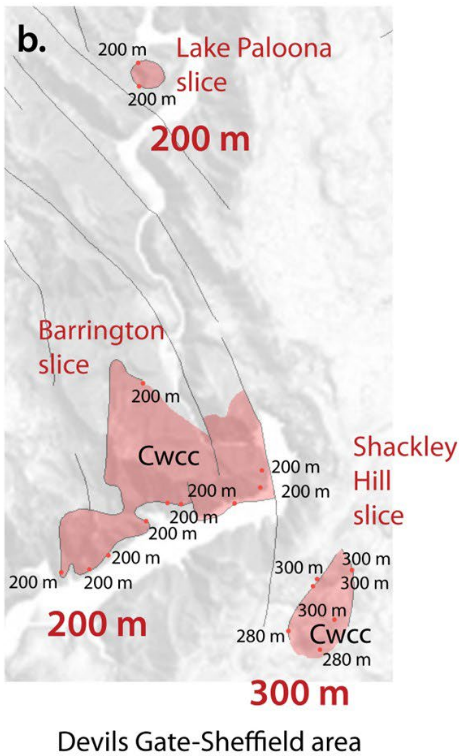


Figure 63. Examples of the Luina Sheet basal fault contact elevations on a Trilobite™ MRT 1:25 000 geological base map. a) Mount Lorymer slice. b) Barren Knob slice. Both slices are gently north-dipping with the fault intersecting and/or sub-parallel with the 200 m elevation contours at the northern ends of the slices.

Figure 64. Spot height map along the basal contact for the different slices of the Luina Sheet. (a) the Penguin-Leven River area and (b) the Devils Gate-Sheffield area. Spot heights are shown by the red dots, contact elevations in black text, and the generalised base level for the different slices by the red bold text.





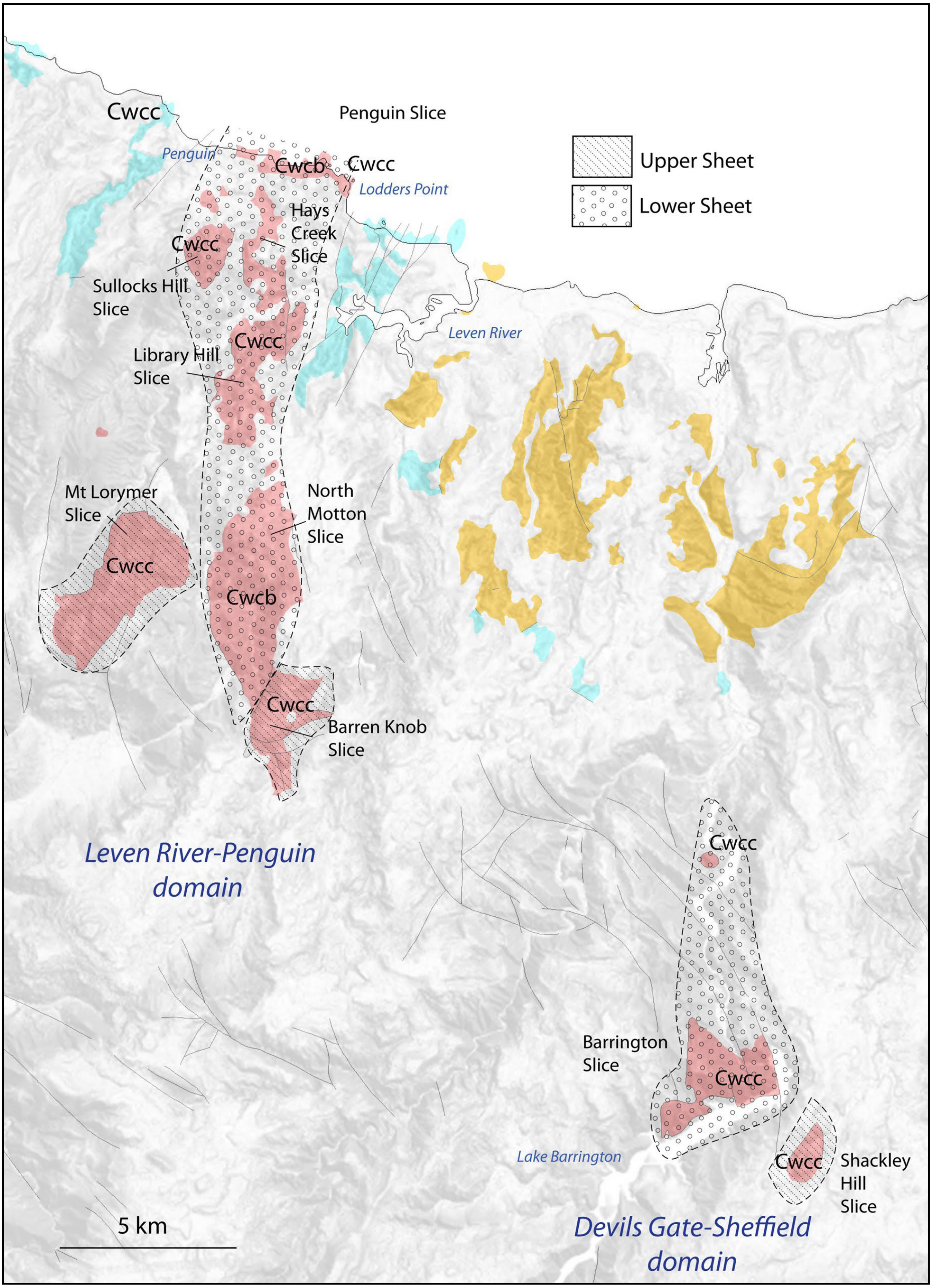


Figure 65. Luina Sheet partitioned into an Upper thrust sheet and a Lower thrust sheet based on regional variation in the topographic level of the basal fault to the sheet. The Upper Sheet has a ~300 m level for the basal fault, whereas the Lower Sheet varies from 0 m (sea level) to 100 m base level in the Leven River-Penguin domain and to 200 m base level further to the south in the Devils Gate-Sheffield domain. See Figure 64 for level details. The Lower Sheet is exposed by erosion of the Upper Sheet with the only relicts of the Upper Sheet preserved at Mt Lorymer, Barren Knob and Shackley Hill.

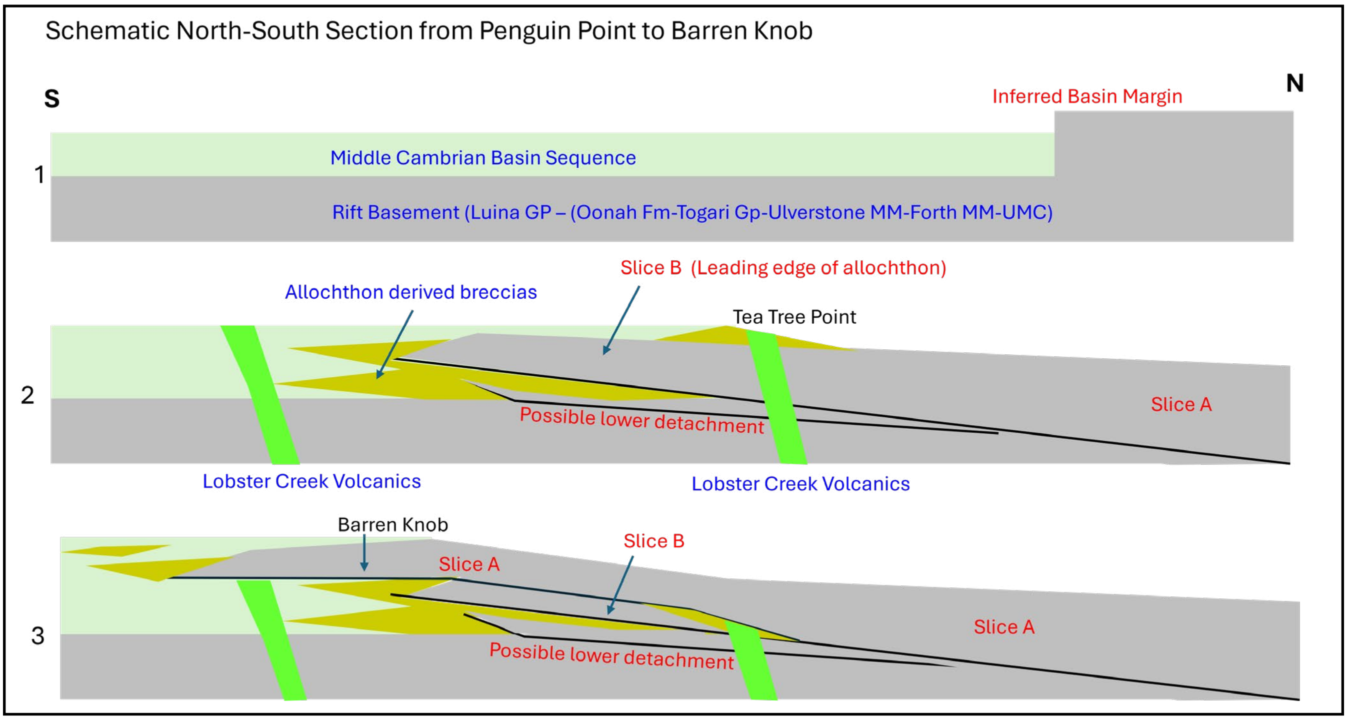


Figure 66. Schematic North-South cross sections depicting temporal emplacement stages of the Luina Sheet.

1. Pre-obduction stage with the northern termination of the Dial Range-Fossey Mountain Trough (grabens).
2. Initial obduction-thrust system with possible lower detachment and development of syn-orogenic sediment and allochthon-derived breccias at the front of the advancing thrust sheet(s).
3. Development of an upper level obduction-thrust with eventual overriding of the syn-orogenic, allochthon derived emplacement breccias.

Pale green unit: Middle Cambrian rift sequence (MRV). Grey unit: basement to the rift including the Oonah L-G Sheet, the Ulverstone and Forth Metamorphic Sheets, Luina Group and possible Ultramafic Sequences. Lemon unit: syn-orogenic, allochthon derived emplacement breccias. Bright green unit: magmatic intrusives including the Lobster Creek Volcanics

4.2 Luina Sheet Emplacement Kinematics

Sheet emplacement kinematics for the Luina Sheet have been determined from the basal fault zone in the immediate hanging wall and footwall, as well as from structural elements within the sheet, including faults with slickensides, kink bands and fault-quartz gash veins (see Section 2.2).

Kinematics from the basal zone include data from the Penguin Thrust at Penguin (DG01-13) of the lower thrust sheet, from the Barren Knob quarry (DG13-66) from the upper thrust sheet, and in the footwall Sprent Formation along the Gunns Plains Road at Sugarloaf gorge (DG13-56), of the lower thrust sheet footwall (see purple shortening vectors, Figure 67). The Luina Sheet transport direction (TD) in the basal zone for the lower thrust sheet is ~040°, whereas the basal fault for the upper sheet has a more northerly trend of ~024°.

Kinematic determinations from the internal parts of the Luina thrust sheet derived from faults with slickensides, kink bands and fault-related quartz gash veins (red shortening vectors, Figure 67) show a consistent east-northeast trend (054° to 074°). Data are primarily from three locations: 1) the Penguin coastal exposures; 2) the Barren Knob area quarries; and 3) the Shackley Hill quarry (Figure 67). Determinations from different elements at the individual locations give remarkably consistent results (Figure 67).

There is, however, a distinct change from the initial sheet emplacement direction recorded by the basal fault zone, to that of subsequent deformation and shortening accommodation within the sheet as it is emplaced.

Comparison of transport directions for all sheets at all levels in the northern Tasmania obduction thrust stack shows consistent NNE-SSW to NE-SW trends with north-over-south sense (Figure 68). This includes the uppermost Luina Sheet (MP3: 204°-220° for basal fault), the Oonah Sheet, the Ulverstone L-G Metamorphic Sheet (MP2: ~188°-224°) and the Forth H-G Metamorphic Sheet (MP1: ~188°-221°).

The data suggest a marked tectonic disconnect between the northern Tasmanian structural and tectonic evolution and the central-southern Tasmanian Tyennan structural and tectonic evolution. This requires an apparent complex plate configuration/interaction for the subduction and exhumation of the Tasmanian microplate.

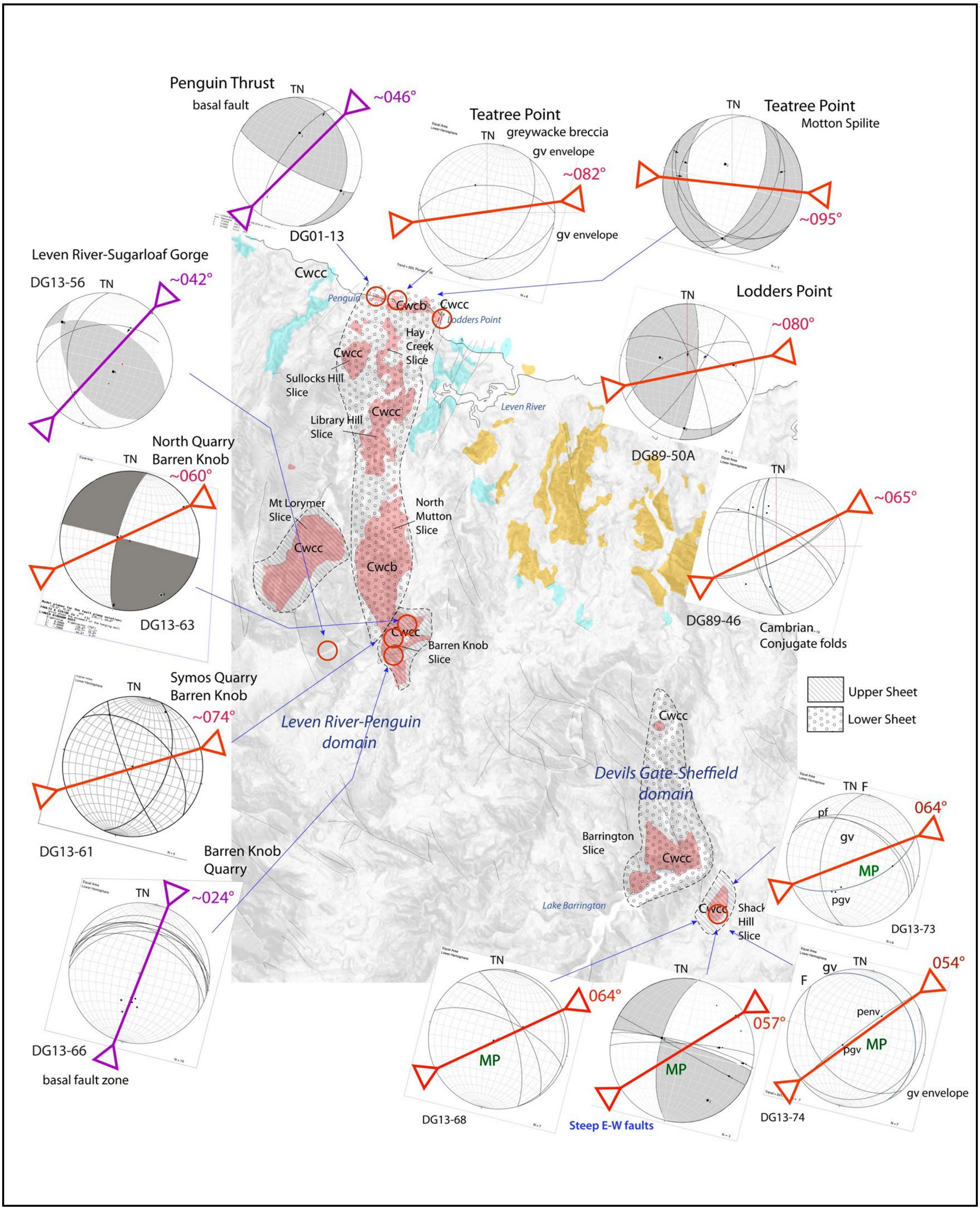


Figure 67. Transport direction (TD) map of the Luina Sheet klippe determined from kinematic analysis of faults with slickensides, kink bands and fault-related quartz gash veins (MP3 data). TD directions from the basal fault zone of the Luina Sheet are shown by the purple arrowed lines. The red arrowed lines show the shortenings internal to the thrust sheet. Faultkin™ beach ball stereonets show TD based on fault and slickenside data. Stereonet plots of fault attitudes and inferred TD are shown for Barren Knob (DG13-66) and Shackleys Hill Quarries (DG13-68). Stereonet plots of gash vein analysis are shown for Teatree Point and Shackley Hill quarry (DG13-73 and DG13-74). Kink Band analysis determinations are shown for Symos Quarry (DG13-61) and Lodders Point (DG89-46).

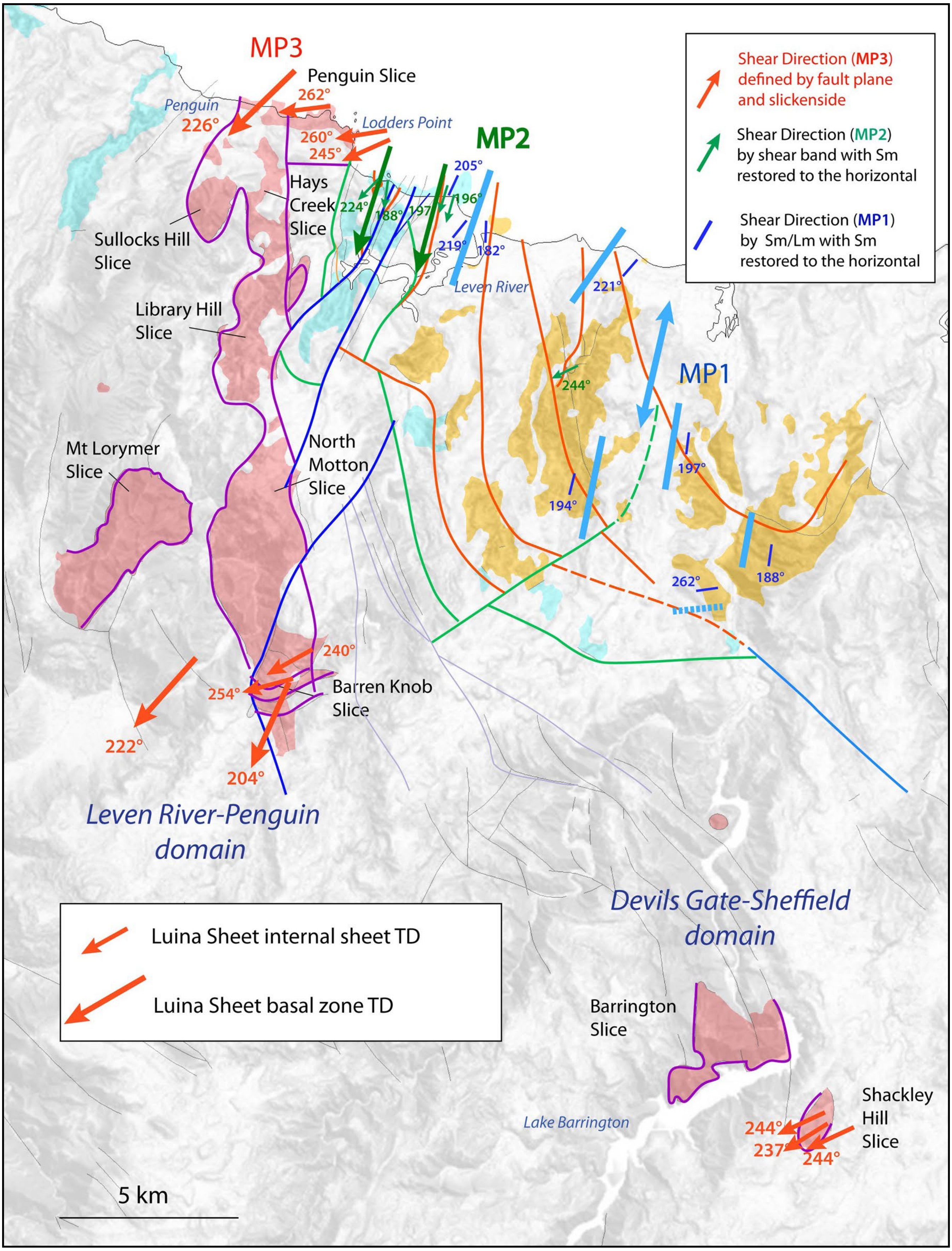


Figure 68. Central North kinematic map for the subduction-exhumation sheet stack of the Forth H-G Metamorphic Sheet (orange coloured unit), the Ulverstone L-G Metamorphic Sheet (orange coloured unit) and the Oonah L-G Sheet (light blue coloured unit). Coloured arrows show the transport directions based on MP1 movement plane determinations from Sm/Lm (blue lines), MP2 movement plane determinations from shear bands in high strain zones (green arrowed lines), and MP3 movement planes from Faultkin™ analysis of faults, analysis of kink bands and gash vein-fault relationships (red arrowed lines).

The Luina Sheet (pink coloured unit) has MP3 movement plane determinations showing patterns both within and at the base of slices/klippe. The basal fault zone(s) has a consistent NNE-to-SSW transport direction (~204°-226°), whereas the internal parts of the Luina Sheet show a strong ENE-WSW shortening direction (~240°-260°).

4.3 Luina Sheet Transport Distance

Minimum distance of emplacement can be established using the positions and separation of the Luina Sheet klippe measured in the transport direction. Using the Barrington Chert klippe a minimum transport distance is ~22 km, while the current location of the Mt Bischoff Klippen suggest a minimum transport distance of up to ~50 km (Figure 69).

4.4 Luina Sheet Emplacement-Temporal Tectonostratigraphic Relationships

Emplacement of the northern part of the Luina Sheet involves syntectonic thrust-sheet erosion and development of sedimentary breccias at the sheet leading edge, with eventual overriding of breccias and incorporation with syn-MRV (Mt Read Volcanics) deposition as well as intrusion into the advancing thrust sheet (Figure 66). Two levels of thrusting, required by the different base levels of the Luina Sheet (see Section 4.1), result in an upper and lower sheet (Figures 65 and 66).

The evolution of the Luina obduction-thrust system is shown in a series of simple schematic temporal-tectonostratigraphic diagrams (Figures 70a and 70b). In summary:

Time T1 at ~496 Ma shows the initial obduction of the oceanic thrust sheet associated with coeval rift-related volcanism. Variation in the chert thickness.

Time T2 at ~495 Ma shows a complex emplacement involving transfer faults (lateral ramps), sheet segmentation, erosion at the leading edge of the allochthon linked with syn-MRV (Mount Read Volcanics) deposition of allochthon-derived breccias.

Time T3 (post 495 Ma) continued obduction thrusting with both frontal and lateral ramp development. Variation in the chert thickness.

Time T4 emplacement to current position and continued erosion with allochthon-derived breccias interbedded with Mindyallan fauna (~492 Ma).

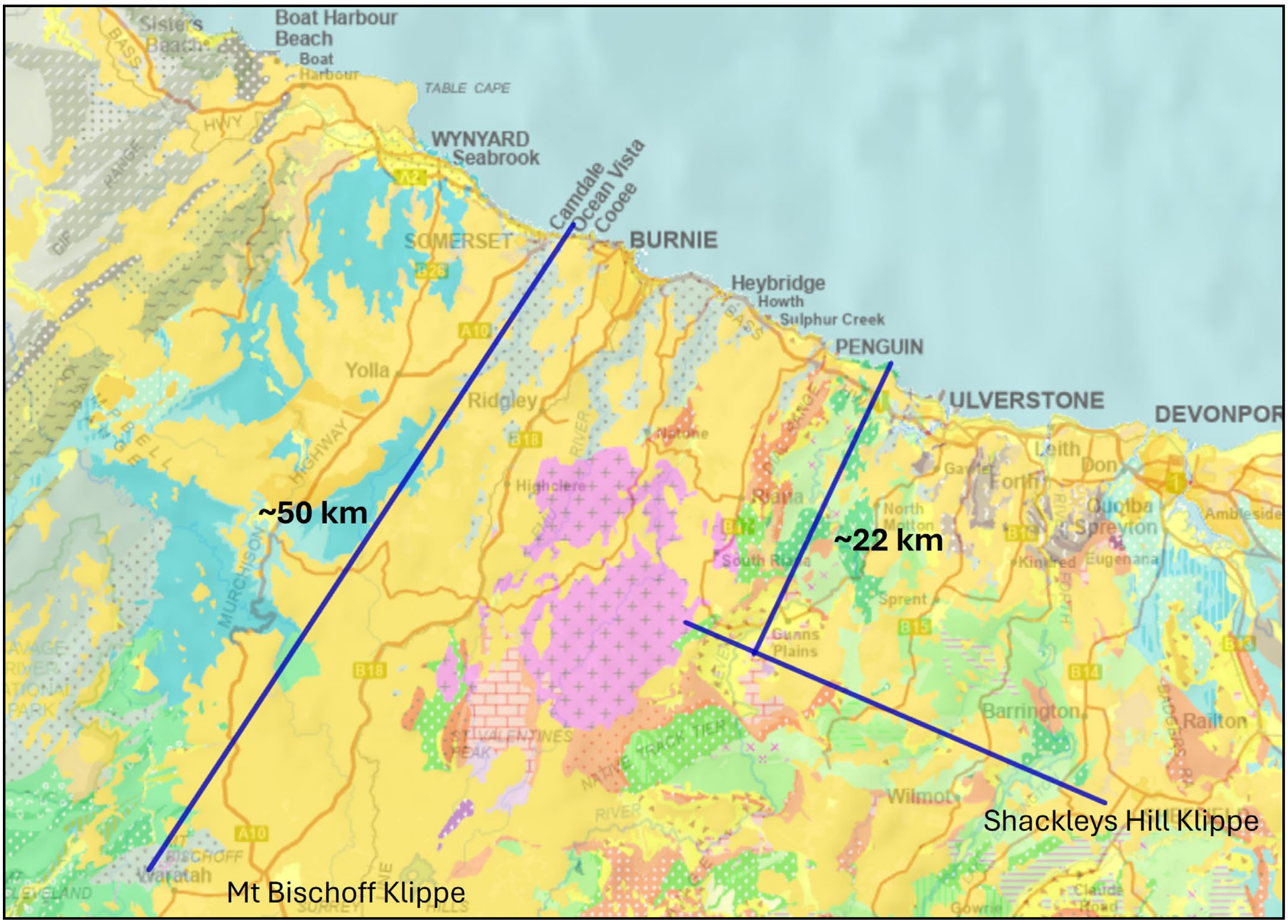
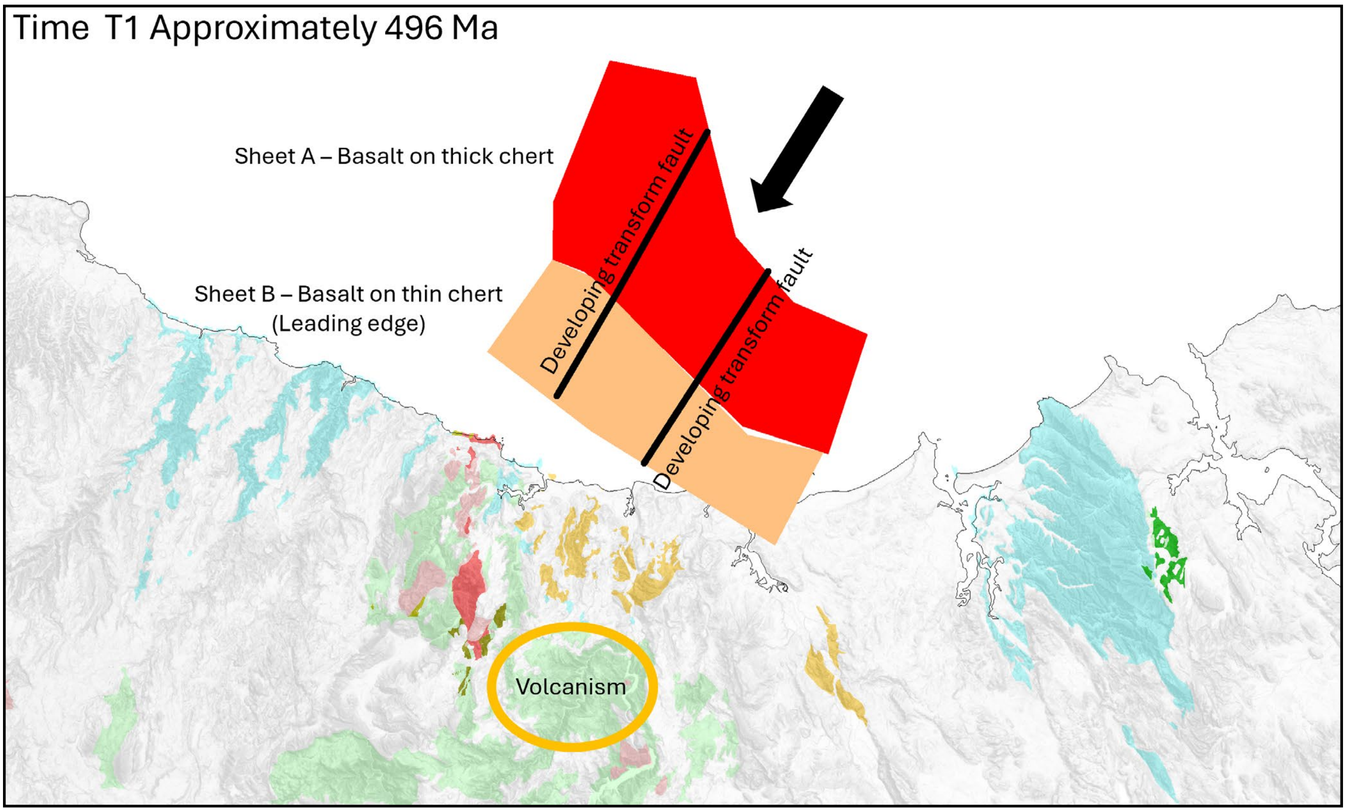


Figure 69. Luina Sheet transport distance minimum estimates using separation distance between klippe measured in the transport direction. A distance of ~22 km is obtained from the Barrington Chert Klippe while a distance of up to ~50 km is suggested by the current location of the Mt Bischoff Klippen.



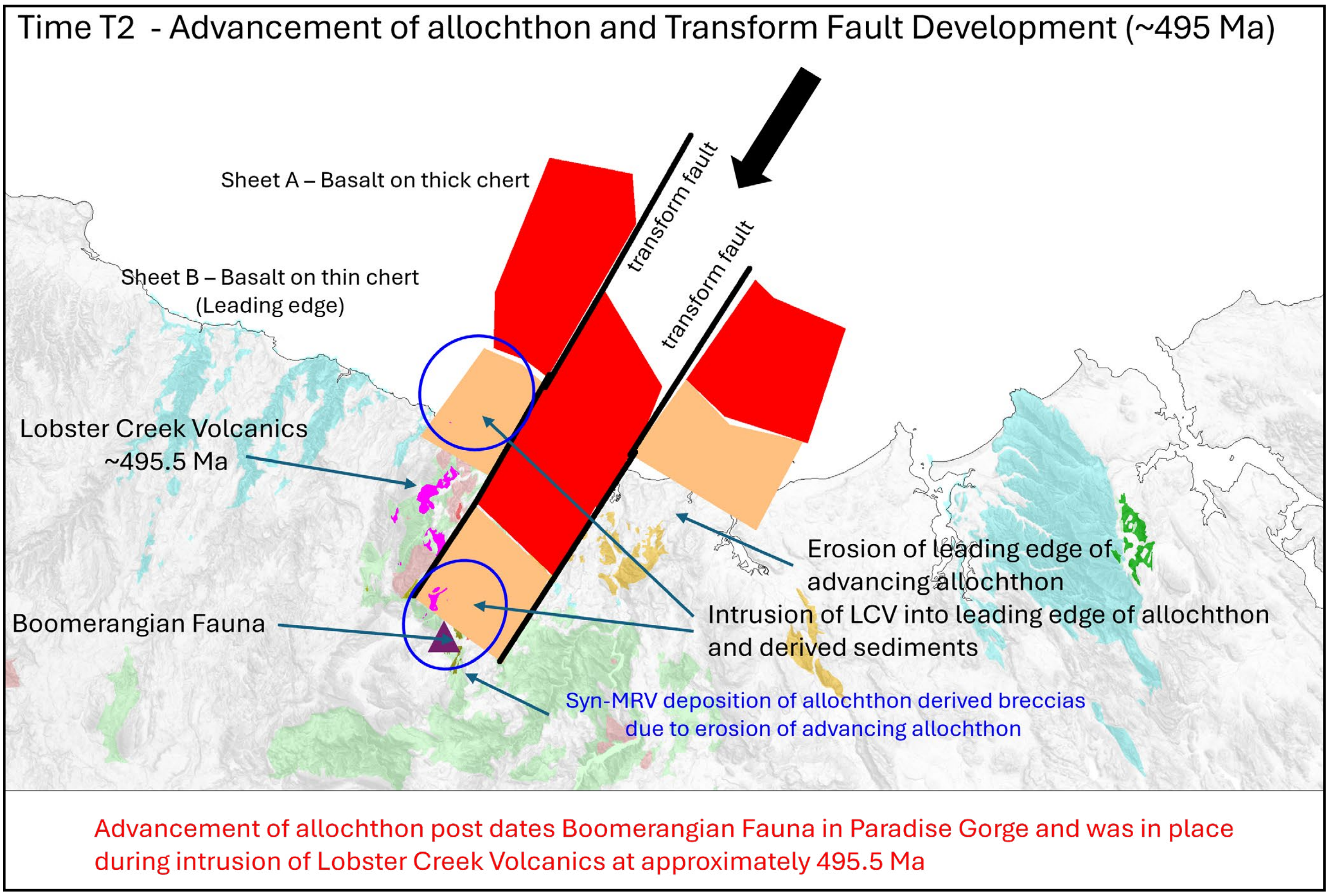
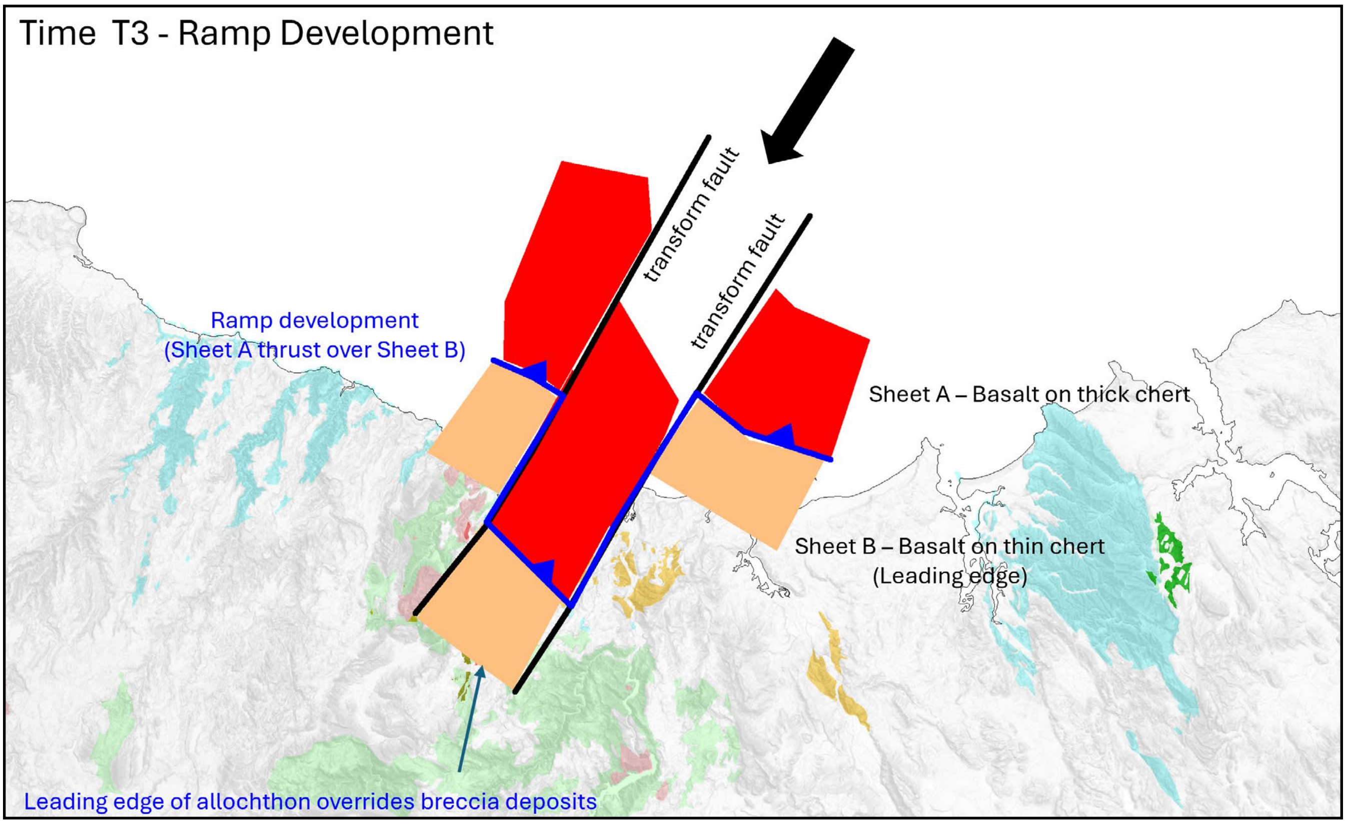


Figure 70a. Early emplacement stages of the Luina obduction thrust sheet.

Time T1 at ~496 Ma shows the initial obduction of the oceanic thrust sheet associated with coeval rift-related volcanism. Variation in the chert thickness

Time T2 at ~495 Ma shows a complex emplacement involving transfer faults (lateral ramps), sheet segmentation, erosion at the leading edge of the allochthon linked with syn-MRV (Mount Read Volcanics) deposition of allochthon derived breccias.



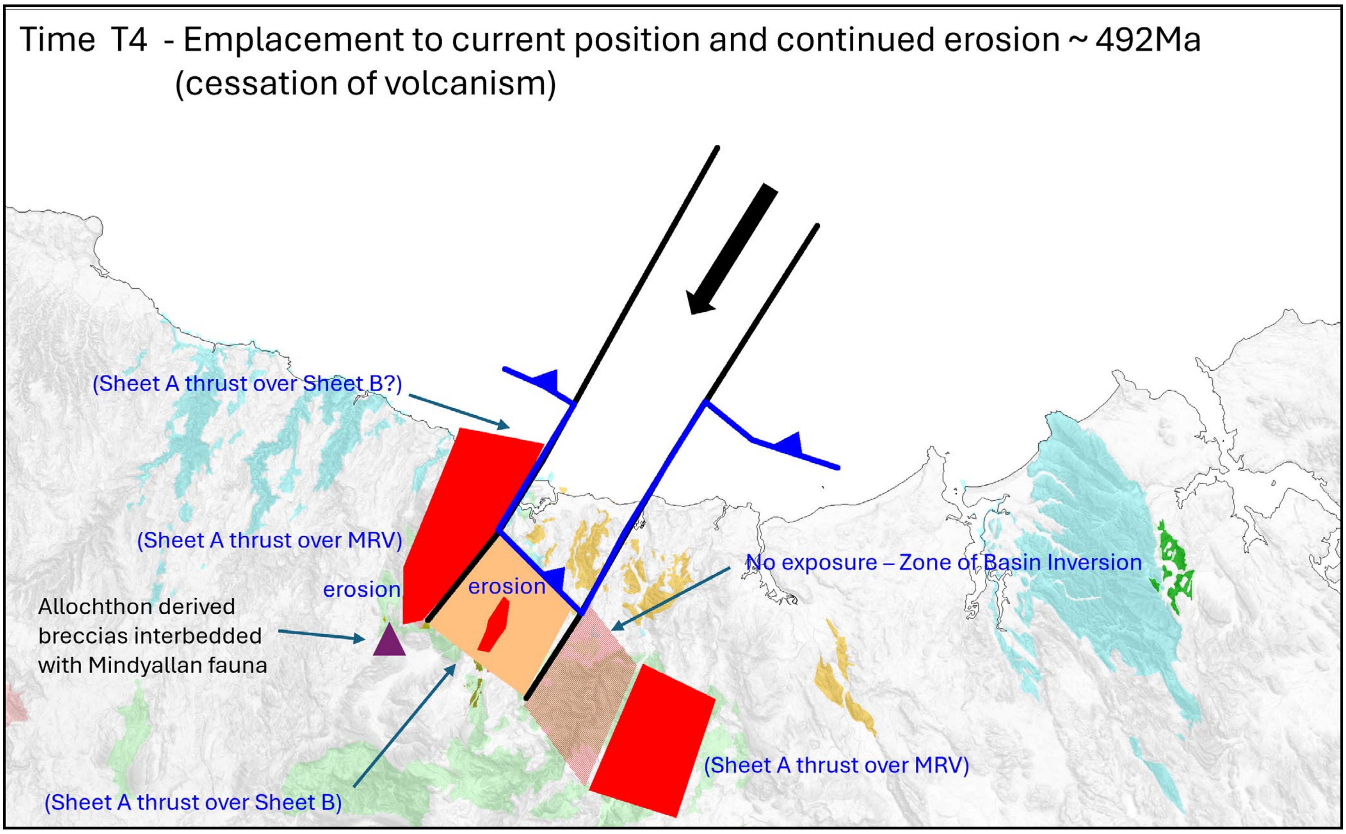


Figure 70b. Early emplacement stages of the Luina obduction thrust sheet continued.

Time T3 (post 495 Ma) continued obduction thrusting with both frontal and lateral ramp development. Variation in the chert thickness

Time T4 emplacement to current position and continued erosion with allochthon derived breccias interbedded with Mindyallan fauna (~492 Ma).

5.0 TECTONIC IMPLICATIONS OF THE LUINA SHEET BASED ON SHEET STRUCTURE

5.1 New Tectonic Element

The group of shallow faults responsible for emplacement of the Luina Sheet are part of the newly designated Narawntapu Thrust Belt. This thrust belt consists high-level thin-skinned north-dipping, approximately north-northwest-trending thrust and reverse faults in a zone extending from Wynyard/Doctors Rocks in the west, to Badger Head/Beaconsfield in the east. The extent of the thrust belt in the transport direction has been estimated to be between 20 and 50 km (Figure 69), constrained by the southern limit of the chert klippe and the current structural position of the Mt Bischoff Klippen.

Within the Narawntapu Thrust Belt, there exist several large basement blocks that have been tectonically transported to the SW during a phase of SW-directed subduction that commenced in the Late Cambrian (Figures 71 and 72). The blocks comprise: the Burnie Block, the Luina Sheet, the Oonah equivalents exposed in the Goat Island to Ulverstone area (including the Ulverstone Metamorphics), the Forth Block, the Great Bend Inlier, the Port Sorell Formation, the Badger Head Block and the ultramafic and adjacent units in the Beaconsfield area. These structural sheets, with the exception of the Forth Block comprise parts of the External Zone (Berry, 2014) and are interpreted to form much of the concealed basement to the Middle Cambrian Fossey Mountain – Dial Troughs in northern Tasmania. They are composed of Neoproterozoic Oonah and Port Sorell Formation, the Early Cambrian Luina Group and Early Cambrian ultramafic sequences. The Forth Block represents a fragment of the underlying Internal Zone (Tyennan equivalents) (Berry, 2014) that has been incorporated into the thrust complex. Most of these blocks have been emplaced within or on the Middle Cambrian basin, however the western part of the Burnie Block, including the Mt Bischoff Klippe has been emplaced outside the inferred basin margins. Parts of the Dial Range Trough, including the largely fault bound early rift sedimentary sequence (Isandula Formation), and potentially the Blyth Creek Formation from the Beaconsfield area, have been incorporated into the developing thrust belt during allochthon emplacement.

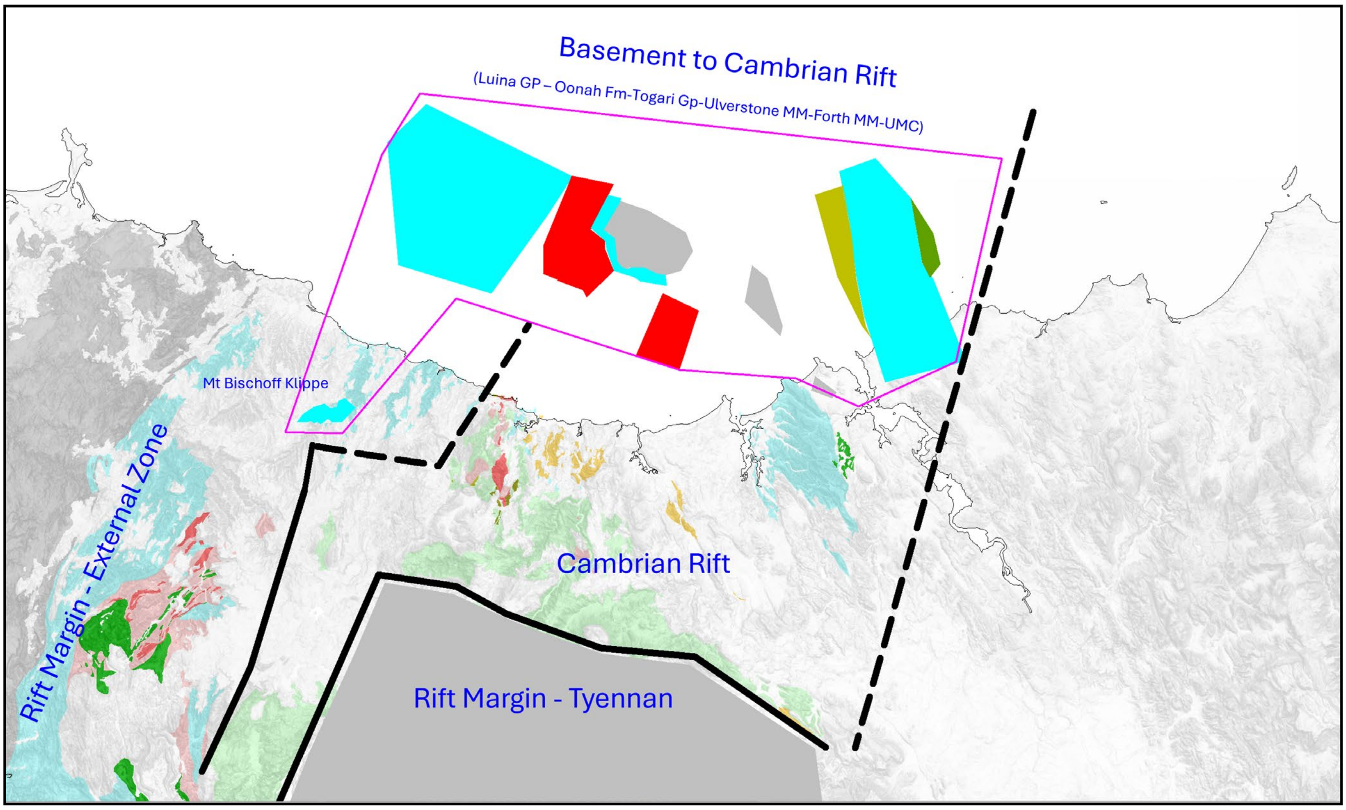


Figure 71. Initial, pre-thrusting state of the tectonic elements that are impacted by the developing Narawntapu Thrust Belt. Black line traces are normal/transfer faults of the combined Cambrian rift graben system. Light blue: Neoproterozoic Oonah correlate sandstone-mudstone association. Red: Early Cambrian Luina Sheet klippe of chert-basalt association. Grey: Proterozoic metamorphosed quartzite-schist-phyllite association. Olive green: Neoproterozoic Port Sorell blueschist association. Deep green: Early Cambrian ultramafic remnants of the obducted ophiolite sheet.

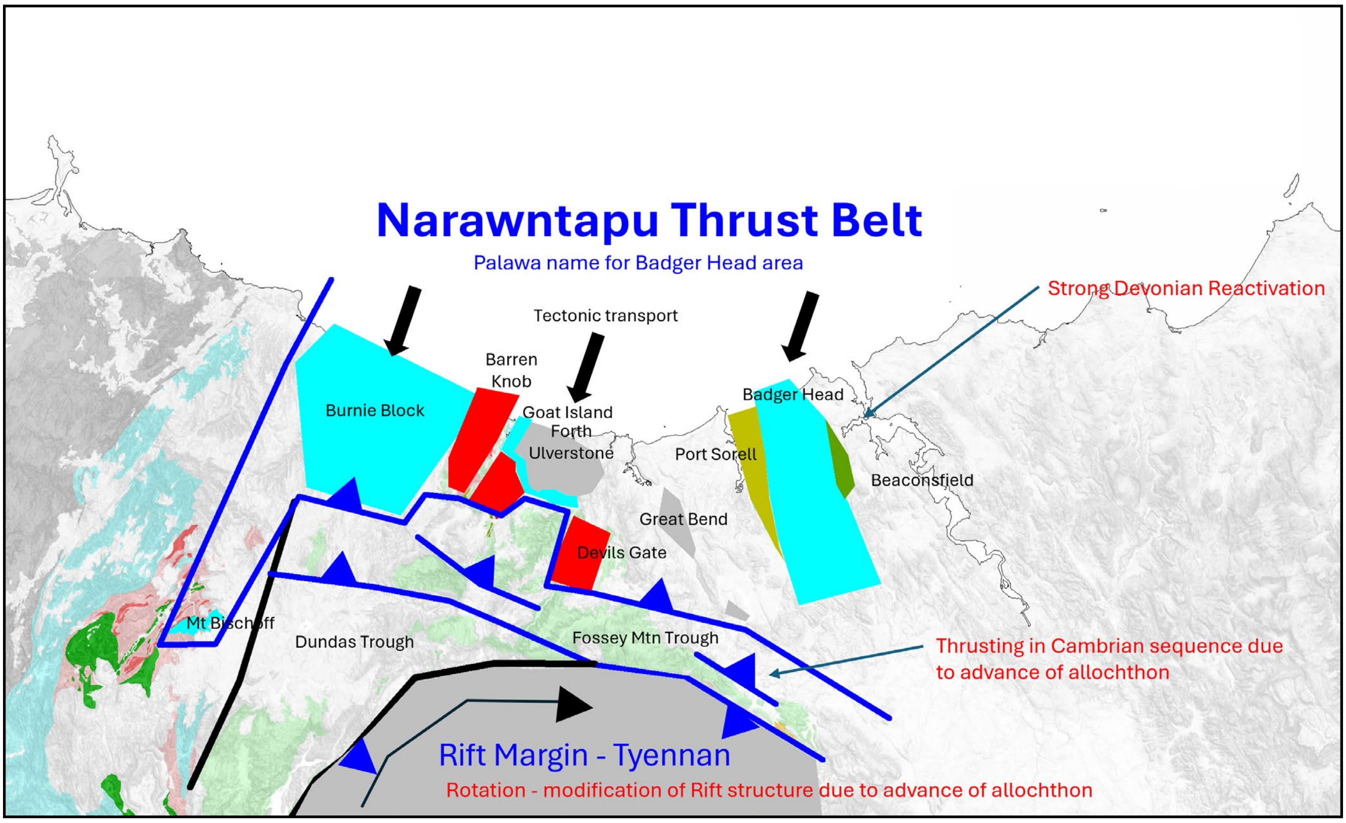


Figure 72. Final state geometry of the Narawntapu Thrust Belt. Thrust fault traces and reactivated Cambrian basin margin faults are shown by the barbed, heavy blue lines. Black line traces are normal faults of the combine rift graben system. Light blue: Neoproterozoic Oonah correlate sandstone-mudstone association. Red: Early Cambrian Luina Sheet klippe of chert basalt association. Grey: Proterozoic metamorphosed quartzite-schist-phyllite association. Olive green: Neoproterozoic Port Sorell blueschist association. Deep green: Early Cambrian ultramafic remnants of the obducted ophiolite sheet.

High-level emplacement of basement-derived thrust sheets is well constrained in the southern part of the Middle Cambrian Dial Range Trough, and locally onto the adjacent Fossey Mountain Trough to the south. These relationships are best shown by the syn-depositional emplacement of the Luina Sheet as previously discussed (see Section 4.0). The Sprent Formation is considered to represent a local coarse breccia apron developed by the marginal disaggregation of the allochthon during emplacement. In places it has been overthrust by the advancing allochthon (see Figure 66). The Sprent Formation is developed at several stratigraphic horizons within the fossiliferous sedimentary sequences that define the Dial Range Trough. These range in age from the Boomerangian in the Paradise Gorge area, to Mindyallan in the Riana area.

Both the Luina Group allochthon and the associated syn-emplacement sedimentary sequence have been intruded by the Lobster Creek Volcanics dated at 495.5+-xxx Ma (Vicary et al., 2015). This suggests that the main thrust dominated event that defines the Narawntapu Thrust Belt was synchronous with the Late Tyndall Group or Zig Zag Hill Formation deposition and coincided with the last phase of Mt Read Volcanic belt volcanism between 496 and 492 Ma (Vicary et al., 2015).

The allochthonous basement blocks and thrust faults comprising the Narawntapu Thrust Belt were emplaced prior to the commencement of the unconformably overlying Owen Group sedimentation, however some faults may have remained intermittently active during progressive slab rollback until the reestablishment of a new subduction system during the Devonian Tabberabberan Orogeny. Such events are recognised in the geological record as local unconformities (ie the Haulage Unconformity) and periods of non-deposition in the subsequent Wurrawinna Supergroup deposition.

During SW-directed thrusting, the northern margin of the Tyennan Block acted as a impediment to thrust propagation, with the development of south-dipping back thrusts and strong reactivation of existing structures developed during the earlier Tyennan Orogeny (Gray et al., 2025). Local rotation of the structures within the northern Tyennan Block and the adjacent Middle Cambrian transfer zone may have commenced during this deformation. Paleomagnetic reconstruction along the southern margin of the Fossey Mountain Rift suggests that the period of rotation may have continued to the Lower Ordovician (Musgrave and Job, 2020).

Within the adjacent Cambrian sequence, in the southern part of Fossey Mountains Trough, north dipping thrusts and E–W to ESE–WNW folding are evident. The north dipping thrusts represent reactivation of Middle Cambrian growth faults. The presence of Zig Zag Hill equivalents in associated synclinal cores suggest that the exposed structural style also developed during the Late Cambrian deformation. Exposed basement slices in the eastern part of the Fossey Mountain Trough may have been uplifted during the Late Cambrian, however there is evidence suggesting later reactivation (Woodward et al., 1993). The fold and thrust development in the southern part of the Fossey Mountain Trough represents a transition to the deeper, thick-skinned style of thrusting in the underlying basement and is continuous with the Late Cambrian deformation style developed in the adjacent Tyennan Block and Dundas Trough to the south.

The structural style of the Narawntapu Thrust Belt is repeated along the eastern margin of the upfaulted Tyennan Block in the Adamsfield area in southern Tasmania where the distal Middle Cambrian sequences overlie – and are structurally intercalated with – basement lithologies of the external zone. The Neoproterozoic Needles slice has been thrust over the tectonically disrupted Cambrian sequence and is unconformably overlain by the Late Cambrian Tim Shea Sandstone, part of the overlying Denison Group sequence. The relationship of the adjacent Cark Group block within the Narawntapu Thrust Belt remains uncertain.

Berry (2014) summarised the major Proterozoic and Cambrian tectonic zones in Tasmania and included the Adamsfield Trough as part of the largely concealed Eastern province of thin-skinned structural tectonic units (Figure 73a). Comparison between the Adamsfield and Dial Range areas suggests that both were deformed in the same Late Cambrian deformation event. Although geological continuity between the two areas is not preserved due to extensive thick Late Carboniferous to Cenozoic cover. It is suggested that the Narawntapu Thrust Belt extends south along the eastern Tyennan margin to the Adamsfield area and encompasses the previously defined Eastern Province. A revised map showing the major Proterozoic and Cambrian tectonic elements of Tasmania is shown in Figure 73b. The Narawntapu Thrust Belt defines a zone of highly faulted upper crust that forms an intermediate belt between the rifted Middle Cambrian and associated Proterozoic elements (the Dundas-Fossey rift sequence and associated basement elements including the uplifted Tyennan Block) to the west, and the Mathinna Terrane to the east. Although much of the sedimentary sequence overlying the largely oceanic basement of the Mathinna Terrane post-date the Late Cambrian development of the Narawntapu Thrust Belt, the proximity of the Mathinna Terrane to the Late Cambrian subduction zone suggests that the underlying basement was also strongly deformed during this event. Both the Narawntapu Thrust Belt and the adjacent Mathinna Terrane reflect hanging wall deformation of the eastern margin of the Tasmanian microcontinent during SW-directed subduction that commenced in the Late Cambrian.

6.0 CONCLUSIONS

The northern Tasmanian part of the Luina Sheet is a series of erosional remnants of isolated klippe, made up of Cambrian chert (Cwcc) and basalt (Cwcb). The once continuous sheet has a basal brittle-fault contact and internal deformation accommodated by an array of faults, kink bands and quartz gash veins. All transport direction (TD) determinations give a consistent northnortheast- south-southwest shortening direction with south-directed thrust transport. The Luina Sheet and the northern Tasmanian region is part of the Middle to Late Cambrian Narawntapu thrust belt.

Transport directions for all sheets, at all levels in the northern Tasmania thrust stack show consistent NNE-SSW to NE-SW trends with north-over-south sense (Figure 67). This indicates that the plate configuration and plate dynamics in northern Tasmania remained consistent for the Early Cambrian subduction/exhumation sheet emplacement (Forth, Ulverstone and Oonah Sheets) to the Late Cambrian obduction-thrust sheet emplacement (Luina Sheet and ophiolite). The role of Late Cambrian thrusting has clearly been underestimated. The effects of the Late Cambrian thrusting can be seen: 1) along the eastern Tyennan margin to the Adamsfield area, encompassing the previously defined Eastern Province; and 2) along the western Tyennan margin through to Zeehan and Mt Bischoff.

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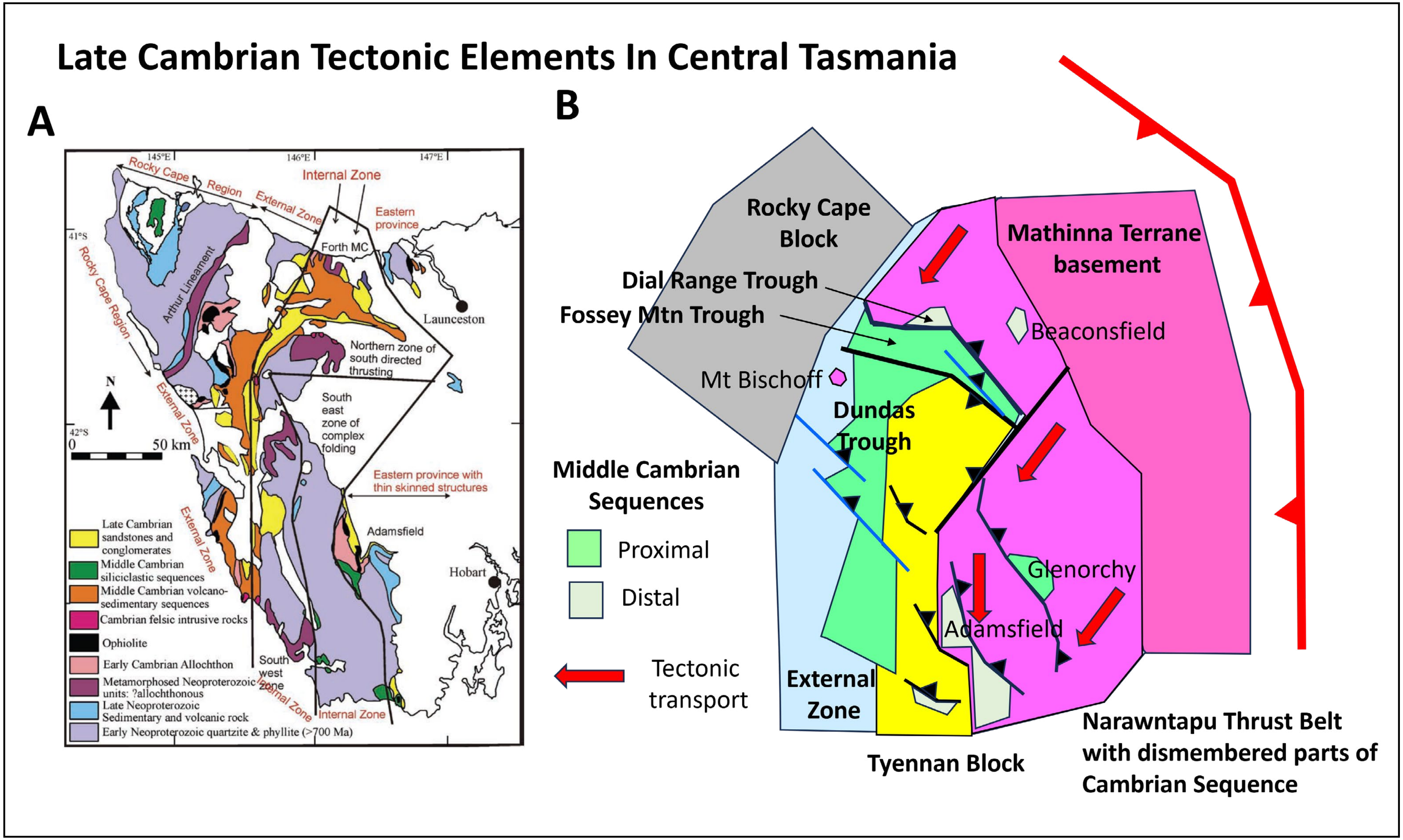

Figure 73. Late Cambrian Tectonic Elements in Central Tasmania. a) Major Proterozoic and Cambrian Elements of Tasmania (Modified from Berry, 2014 and Figure 5 in Berry and Bull, 2012). b) Revised Late Cambrian Tectonic Elements of Central Tasmania.

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APPENDIX A

Field notebook scans for Penguin Fault and Lodders Point outcrops

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