

Gold mineralisation and the regional Palaeozoic structure of the Mathinna Supergroup, eastern Tasmania

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CONTENTS

SUMMARY	3
INTRODUCTION	4
Access and infrastructure	4
Gold discovery and production	4
Comparisons with Victorian gold deposits	6
Mineralisation style	6
Previous structural studies	7
Terminology	7
REGIONAL STRATIGRAPHY AND STRUCTURE EAST OF THE RIVER TAMAR	9
Mathinna Supergroup	9
<i>Introduction</i>	9
<i>Structures west of the Scottsdale Batholith</i>	9
D ₁ and D ₂	9
D ₃	14
<i>Structures east of the Scottsdale Batholith</i>	18
D ₂	18
D ₃	21
<i>Kinking and megakinking</i>	22
<i>Deformation ages</i>	22
<i>A revised turbidite stratigraphy</i>	23
Igneous and post-Mathinna Supergroup sedimentary rocks	23
<i>Granitoid rocks</i>	23
<i>Post-Carboniferous rocks</i>	23
STRUCTURAL SETTING OF GOLD MINERALISATION EAST OF THE RIVER TAMAR	24
Introduction	24
Lefroy and Back Creek goldfields	24
<i>Lefroy</i>	24
Reef offset at Lefroy	27
<i>Back Creek</i>	27
<i>Regional-scale structures</i>	27
Alberton, Mathinna and Mangana	29
<i>Alberton</i>	29
<i>Mathinna</i>	30
<i>Mangana</i>	33
<i>Controls on reef orientation</i>	33
EFFECTS OF STRUCTURE ON GOLD MINERALISATION	35
Origin of the gold	35

Faulting and gold mineralisation	35
Fluid reduction	36
CRUSTAL-SCALE STRUCTURE	37
Correlations with rocks west of the River Tamar	37
Correlations with mainland Australia	39
MODELS AND TECHNIQUES FOR MINERAL EXPLORATION	41
Introduction.....	41
Historical models for Au mineralisation	41
Structural mapping in mineral exploration	41
Aeromagnetic data	42
Geochemistry	42
Drilling	42
CONCLUSIONS	43
ACKNOWLEDGEMENTS.....	43
REFERENCES	44

Tables

1. Summary of structural interpretations.....	8
2. Relationships between deformations	7

Figures

1. Simplified geology showing the major goldfields of eastern Tasmania and the West Tamar region ...	5
2. Production and grade of lode gold in Victoria, eastern Tasmania and the West Tamar region	6
3. Alternate carbonate-rich and quartz-rich layering in the Tasmania Reef at Beaconsfield	8
4. Time-space diagram for rocks in eastern Tasmania and the West Tamar region	10
5. Simplified geology and approximate locations of formation boundaries in the area west of the Scottsdale Batholith and east of the River Tamar.....	11
6. Recumbent fold in the Turquoise Bluff Slate, Colgraves Road	12
7. Thrusting and adjacent shortening of Mathinna Supergroup sedimentary rocks near Back Creek	13
8. Open to upright chevron fold in Bellingham Formation, Bridport Road	14
9. Data illustrating regional D ₃ deformation in the Lefroy and Back Creek area	15
10. Mechanism and problems associated with generating a recumbent geometry at Lefroy	16
11. Inferred changes in fold and fault geometry with depth above a variably dipping thrust	15
12. Typical fold, thrust, foliation and reef geometry in the vicinity of the Lefroy Goldfield	17
13. Fold styles and data from the Alberton, Mathinna and Mangana areas	18
14. Thrusting near the hinge of a macroscopic upright chevron fold at Ralphs Falls	19
15. Plotted poles to bedding across the South Esk River at Mathinna	20
16. Carbonate-spotted phyllite from the Mangana goldfield	21
17. Geology of the Lefroy goldfield	25
18. Area in the vicinity of the Volunteer Reef and ore body	26
19. Mohr diagrams modelling reef orientation as a result of changes in effective stress states	28
20. Sketch showing how varying degrees of shortening on either side of the Lefroy fault reefs can determine the apparent lateral movement sense	29
21. Sketch geology of the Alberton goldfield showing gold deposit and prospect locations	30
22. Aeromagnetic image of the Alberton goldfield showing geology, gold deposit and prospect locations	31
23. Cross-section through the Ringarooma Fault, as mapped in the Ringarooma United mine	32
24. Interpreted structure of the Mathinna Goldfield	32
25. Southeast extent of the Mathinna Goldfield	34
26. Coulomb-Mohr diagram illustrating the effects of increasing differential stress and pore fluid pressures on fault development in the Alberton, Mathinna and Mangana areas	34
27. Simplified sketch block diagram of eastern Tasmania showing possible linked fault architecture	35
28. Sketch diagram illustrating possible interrelationships during middle Palaeozoic orogenesis and sedimentation at the boundary between eastern and western Tasmania	38
29. Proposed correlation between Proterozoic rocks in western Tasmania with those underlying the Melbourne Zone in Victoria, and between eastern Tasmania and the Tabberabbera Zone in eastern Victoria	39

Summary

Several hundred vein-hosted deposits and prospects are hosted within Cambrian to Devonian Mathinna Supergroup meta-sedimentary turbidites east of the Tamar Valley. The regional structural history of the Mathinna Supergroup has remained poorly understood, with work only recently resulting in revision of the turbidite stratigraphy. In particular, it has been recognised that recumbent folding affecting turbidites containing Lower to Middle Ordovician (Bendigonian Be1 to Darriwilian Da3) fossils, but not stratigraphically overlying turbidites containing Silurian (Ludlow) graptolites, is of a timing consistent with Ordovician to Silurian Benambran orogenesis on the Australian mainland. Two subsequent phases of upright folding post-date deposition of turbidites containing Devonian plant fossils but pre-date intrusion of Middle Devonian granitoids, and are of Tabberabberan age. Overall, parts of the Mathinna Supergroup have experienced three regional deformation events spread over two orogenic episodes.

The previous grouping of all pre-Middle Devonian turbidites in eastern Tasmania into the one Mathinna 'Group' was misleading in that the turbidite sequence could be subdivided into two distinct sedimentary packages separated by an event best correlated with the Benambran Orogeny on the Australian mainland. This resulted in the Mathinna Supergroup being given supergroup status and existing formations placed into two new groups: an older Early to Middle Ordovician Tippogoree Group and a younger Silurian to Devonian Panama Group.

Lode-style gold mineralisation throughout eastern Tasmania coincided with the third 'regionally extensive' phase of compressional deformation. This

deformation is best developed at Beaconsfield where southwest-directed thrusting accompanied formation of Tasmania's largest mesothermal lode gold deposit, the Tasmania Reef.

The geometry and location of gold lodes throughout eastern Tasmania was influenced by rheological contrasts between sedimentary rock units. The shape and orientation of structures formed during earlier deformations has also influenced the orientation of reefs formed during D_3 . In the Alberton, Mathinna and Mangana goldfields, sub-vertical bedding on the steep northeast limbs of upright D_2 folds was in an orientation conducive to shear failure during D_3 , resulting in reefs striking predominantly northwest and parallel to regional fold trends. In contrast, the Lefroy goldfield is unique within southeast Australia because mineralised fault reefs strike in an easterly direction, at a high angle to the predominantly northwest strike of bedding and folds. A sub-vertical orientation and discordant relationship of the mineralised reefs to bedding, as well as the lack of gold mineralisation along bedding and pre- D_3 structures, indicate the reefs here formed during a period of wrench faulting.

At the regional scale, gold mineralisation is typically hosted by cyclic mixed sandstone and shale sedimentary successions transitional between underlying sandstone-rich and overlying shale-rich rock packages. Ductility contrasts between stratigraphically adjacent units played a critical role in determining fold and fault geometry, with transitional rocks of mixed sedimentary character providing an excellent environment for dilation and gold mineralisation.

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Introduction

Several hundred vein-hosted deposits and prospects located in Cambrian to Devonian Mathinna Supergroup meta-sedimentary rocks east of the Tamar Valley, and in similar aged Denison Group rocks in the Beaconsfield region, west of the River Tamar (fig. 1), have yielded in excess of 70 tonnes of gold over the past 140 years. More than 80% of this gold was mined between 1881 and 1912, with many of the deposits exploited without the availability of modern geological or mining techniques.

Almost all these deposits were the result of surface discoveries. With most of the surface deposits likely now discovered, and with gold mineralisation exhibiting characteristically narrow to non-existent alteration envelopes, explorers today are faced with the considerable problem of how to effectively assess prospective ground for additional or new gold resources. Until recently little information detailing the structural, geophysical or geochemical setting of the gold mineralisation was available, making it difficult to develop an effective model for exploration. In recognition of this problem the Tasmanian Government in 1993 instigated the North East Tasmania Gold Province (NETGOLD) study, the principal aim of which was to provide explorers and researchers with a better knowledge of the regional setting of the gold mineralisation upon which exploration models could be constructed and tested.

Despite recognition as early as last century of the strong relationship between deformation and the location of the lode gold deposits, the regional structural setting of the gold mineralisation has, until recently, remained unknown. Structural studies were typically carried out in complexly deformed mineralised areas without first establishing, or at least describing, the commonly more simple regional context of such sites.

This report focuses on documenting the *regional structure* of eastern Tasmania and presents examples from selected goldfields of the role played by structure in controlling gold mineralisation.

Access and infrastructure

This report covers that portion of Tasmania east of the River Tamar and approximately north of the Esk Highway. Here, the topography is flat to moderately rugged, the latter in the hornfelsed aureoles of the Devonian granitoids and in areas of Jurassic dolerite. The climate is mild, with approximately 500 mm to 1000 mm of rainfall per year. Farming and forestry are the main industries. Away from farming areas, the vegetation is dominated by temperate eucalypt and plantation pine forests. All-weather access is provided by a network of well-formed sealed and gravel roads. Launceston is the nearest city and is located inland at the head of the River Tamar. A deep-water port is

located further north at Bell Bay, on the eastern side of the River Tamar.

Gold discovery and production

Gold was first discovered in Tasmania at Mangana by James Grant in 1852, with the first lode gold produced from the Sovereign mine in 1859 (Twelvetrees, 1907). In total, the Mangana field reportedly produced only 208 kg from lode gold deposits and up to 470 kg from alluvial deposits, although the poor quality of record keeping suggests production was probably much greater (Bottrill, 1992). The Mathinna field was discovered soon after, with production between 1880 and 1932 exceeding 9000 kg, about 90% of which originated from the Golden Gate mine (Twelvetrees, 1914). The adjacent Dans Rivulet and Tower Hill mineral fields produced a combined total of only 141 kg gold (Hughes, 1947; Taheri, 1992), although again, records are poor and production was probably much greater than that documented. There are no records of alluvial gold production from the Mathinna, Dans Rivulet and Tower Hill goldfields, where mining was predominantly undertaken by itinerant workers (Taheri, 1992).

Auriferous quartz veins were first discovered at Alberton sometime prior to 1883 (Thureau, 1883), with over 100 lodes worked intermittently up to 1939. At one stage the area was expected to become the richest goldfield in Tasmania (Hughes, 1952) yet only about 425 kg were produced, 255 kg of which originated from the Ringarooma United mine.

The total recorded production of gold from the Warrentinna and Forester goldfields is 112 kg (Bottrill, 1994b), 104 kg of which was mined from the New Golden Mara mine (Bottrill, 1994b; Taheri and Bottrill, 1994).

Most gold deposits in the Lyndhurst–Mangana belt were worked to shallow depths (up to 60 m), the exceptions being the New Golden Gate and Ringarooma United mines which were eventually mined to depths of about 500 m (Taheri, 1992) and 119 m (Taheri, 1993), respectively.

The Lisle, Denison and Golconda fields were not discovered until after 1872 (Bottrill, 1994a). Of these, the Lisle field produced the most gold, officially 2700 kg, but possibly in excess of 9000 kg (Twelvetrees, 1909). Lode gold was first discovered at Lefroy in 1869 with mining typically to depths of 120 m (the deepest being 380 m) and with the field producing a total of about 5500 kg of gold (McClenaghan, 1994). Back Creek was discovered in 1869 but produced only 311 kg of gold before closing in 1920.

Many of the mines in eastern Tasmania were abandoned before any organised mining development could be established. Thinning of the gold-bearing quartz veins, both vertically and laterally

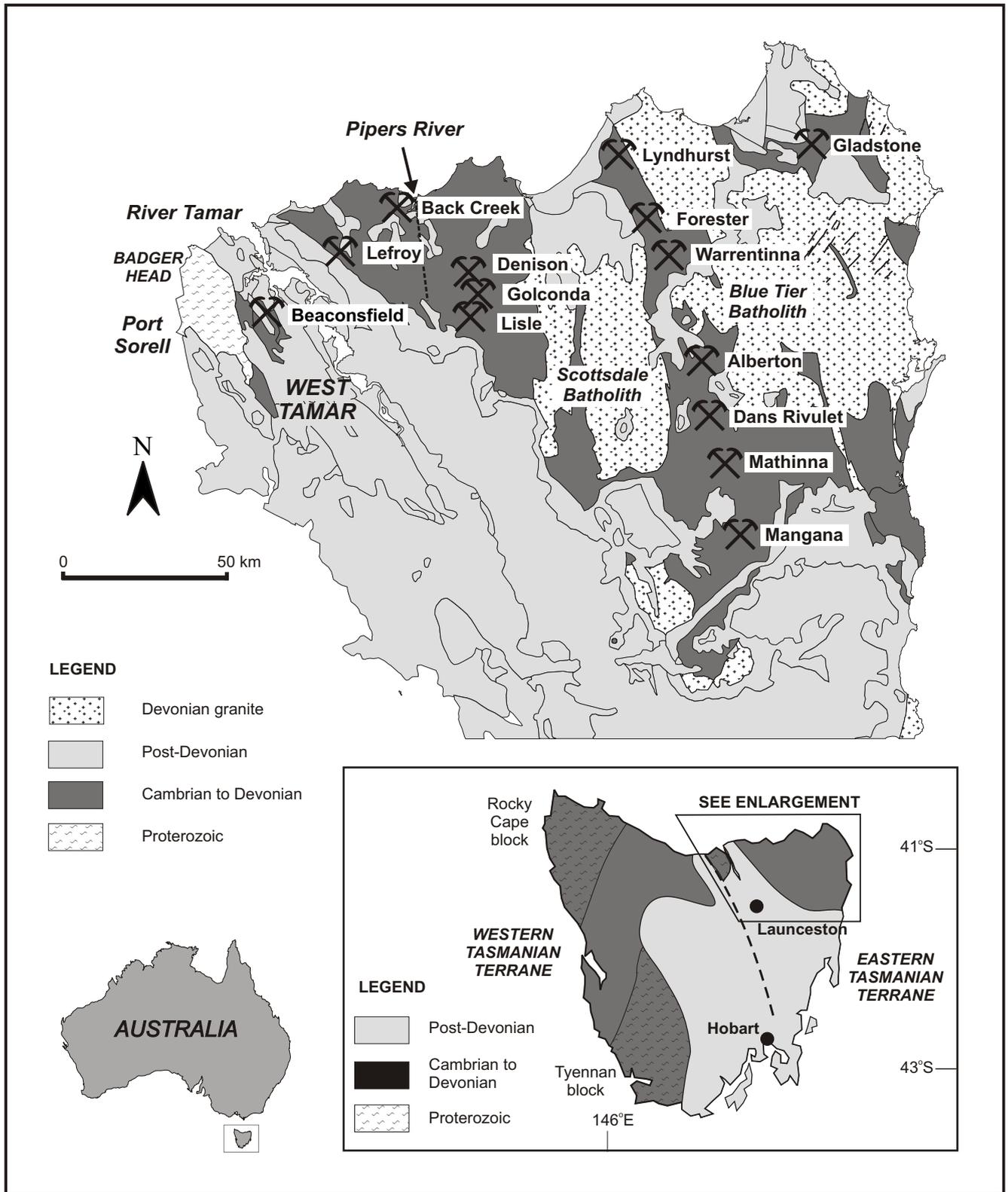


Figure 1

Simplified geology and location map showing the major goldfields of eastern Tasmania and the West Tamar region. Also shown is the location of Pipers River, which approximately separates recumbently folded rocks in the west from predominantly upright folded rocks to the east.

(Montgomery, 1892), an increase in the amount of refractory sulphides at depth, problems with water and a lack of sufficient capital for proper development or exploration were the main contributors to mine closures.

Comparisons with Victorian gold deposits

Goldfields in eastern Tasmania and at Beaconsfield are of a similar range in both size and grade to most turbidite-hosted lode-style goldfields in Victoria (fig. 2). A Tabberabberan timing for gold mineralisation in eastern Tasmania and at Beaconsfield coincides broadly with a period of gold mineralisation on the mainland extending from the Silurian to the Middle Devonian (Phillips and Hughes, 1996; Gray and Foster, 1997; Foster *et al.*, 1999; Foster and Gray, 2000; VandenBerg *et al.*, 2000; Bierlein *et al.*, 2001).

A number of structures host gold mineralisation in Victoria, including saddle, leg and spur reefs, with faulting and gold mineralisation typically accompanied by the formation of complex vein arrays in adjacent rocks (e.g. Cox *et al.*, 1991b; Cox *et al.*, 1995; Phillips and Hughes, 1996). Mineralised reefs typically strike parallel to the axes of folds of the same age (Phillips and Hughes, 1996) with gold mineralisation formed coincident with a horizontally orientated minimum compressive (far field) stress (Cox *et al.*, 1995).

The Tasmania Reef at Beaconsfield and the New Golden Gate mine at Mathinna are the two largest

mines in eastern Tasmania and the west Tamar region. The Tasmania Reef at Beaconsfield has a pre-mining ore reserve of about 57 000 kg of gold, about half of this now mined (Hills, 1998), making it southeastern Australia's largest single gold-producing reef [compared to Victorian deposits using the Victoria GIS data set (November 2000) Department of Natural Resources and Environment]. The New Golden Gate deposit, although much smaller than that at Beaconsfield (about 8000 kg of gold mined), is still within southeastern Australia's top twenty deposits in size. Recent drilling at Mathinna has discovered two new reefs at the New Golden Gate deposit, with an indicated and inferred resource of 212 000 tonnes of mineralisation grading 5.5 g/t gold (Defiance Mining NL, Quarterly Report to the Stock Exchange, June 2000).

Mineralisation style

Auriferous quartz-rich veins (fig. 3) in Mathinna Supergroup rocks vary in length up to 2000 m and in width up to about seven metres. The form of the veins is commonly erratic, as are gold grades, which can vary from barren to a maximum-recorded grade of 1354 g/t (Twelvetrees, 1907). The average grade of mined deposits is typically between 15 g/t and 30 g/t with the largest deposit east of the Tamar Valley, the New Golden Gate mine at Mathinna, averaging 23 g/t.

Quartz veins are numerous throughout the Mathinna Supergroup and are commonly cross cutting, demonstrating a complex history of multiple events of quartz precipitation from hydrothermal fluids. Keele

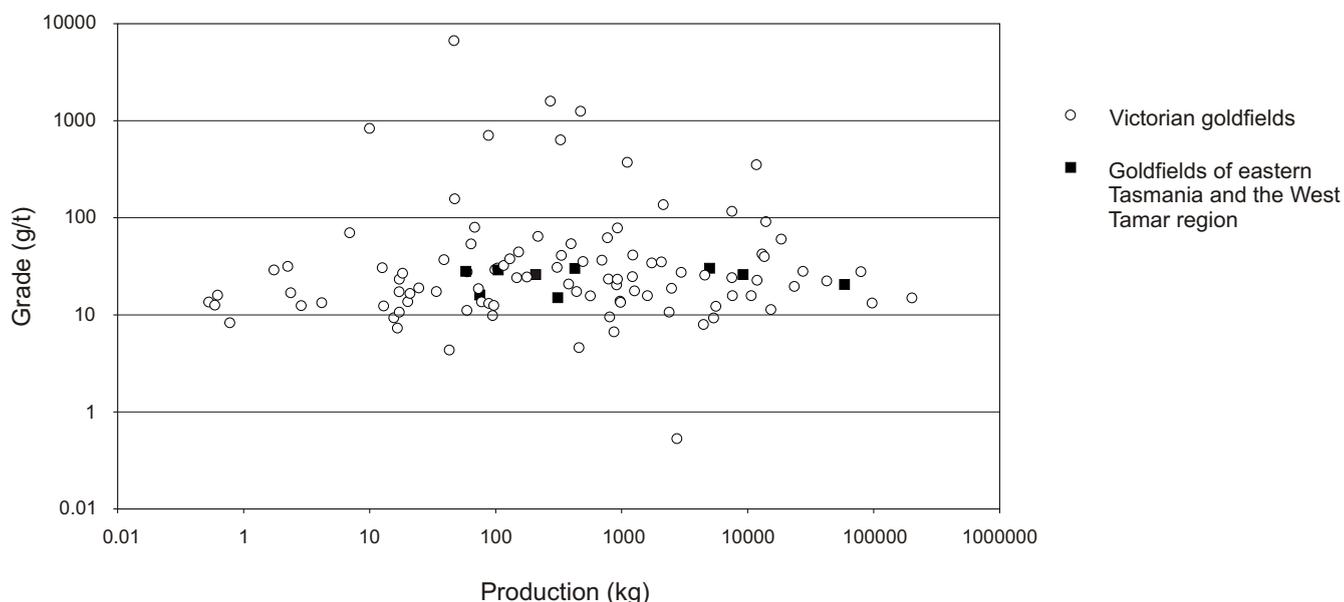


Figure 2

Graph showing production (kg) and grade (g/t) for goldfields (lode gold only) in Victoria, eastern Tasmania and the West Tamar region. Records of production and grade are commonly incomplete; those data shown are indicative only and likely represent minimum values. Victorian deposit data calculated from Department of Natural Resources and Environment data (Victoria GIS data package, November 2000). Tasmanian data compiled from: Thureau (1883), Twelvetrees (1909, 1914), Hughes (1947, 1952), Bottrill (1992), Taheri (1992, 1993), Bottrill (1994a, 1994b), McClenaghan (1994), and Taheri and Bottrill (1994).

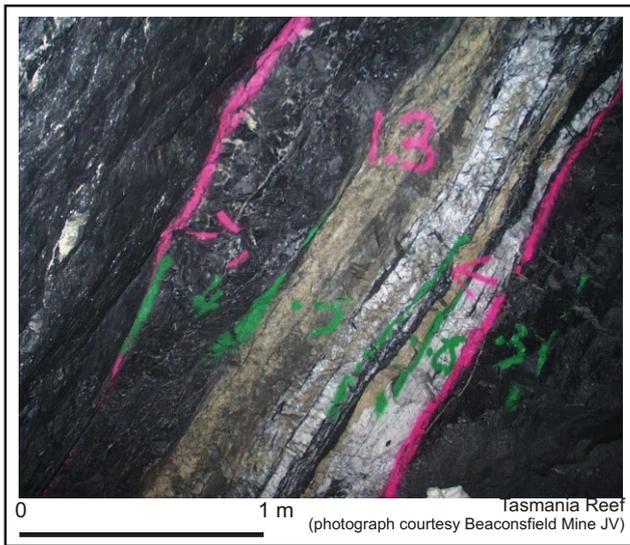


Figure 3

Photograph of alternate carbonate-rich and quartz-rich layering in the Tasmania Reef at Beaconsfield (courtesy Peter Hills, Beaconsfield Mine JV).

(1994) described nine vein types, subdividing them into three broad categories representative of three main fluid stages: early barren and economically important laminated veins; white intermediate; and late white to grey sulphide and carbonate-bearing veins. Mineralised veins are commonly laminated and typically grey in colour. This colour is the result of very fine auriferous pyrite and arsenopyrite with lesser chalcopyrite, sphalerite and galena (Bottrill, 1992; Keele, 1994). White, buck quartz-filled veins are more common but rarely contain gold. Auriferous breccias are rare but highly prospective (Twelvetrees, 1907) and comprise angular wallrock or early-formed quartz clasts in a cherty to medium-grained quartz matrix (Bottrill, 1992).

The origin of the gold and mechanisms of transport and deposition are discussed in detail by Taheri and Bottrill (1994). In summary, the gold in turbidites in eastern Tasmania is thought to have been derived at depth from devolatilisation of basalts, ultramafic rocks or greywackes during greenschist to amphibolite-grade metamorphism. Transport of the gold was as a bisulfide complex in low salinity CO₂-rich fluids. Deposition was predominantly caused by fluid immiscibility and phase separation instigated by rapid decompression during tectonism. Fluid reduction may also have promoted mineralisation, with the

association of gold and carbon-bearing rocks first being observed by Twelvetrees in 1904.

Previous structural studies

Detailed descriptions of the structure of specific areas are available in Broadhurst (1935), Finucane (1935), Groves (1965), Threader (1967), Powell (1967), Marshall (1969), Gee and Legge (1979), Lennox (1981), Goscombe and Findlay (1989), Williams (1989), Powell (1991), Powell and Baillie (1992), Taylor (1992), Taheri (1992, 1993), Goscombe *et al.* (1994), Keele (1994), Manzi (1995), Keele (1996), and Patison (1999) (Table 1). These studies were typically constrained to only parts of eastern Tasmania and commonly involved inspection of structurally complex and commonly mineralised areas. As a result, the context of these studies with respect to the regional geology is, in places, difficult to assess.

Terminology

Denoting a structural sequence using subscripts representative of generations of deformations proves confusing where a number of deformations have affected rocks of different ages (e.g. younger sequence S₁ = older sequence S₂). For this reason, the terminology used in this report refers to the 'regional' sequence of deformations observed in rocks east of the Tamar Valley (Table 2). Three deformations are recognised in rocks in the Back Creek and Lefroy areas, with associated structures denoted by the subscripts 1 to 3. Only the latter two deformations are recognised in rocks further east, but for simplicity, and to facilitate discussion, these events are referred to by the subscripts 2 to 3. Individual deformations do not necessarily equate to discrete orogenic events.

Contours shown on stereonet diagrams have been calculated using Gaussian methodology of Robin and Jowett (1986) with a weighting function of k = 100. Contours are in 2% intervals (unless stated otherwise) above an expected count calculated using a 1% counting circle.

Table 2

Relationships between deformations referred to in this report

<i>Back Creek and Lefroy areas</i>	<i>East of Back Creek and Lefroy</i>
D ₃	D ₃
D ₂	D ₂
D ₁	Not present or unrecognised

Table 1

Summary of structural interpretations for areas in eastern Tasmania showing structural history and relationship of structure to gold mineralisation

<i>Author</i>	<i>Area of Interest</i>	<i>Results</i>	<i>Relationship of structure to gold mineralisation</i>
Finucane, 1935	Mathinna	Variably intense northwest-trending folds with locally intense shearing and close folding.	Associated with northwest-trending zone of close folding.
Groves, 1965	Lefroy	D ₁ : NE-SW directed compression associated with recumbent folding and faulting. D ₂ : Locally pervasive deformation sub-coaxial to D ₁ .	Syn-D ₁
Threader, 1967	Mangana-Waterhouse	D ₁ : NNW-trending folding with coeval NNW and ENE-trending faults. Subsequent kinking.	Syn-D ₁
Marshall, 1969	Pipers River	D ₁ : NE-directed compression associated with recumbent and upright folding in the west and east respectively. D ₂ : Continuous with D ₁ .	Lode gold not discussed
Gee and Legge, 1979	Lefroy	D ₁ : Major NNW-trending recumbent syncline between Beechford-Lefroy and Stony Head. D ₂ : Refolding and tightening of D ₁ structure.	Referred to Groves, 1965
Lennox, 1981	Mangana	D ₁ : Northwest-trending folding and possible subsequent discordant cleavage development.	Not specified
Goscombe and Findlay, 1989	Northeast Tasmania	D ₁ : NE-SW directed compression and associated upright folding and folding. D ₂ : NW-SE compression associated with kinking.	Not specified
Williams, 1989	Stony Head	NW-trending folding followed by kinking and subsequent fold tightening.	Not specified
Powell, 1991	Lefroy	D ₁ : NE-directed compression associated with folding and faulting. D ₂ : Deformation of D ₁ folds.	Syn-D ₂
Powell and Baillie, 1992	Lefroy-Bridport	D ₁ : NE-directed compression associated with upright folding and faulting. D ₂ : Deformation and rotation of D ₁ folds to a recumbent attitude.	Not specified
Taylor, 1992	Scamander	D ₁ : ENE-directed thrusting and folding. D ₂ : Weak localised sub-horizontal cleavage development.	Not specified
Taheri, 1992, 1993	Mangana-Forester	D ₁ : Northwest-trending upright folding and faulting. Dextral wrenching on northwest-trending structures.	D ₁ but associated with late dilation during dextral wrenching.
Goscombe <i>et al.</i> , 1994	Northeast Tasmania	D ₁ : NE-directed compression and associated upright folding and folding. D ₂ : WSW-directed thrusting in Pipers River/Lefroy area. D ₃ : NW-SE compression associated with kinking.	Not specified
Keele, 1994	Mangana-Forester	D ₁ : East-directed thrusting and development of northwest-trending folds. D ₂ : Steep WNW and NNW-trending dextral faults. North to NE-trending open folds. D ₂ /D ₃ : North-trending sinistral faults. D ₃ : Reverse reactivation of D ₂ faults. Possible folding.	Associated with D ₂ wrenching.
Manzi, 1995	Mangana	D ₁ : Northwest-trending folding. D ₂ : Northwest-trending dextral wrenching. D ₃ : Reverse reactivation of D ₂ wrench faults. D ₄ : ENE-trending dextral shears.	Syn-D ₃
Keele, 1996	Mathinna, Lefroy	Summarises 1994 paper for Mathinna. Lefroy D ₁ : East-verging upright folds. Lefroy D ₂ : Deformation of D ₁ folds into recumbent attitude as per Powell & Baillie (1992).	Associated with D ₂ wrenching and rotation of stress field.
Patison, 1999	Alberton	Two to three deformations.	Not specified

Mathinna Supergroup

INTRODUCTION

The oldest outcropping rocks in eastern Tasmania (fig. 4) are an, overall, poorly understood turbidite package [Mathinna Supergroup (Powell *et al.*, 1993); previously Mathinna Beds (Banks, 1962)] that extends from the Forestier Peninsula on the southeast coast of Tasmania north into the Furneaux Group of islands in Bass Strait. A stratigraphy has been defined only for those rocks east of the River Tamar and west of the Scottsdale Batholith. Here, an eastward-younging succession >7 km thick includes (from oldest to youngest) the Stony Head Sandstone, the Turquoise Bluff Slate, the Bellingham Formation and the (informally named) Sidling sandstone (Powell *et al.*, 1993). The Stony Head Sandstone is a thick bedded and typically unfossiliferous sandstone-dominated succession and contrasts with the predominantly fine-grained rocks (shale, mudstone, chert and fine-grained sandstone) in the stratigraphically overlying Turquoise Bluff Slate. The Bellingham Formation and Sidling sandstone comprise classical turbidites of both proximal and distal facies (Powell *et al.*, 1993).

The turbidite biostratigraphy west of the Scottsdale Batholith is poorly constrained by only two fossil localities, one site in the Turquoise Bluff Slate yielding two poorly preserved graptolites of Early to Middle Ordovician age [late Arenig (Banks and Smith, 1968); Bendigonian Be1 to Darriwilian Da3 (A. H. M. Vandenberg, pers. comm. 2001)], and a second site further east and higher in the stratigraphy containing Devonian plant fragments (Banks, 1962; Powell *et al.*, 1993). East of the Scottsdale Batholith the stratigraphy remains undifferentiated, with a small number of fossil locations indicating a predominantly Silurian to Early Devonian age for turbidite deposition. These rocks are most likely equivalent to the uppermost sedimentary rock units where they have been defined west of the Scottsdale Batholith (Powell *et al.*, 1993).

STRUCTURES WEST OF THE SCOTSDALE BATHOLITH

*D*₁ and *D*₂

The turbidite sequence west of the Scottsdale Batholith was inferred to be conformable, based on interpretations of the structure measured along a west-to-east transect centred between George Town and Bridport (Powell and Baillie, 1992). This transect was cut by the north-flowing Pipers River at approximately the contact between the Turquoise Bluff Slate and Bellingham Formation (fig. 5). West of the Pipers River the Turquoise Bluff Slate and Stony

Head Sandstone are deformed into east-facing open to tight recumbent folds, the axes of which plunge both northwest and southeast (fig. 6). Folding is associated with development of a slaty to disjunctive cleavage.

Thrusts occur in a number of localities including the Australasian Slate quarry (504 600 mE, 5 456 500 mN*) (fig. 7) and Sir John Franklin mine (504 600 mE, 5 455 800 mN) in the Turquoise Bluff Slate, and in drill core from the Volunteer mine (499 320 mE, 5 448 210 mN) located near the contact between the Turquoise Bluff Slate and the stratigraphically underlying Stony Head Sandstone. Thrusts appear as sub-horizontal high-strain zones up to 300 mm thick, commonly silicified and typically strongly foliated. Isoclinal folding of chert beds indicates shortening of up to 90% adjacent to thrust planes. Fold vergence and quartz-fibre growth in thrusts at the Australasian Slate quarry (orientated to 057°) indicate tectonic transport of hanging-wall rocks to the northeast.

In contrast to the older Stony Head Sandstone and Turquoise Bluff Slate, younger Bellingham Formation turbidites, approximately east of the Pipers River, are deformed into upright to northeast-verging open chevron to concentric folds (fig. 8). Axial planes typically dip steeply southwest and strike northwest, with folding accompanied by a weakly developed to slaty axial-planar cleavage. Importantly, this is the oldest fabric preserved in the Bellingham Formation. Upright folds of similar geometry occur throughout eastern Tasmania and can reach amplitudes of several kilometres.

The contact between the recumbently folded and upright folded rocks does not crop out. It lies near, and probably slightly east of, the Pipers River along the Bridport to George Town road, roughly following the course of the river southward (fig. 5). The contact is inferred, from offshore seismic data, to dip east, separating more reflective recumbently-folded rocks in the west from less reflective upright folded rocks further east (Barton, 1999).

Both recumbent and upright folds are deformed by southwest-verging open folds and a northwest-striking, variably northeast-dipping, spaced crenulation cleavage (fig. 9). This third event is the latest to result in regional development of a foliation in eastern Tasmania and is discussed in more detail in following sections.

Previous studies west of the Scottsdale Batholith (Powell and Baillie, 1992; Reed, 1999) in eastern Tasmania have focussed on documenting the structural geology along the main Bridport to George Town road. These studies noted an apparent lack of upright refolding of recumbent folds west of Pipers River and concluded that both upright and recumbent

* All grid references are Zone 55, AGD 66.

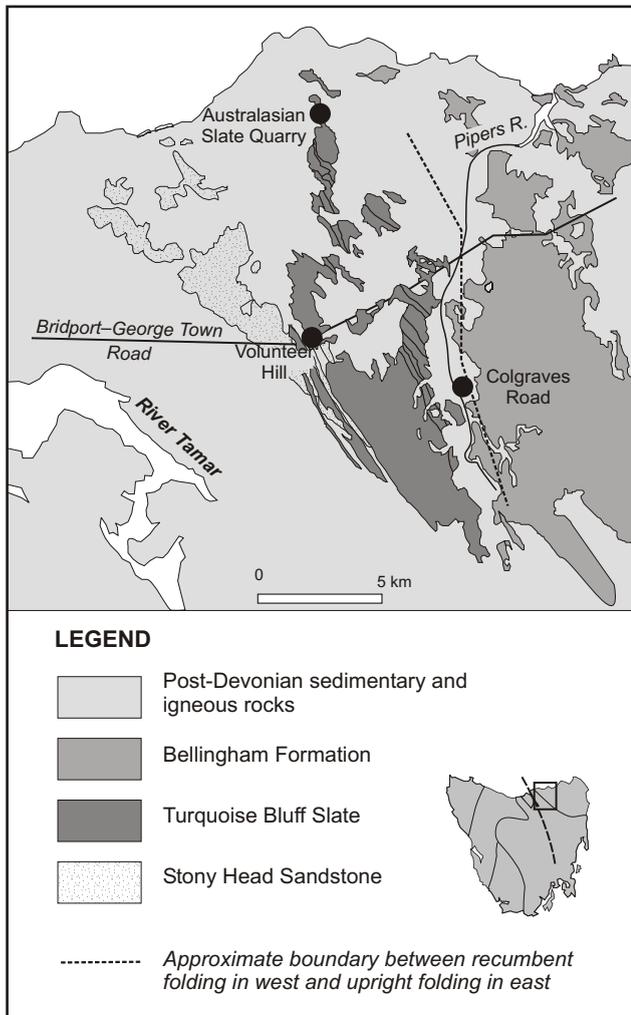


Figure 5

Map of the area west of the Scottsdale Batholith and east of the River Tamar showing the simplified geology and approximate locations of formation boundaries.

folding were of the same or similar age. Powell and Baillie (1992) interpreted the recumbent folds as originally being upright, with rotation into their current recumbent attitude achieved through a process of block rotation above a northeast-dipping thrust ramp (fig. 10). The age of this thrust was inferred as being of the same age as northeast-dipping thrusts emergent west of the River Tamar.

There are considerable problems with the Powell and Baillie (1992) model. It required an excessive thrust ramp angle of greater than 40° and also necessitated that the rotated block containing the now-recumbent folds experienced no internal deformation. This lack of internal deformation results in marked space problems at the block margins, between rotated and unrotated strata. Although this model has been incorporated into regional schematic cross-sections for eastern Tasmania (Patison *et al.*, 2001, fig. 7), it cannot explain overturning of the sedimentary strata to the extent observed in outcrop.

Reed (1999) also proposed that recumbent and upright folds were of the same age, but that the recumbent

folds were indicative of higher strain above a shallowly west-dipping thrust (fig. 11). There are also problems with this model. Firstly, interpretations of seismic data (Barton, 1999) indicate that the contact between recumbent and upright-folded rocks dips east, which is inconsistent with northeast-directed thrusting and recumbent folding above a southwest-dipping detachment. Secondly, there is no increase in strain approaching the proposed thrust, which must emerge somewhere near Pipers River. Nor is there an indication of any thrusting in rocks in the immediate footwall to the thrust, despite strain being so high as to result in recumbent folding in more than two kilometres of succession overlying the proposed thrust. Finally, Patison *et al.* (2001), using illite crystallinity, showed that there is no distinct change in metamorphic grade across the boundary in which older, recumbently-folded rocks are purportedly thrust over younger, less deformed rocks.

Timing relationships between recumbent and upright folds are more clearly apparent south of the Bridport to George Town road (e.g. near Colgraves Road; 513 000 mE; 5 439 500 mN), in rocks correlated with the Turquoise Bluff Slate. Here, a slaty cleavage associated with formation of the tight recumbent folds is refolded and overprinted by a second, closely spaced, disjunctive cleavage in pelitic units. This second cleavage formed at the same time as upright chevron folds, which are also exposed in outcrop. These rocks show that formation of the upright folds clearly followed that of the recumbent structures. Regionally, plotted measurements of the earliest cleavage observed in outcrop also show a distribution consistent with chevron refolding of earlier recumbent structures.

In contrast, chevron refolding of recumbent structures is not demonstrably evident in outcrop exposed along the Bridport to George Town road, contributing to previous interpretations that the recumbent and upright folds were of the same age. However, like the rocks further south, the rocks along the Bridport to George Town road also contain two cleavages, both pre-dating the late northeast-dipping crenulation cleavage. These two cleavages lie at an acute angle to one another and both are near to axial planar to the recumbent folds. This is best observed in a road cutting through the top of Volunteer Hill (499 400 mE; 5 448 400 mN) (fig. 12), where a finely spaced disjunctive cleavage overprints a slaty cleavage in pelitic beds, and a spaced cleavage locally overprints a slaty to spaced cleavage in sandstone strata. The lack of upright folding and clearly demonstrable overprinting relationships indicates local reactivation of the early recumbent structures during subsequent upright folding. Refolded foliations associated with thrusting are also evident in outcrop (e.g. Australasian Slate Quarry; fig. 7) and similarly indicate thrust reactivation.

The proposed reactivation of recumbent structures during the event producing the upright folds is

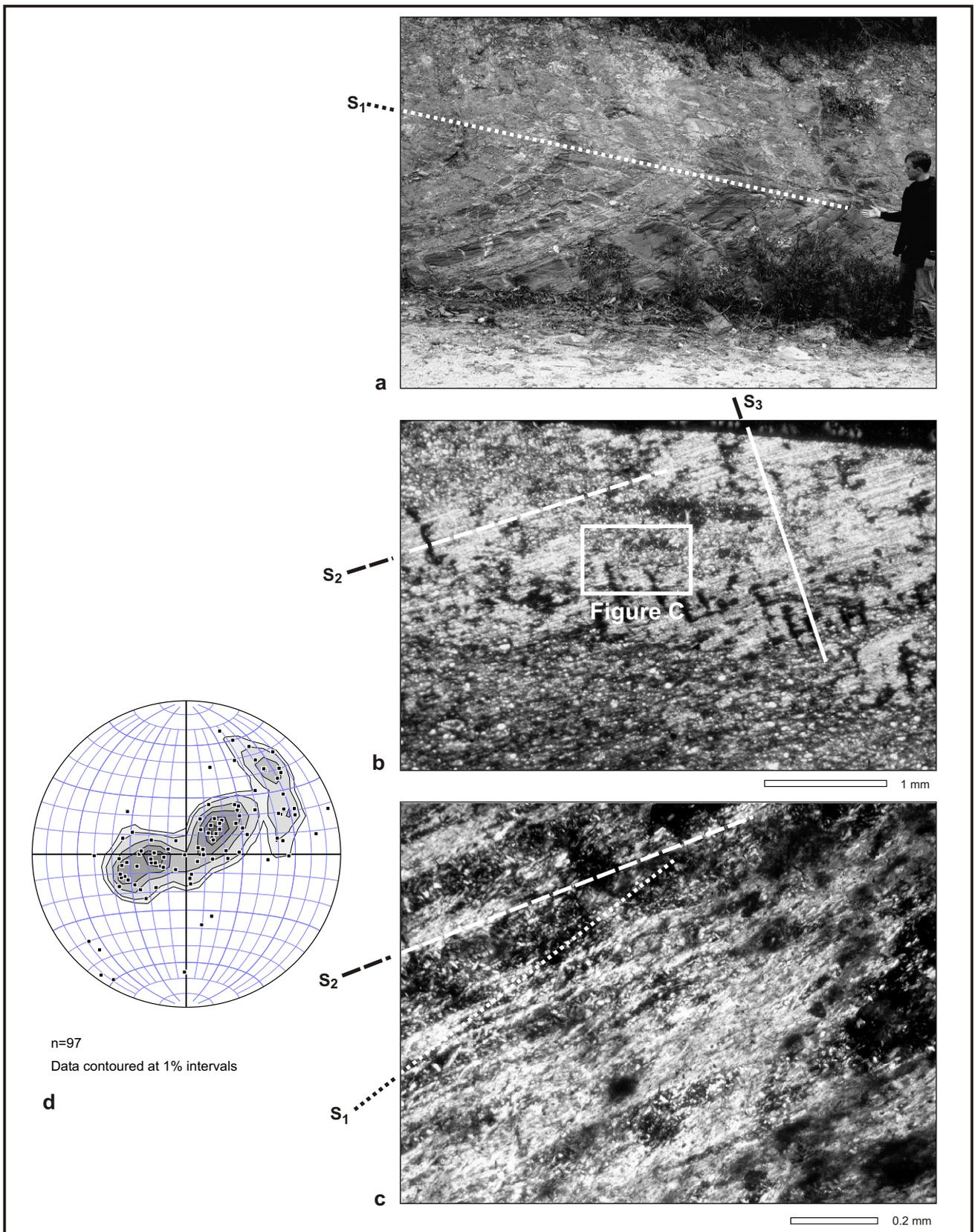


Figure 6

- (a) A recumbent F_1 fold in the Turquoise Bluff Slate, Colgraves Road (513 000 mE; 5 439 300 mN), St Patricks 1:100 000 scale map sheet (8315).
- (b) Thin-section photograph of spaced disjunctive cleavage (S_2) and overprinting weakly developed spaced crenulation cleavage (S_3) in Turquoise Bluff Slate: TASROK No. 007269 (Mineral Resources Tasmania).
- (c) Magnification of Figure 6b showing spaced disjunctive cleavage (S_2) overprinting slaty cleavage (S_1).
- (d) Stereoplot of poles to S_1 data with the bimodal distribution about a vertical northwest-trending plane consistent with upright chevron refolding.

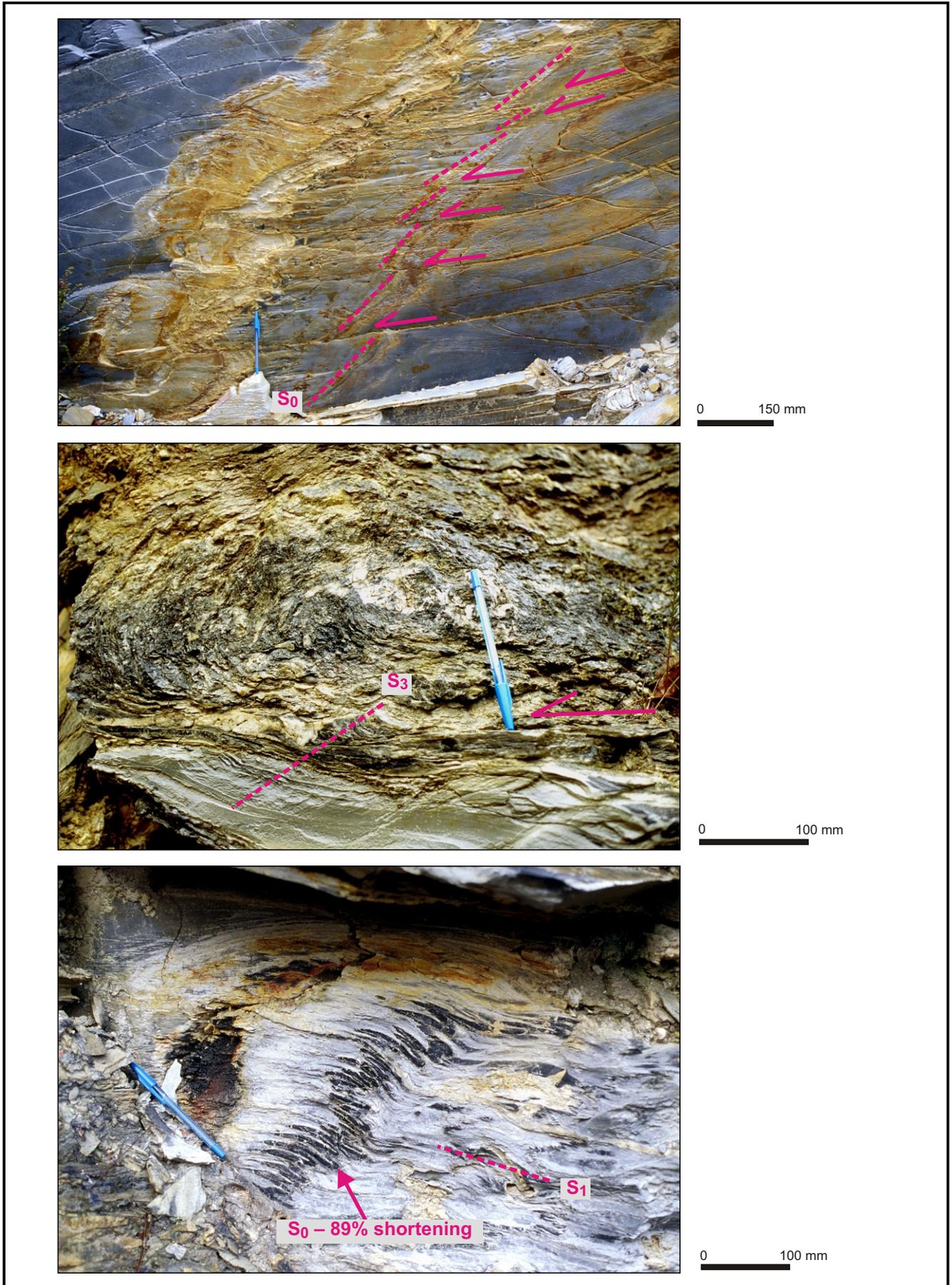


Figure 7

Illustrations of thrusting and adjacent shortening of Mathinna Supergroup sedimentary rocks (Turquoise Bluff Slate) at the Australasian Slate Quarry near Back Creek (504 600 mE; 5 456 500 mN), St Patricks 1:100 000 scale map sheet (8315).

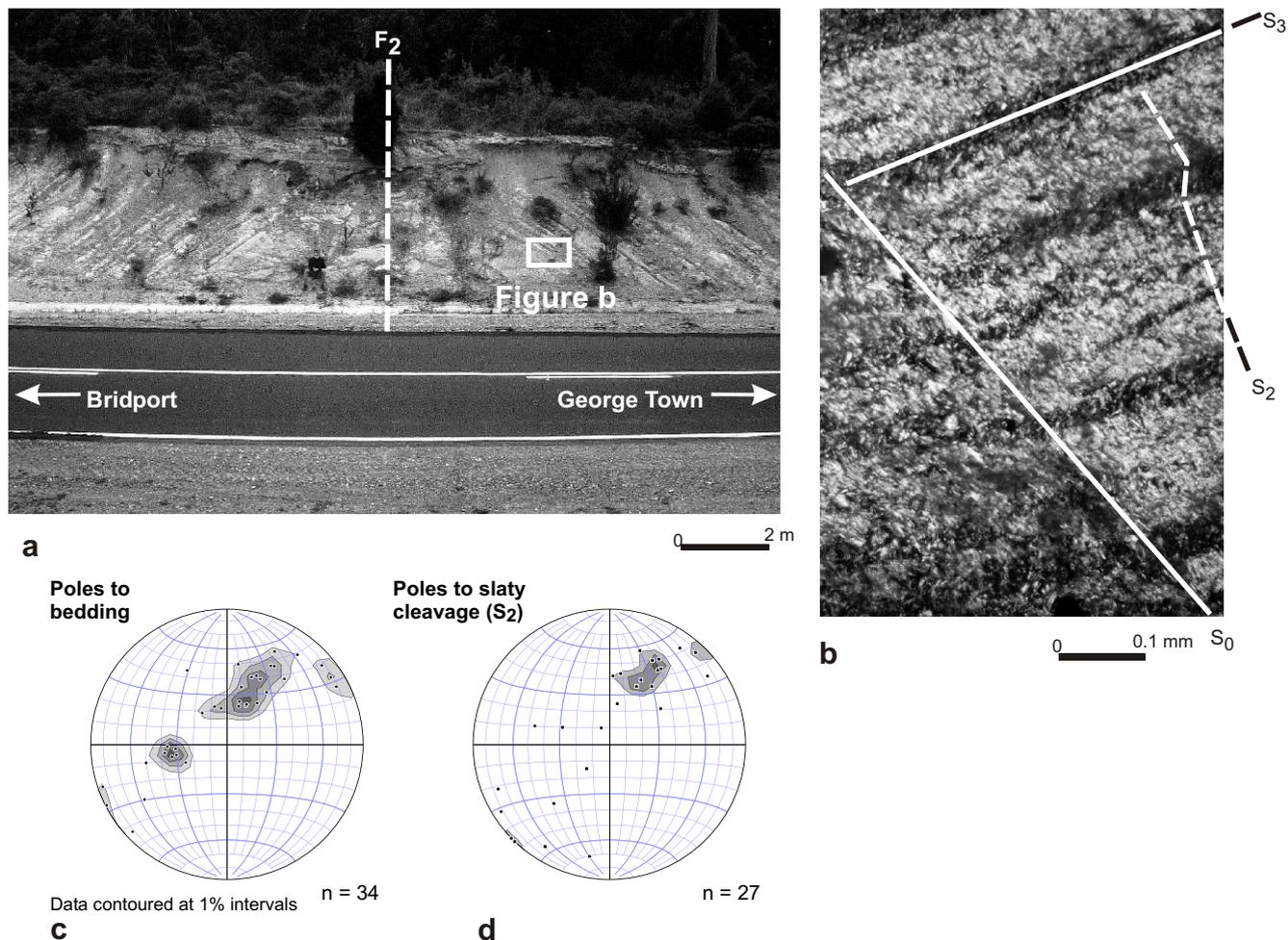


Figure 8

- (a) Open upright chevron fold (regional F_2 , but local F_1) in Bellingham Formation: Bridport to George Town road (512 770 mE; 5 452 170 mN), St Patricks 1:100 000 scale map sheet (8315).
- (b) Thin-section photograph of Bellingham Formation showing slaty cleavage (regional S_2) associated with upright chevron folding, overprinted by spaced crenulation cleavage (regional S_3): TASROK No. 007271 (Mineral Resources Tasmania).
- (c) Stereoplot showing distribution of bedding (S_0) data consistent with chevron folding.
- (d) Stereoplot showing predominantly upright to steep southwest dip to S_1 cleavage.

consistent with both events demonstrating northeast tectonic vergence. Shortening, manifest as upright folding east of the Pipers River, appears to have been (at least locally) accommodated further west by reactivation rather than refolding of older structures. There is little doubt that the recumbent and upright folding events are the products of separate deformations.

D_3

The effects of deformation related to southwest-directed thrusting in upright-folded rocks east of the Pipers River are subtle. Along the Bridport–George Town road at 512 776 mE, 5 452 177 mN, a sub-horizontal spaced crenulation cleavage (regional S_3) cross-cuts the slaty cleavage associated with development of an F_2 chevron fold (fig. 8). In outcrop, this cleavage is evident only on the southwest limb of the F_2 fold, strain on the northeastern limb instead being accommodated by shearing along bedding. Complex conjugate arrays of

en echelon tension gashes in sandstone beds on the northeast limb of the F_2 structure may also be D_3 in age and related to bedding-parallel shear. Alternatively, they may be related to flexural shear during fold formation, although their absence from the other fold limb does not support this hypothesis.

The S_3 cleavage commonly appears as a discrete fracture-style cleavage in more pelitic units. In thin section it can be seen that this fracturing is the result of preferential weathering and oxidation along the S_3 crenulation plane. S_3 is typically rarely developed in sandstone.

The sense of shear on S_3 and the vergence of F_3 folds are top-to-the-southwest, opposite to those of D_1 and D_2 . The S_3 cleavage strikes northwest and is rotated about 10° to 15° clockwise relative to S_1 (consistent with the findings of Powell and Baillie (1992) and Marshall (1969)). S_3 dips variably northeast, but may be near to horizontal where formed adjacent to a

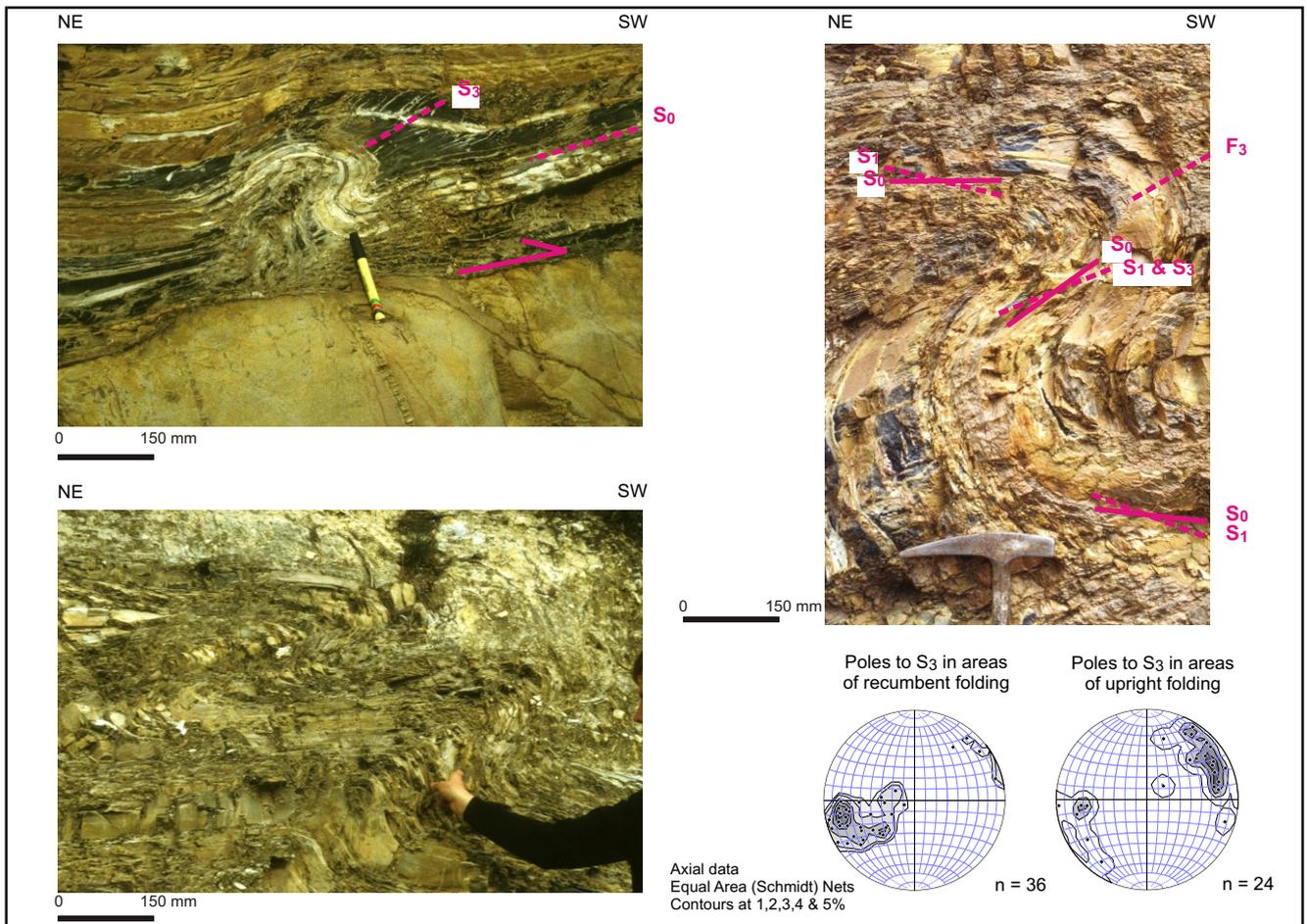


Figure 9

Photographs and data illustrating regional D_3 deformation in the Lefroy and Back Creek area. The vergence of the D_3 folds and the increasing strain westward is consistent with southwest-directed thrusting of Palaeozoic strata west of the River Tamar. Location (503 050 mE; 5 446 500 mN) is near the corner of Trooper Track and Industry Road, St Patricks 1:100 000 scale map sheet (8315).

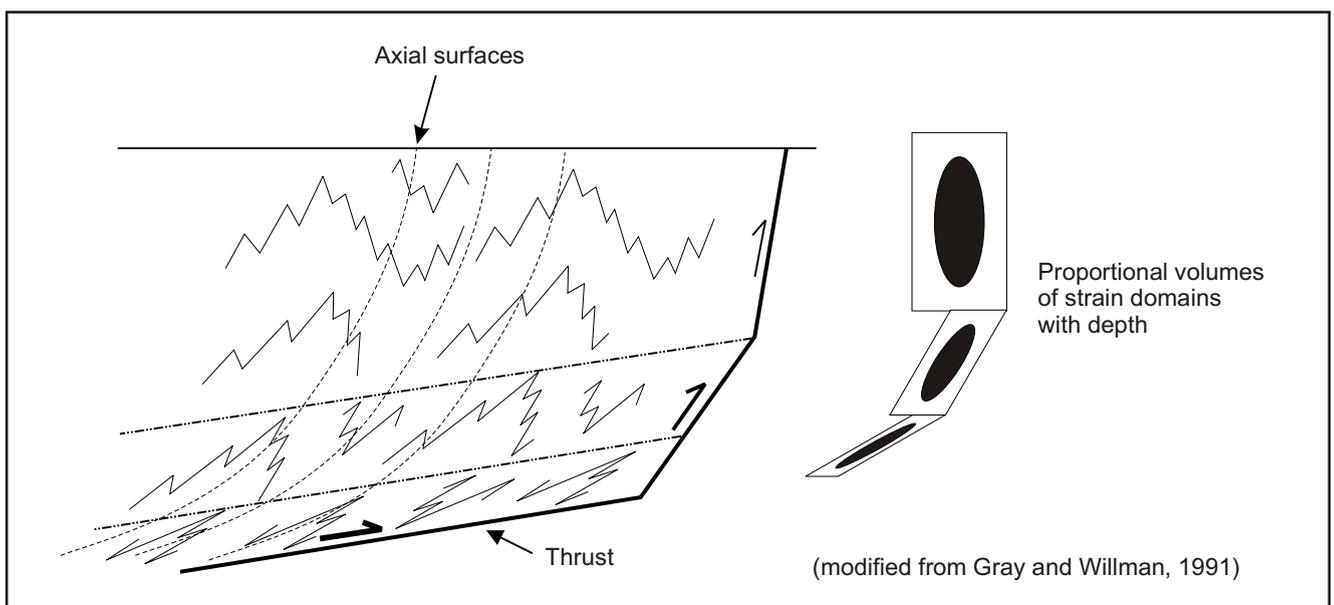


Figure 11

Diagram showing the inferred changes in fold and fault geometry with depth above a variably dipping thrust. Horizontal shortening caused by displacements on the near flat-lying portions of the thrust are not matched higher in the structural profile and must be accompanied by deformation of hanging wall rocks in the form of folding. The increasing strain associated with deformation near the thrust surface is accompanied by the progressive rotation of σ_1 towards a vertical orientation, resulting in an increasingly flat-lying fold geometry.

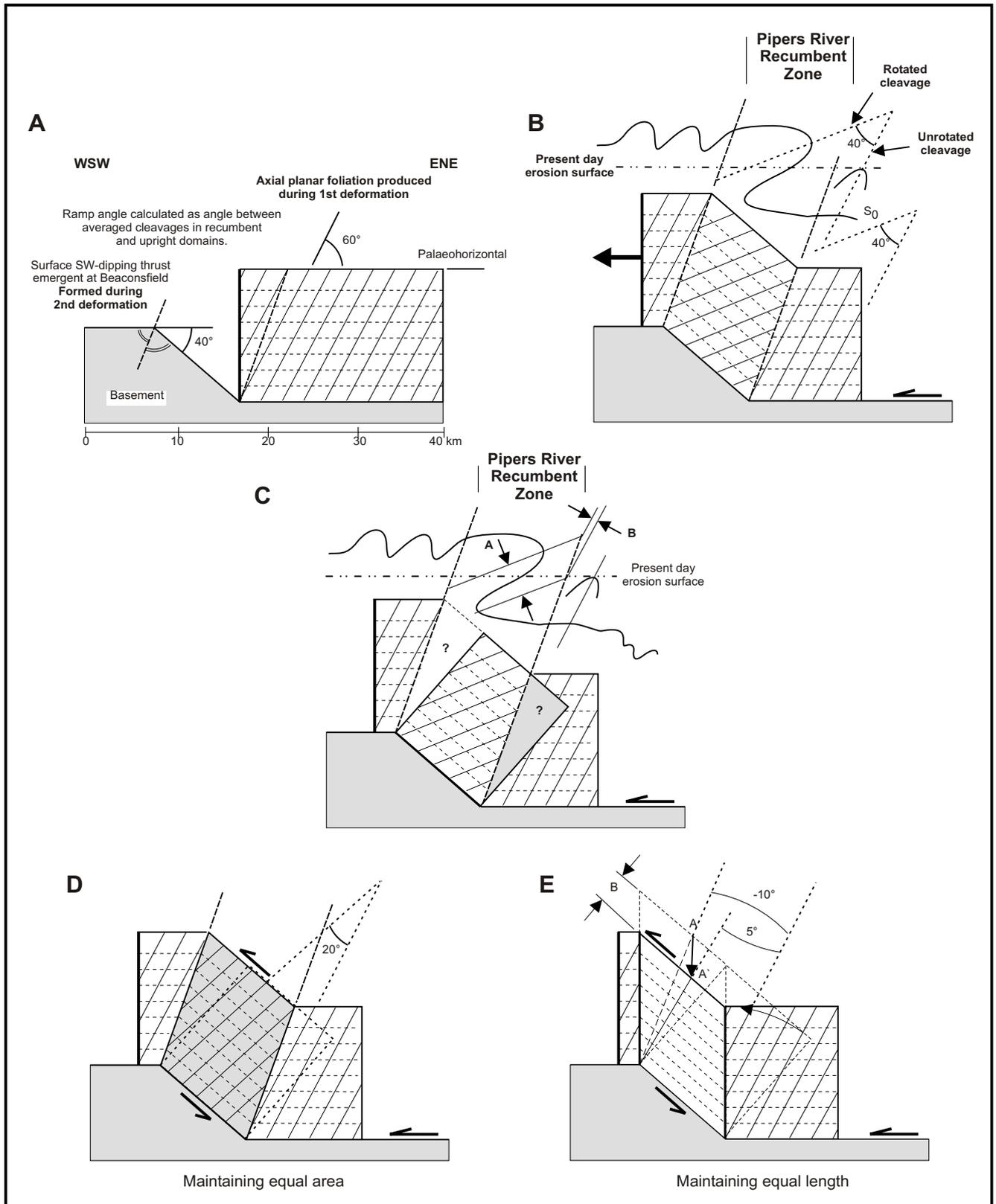


Figure 10

Diagrams showing the mechanism and problems associated with generating a recumbent geometry at Lefroy (Powell and Baillie, 1992) by block rotation above a D₃ thrust ramp. The model assumes only two deformations affected all Mathinna Supergroup rocks and that upright folds east of the Pipers River are the same age as recumbent structures further west.

(A) Assumptions made for rocks prior to their deformation. (B) Rotation of first generation structures in rocks in the hanging wall to thrust ramp. (C) Rotation of the hanging wall block without internal deformation results in space problems at the block margins. (D) Maintaining the area within the rotated block but deforming the block by simple shear to avoid space problems results in a net rotation of the early-formed structure by about half that desired. (E) Maintaining length in the hanging wall block rotates the earlier-formed cleavage in a sense opposite that desired. Decreasing the volume of the block results in a positive rotation of about 5° although this is still significantly less than desired.

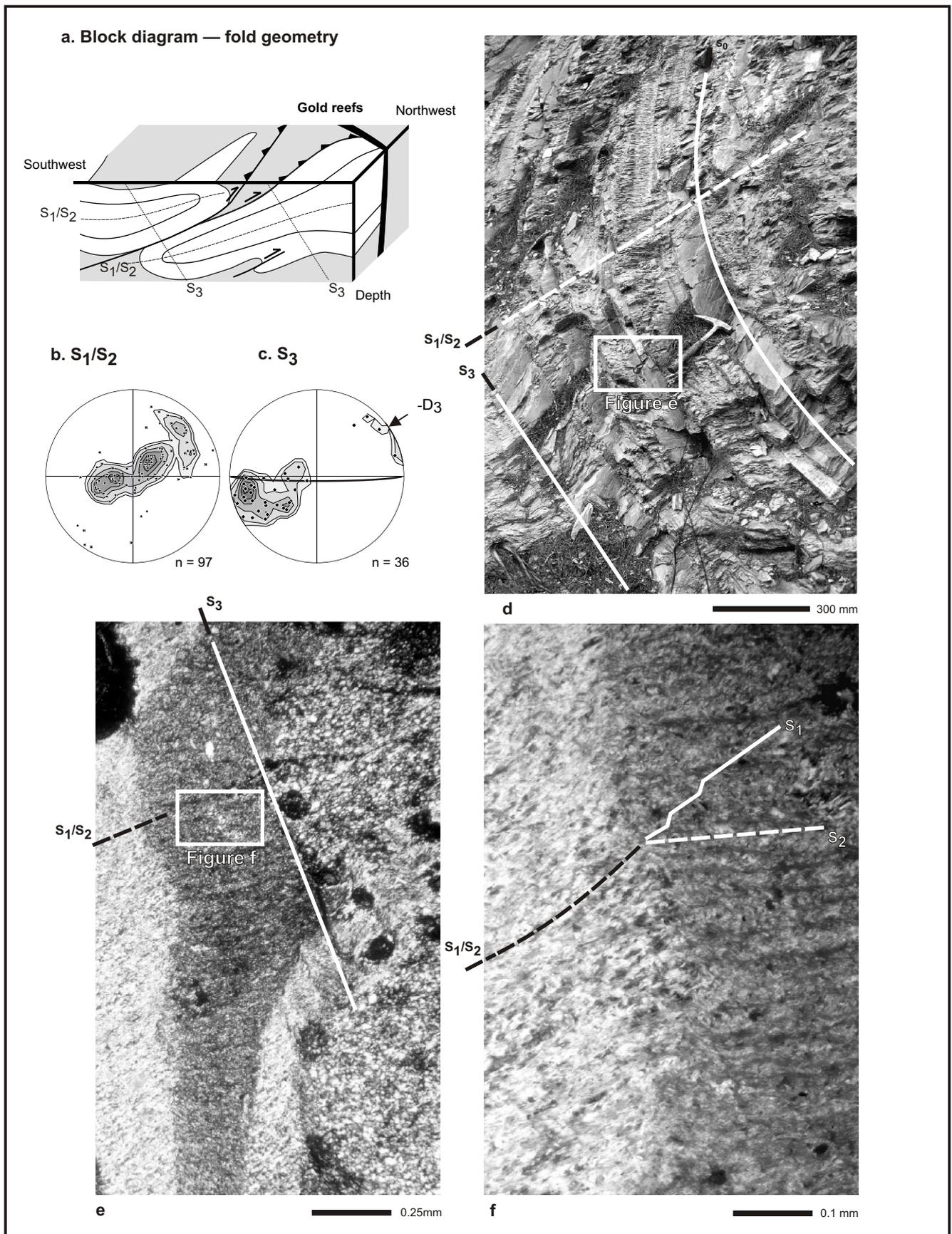


Figure 12

(a) Block diagram showing typical fold, thrust, foliation and reef geometry in the vicinity of the Lefroy goldfield. (b) Poles to the S_1 (Reed, 2001) and S_2 cleavages. (c) Poles to the S_3 . (d) Outcrop photograph (Trooper Track and Industry Road, St Patricks 1:100 000 scale map sheet (8315), 503 050 mE; 5 446 500 mN) showing hinge of D_1/D_2 fold, and the S_1/S_2 and S_3 cleavages. (e and f) Thin section photographs (TASROK No. 8441, Mineral Resources Tasmania) of rock pictured in (d) showing S_1 , S_2 and S_3 cleavage relationships.

similarly-oriented bedding plane (e.g. 503 050 mE; 5 446 500 mN).

Southwest-directed thrusting during D_3 has resulted in superimposed normal separations of several metres on D_1 thrusts southeast of Lefroy (503 050 mE; 5 446 500 mN). Here, isoclinal D_1 folds are also refolded and rotated into a more upright orientation.

Except where vergence is clear, it is not always possible to distinguish the effects of D_2 and D_3 deformation on D_1 structures. Open upright folding of S_1 folia from throughout the Lefroy and Back Creek areas is probably a combination of both D_2 and D_3 events. These deformations appear to have accentuated what was probably a variable angular relationship between bedding and the S_1 cleavage resulting from refraction of S_1 across bedding.

Strain associated with D_3 increases westward towards the River Tamar. This strain is of the same age relative

to the stratigraphy and earlier deformations as steeply northeast-dipping thrusts west of the River Tamar (Powell, 1991; Reed, 2001).

STRUCTURES EAST OF THE SCOTTSDALE BATHOLITH

D_2

The stratigraphy of this region remains undefined, although Powell *et al.* (1993) considered these rocks to be equivalent in age to the younger Bellingham Formation and Sidling Sandstone, west of the Scottsdale Batholith (fig. 4). The structural geology of this area is more simple than that west of the Scottsdale Batholith. There are no structures of consistently similar style to the recumbent folds and thrusts in older rocks west of the Scottsdale Batholith, consistent with the hypothesis (Reed, 2001) that these rocks post-date Silurian orogenesis.

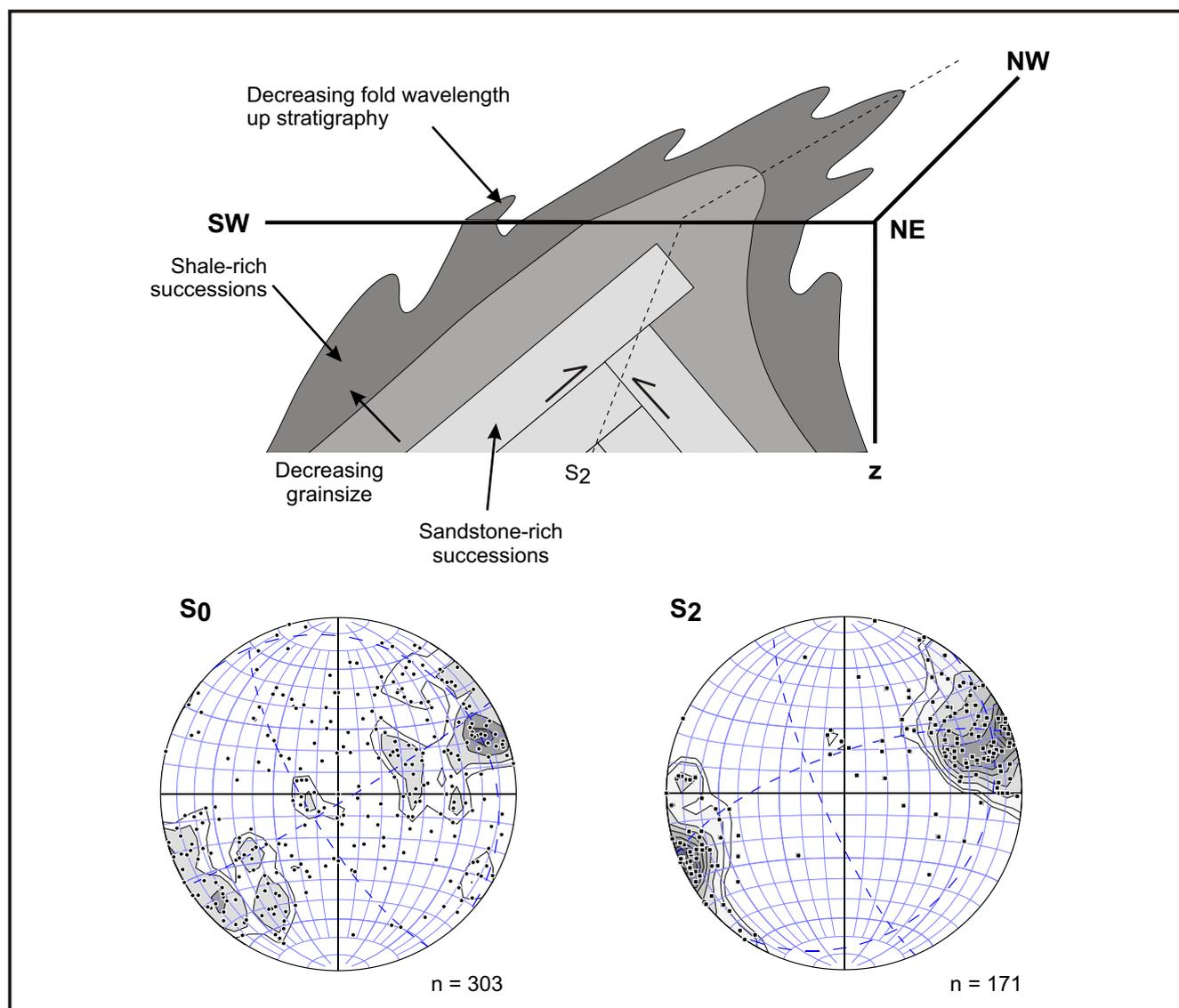


Figure 13

Illustration of fold styles and data from the Alberton, Mathinna and Mangana areas. Fold wavelength increases up stratigraphy coincident with increasing proportions of shale over sandstone within the sedimentary succession. Stereoplots show poles to bedding (S_0) and regional S_2 (local S_1), respectively.

East of the Scottsdale batholith, axial planes to undeformed D_2 folds typically trend northwest to north-northwest and dip steeply southwest. Folds plunge up to 30° both northwest and southeast (fig. 13). Folds are typically open to closed and chevron to concentric in style in sandstone, with a similar geometry more common in shale-dominated units.

Fold shape and wavelength is dependent on the overall composition of the host succession. The hinge zone of a macroscopic chevron fold with a wavelength exceeding three kilometres is exposed in a well-bedded massive sandstone sequence in the Ralphs Falls and Cashes Gorge areas (fig. 14) east of Alberton (570 400 mE; 5 425 250 mN). Reconnaissance mapping in the Alberton–Mangana region suggests that this unit is the stratigraphically lowermost of a sequence that fines upward through cyclic mixed sandstone and shale packages into a shale-dominated succession, best exposed northeast of Tower Hill. Deformation within the hinge zone of the folded sandstones appears dominated by faulting (see below). Patison (1999) describes the Ralphs Falls and Cashes Gorge area in detail.

Folding in stratigraphically overlying and increasingly micaceous sandstone is chevron to sub-concentric, with folds typically exhibiting steep to overturned northeast limbs. Buck quartz-filled saddle reefs are common in fold hinges, with well-developed near bedding-parallel foliations in shale interbeds attesting to the importance of flexural shear during fold development.

Veins formed during folding assume a high angle to bedding (60° to 80°) in brittle units and a low angle (about 15°) in shale. Samples from these veins contain less than 0.5 g/t gold.

Fold wavelength decreases up-stratigraphy concomitant with increasing proportions of shale over sandstone and decreasing competency to the overall rock package. The transition from a sandstone-dominated into cyclic mixed sandstone and shale succession coincides with a decrease in fold wavelength. Veins become increasingly axial planar and folds progressively more tight to isoclinal and similar in form in more pelitic units.

Faulting is common in more sandstone-rich rocks, particularly in the hinge zones of macroscopic F_2 folds.

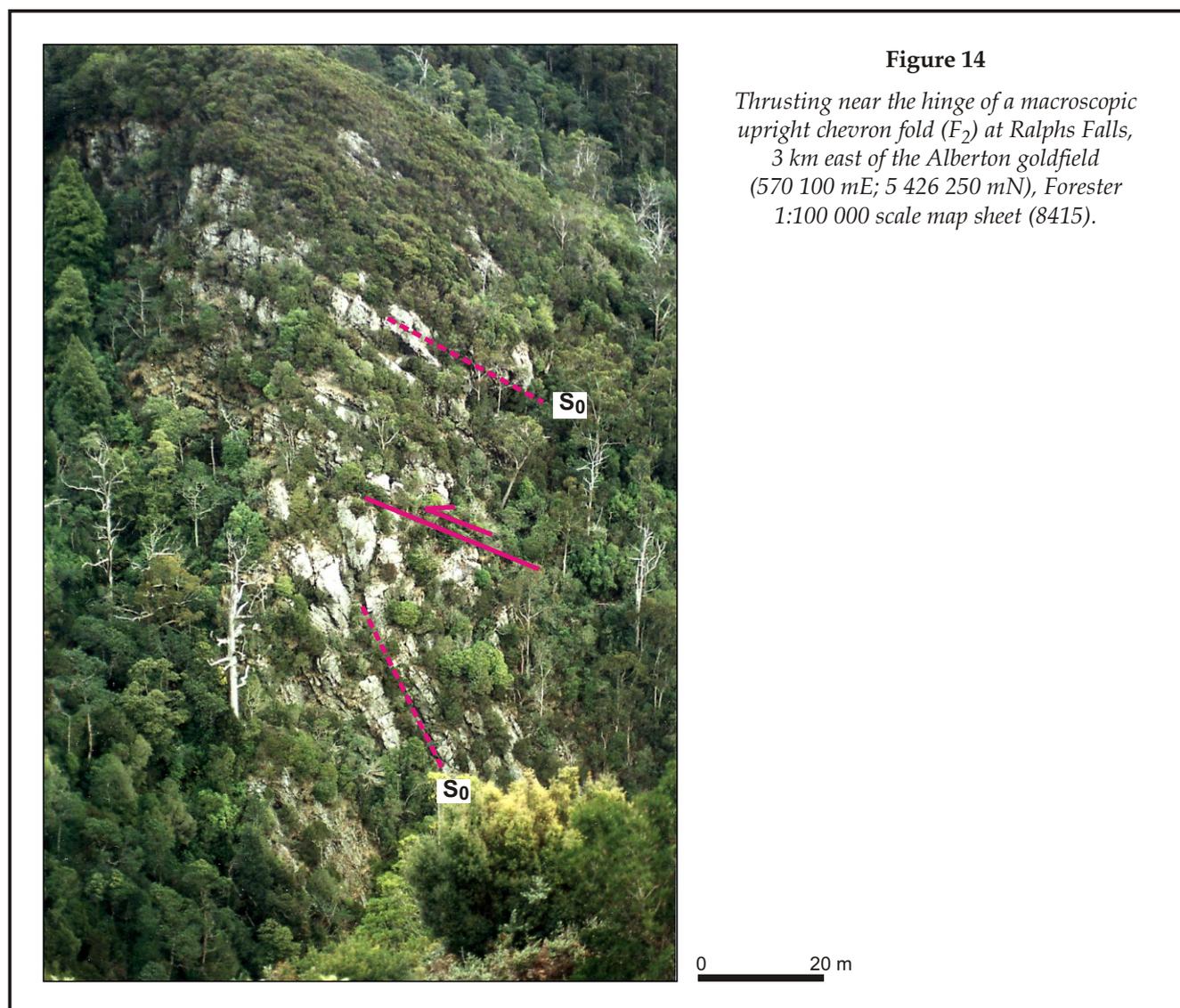
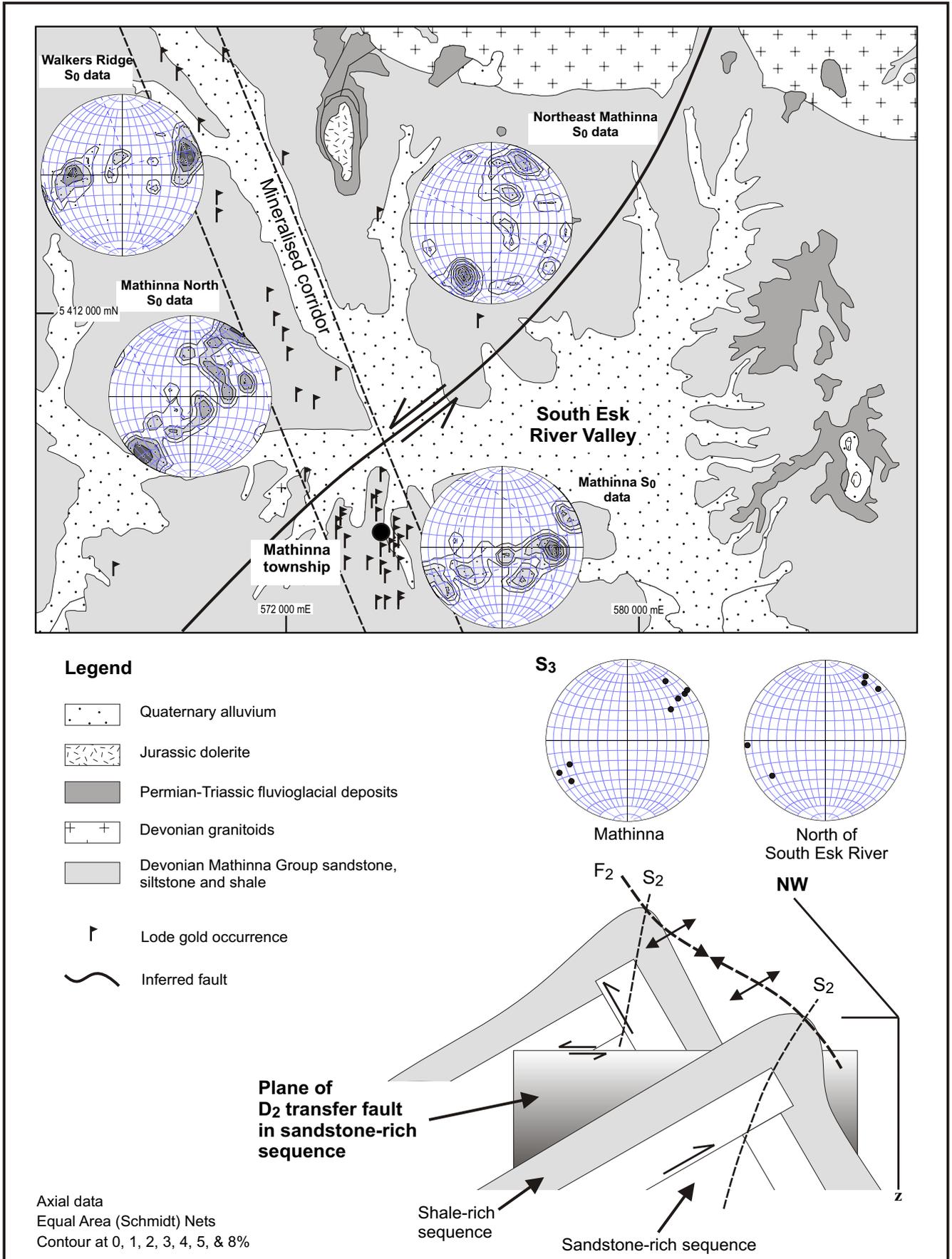


Figure 14

Thrusting near the hinge of a macroscopic upright chevron fold (F_2) at Ralphs Falls, 3 km east of the Alberton goldfield (570 100 mE; 5 426 250 mN), Forester 1:100 000 scale map sheet (8415).



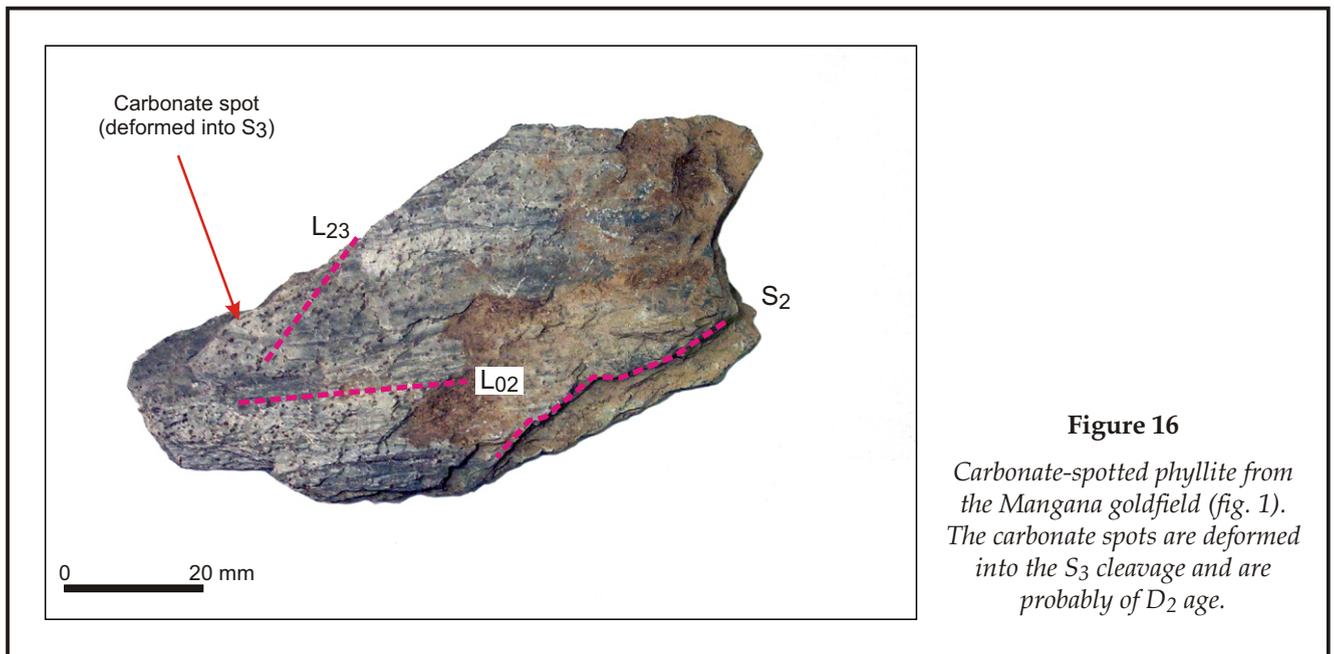


Figure 16
Carbonate-spotted phyllite from the Mangana goldfield (fig. 1). The carbonate spots are deformed into the S₃ cleavage and are probably of D₂ age.

In the Ralphs Falls and Cashes Gorge area, conjugate shallowly southwest-dipping and steeply northeast-dipping reverse faults (concordant to bedding on each fold limb) have accommodated fold hinge thickening. A third northeast-trending fault set probably accommodated variations along strike in offset across the two concordant fault sets. This fault set does not appear to penetrate any distance into overlying, more ductile sedimentary rock units.

An inferred northeast-trending fault north of Mathinna (Goscombe *et al.*, 1992, 1994; Keele, 1994) coincides with a change in strike of D₂ fold axial planes and S₂, although D₃ structures remain unaffected (fig. 15). The variation in strike of S₂ and S₀ could be the result of discrepancies in lateral offset across northeast-striking faults formed as transfer structures at depth. If such northeast-striking faults were restricted to the stratigraphically lower sandstone-dominated successions, then strain in overlying more pelitic units would manifest itself as the observed change in strike of S₂.

Faults commonly occur on the steep northeast limbs of D₂ folds in pelitic units stratigraphically overlying the sandstone-rich successions. They typically appear as bedding-parallel schistose zones up to three metres wide associated with complex networks of commonly cross-cutting, comb-filled and buck quartz-filled, reefs, breccias and stockworks.

The transition into cyclic sandstone and shale successions appears to be important from the perspective of fault geometry. Although more work is required, it appears that faults splay, with strain distributed and largely taken up by folding, in the overlying more pelitic rocks. This coincides with an increase in fold frequency.

Observations of alteration adjacent to faults are restricted to zones of carbonate spotting where faults

cut carbonaceous shales (fig. 16). This is discussed further in following sections.

Cleavage intensity is related to rock competency, with shale and sandstone showing slaty and disjunctive cleavages, respectively. An axial planar slaty cleavage (S₂) is best developed in pelitic units, striking predominantly northwest but locally west-northwest. In sandstone, S₂ is normally poorly developed and commonly lies at a high angle to bedding. In contrast, the penetrative S₂ cleavage developed in carbonaceous shale is normally near bedding-parallel and masks pre-existing sedimentary fabrics.

D₃

A regional southwest-directed D₃ compressional event has not previously been clearly described for the Alberton–Mangana area, although Keele (1994) and Manzi (1995) both noted structures formed during northeast and southwest-directed compression that post-dated those of D₂ age (Table 1). Possibly the earliest observations of D₃ structures were made by Finucane (1935) who wrote, regarding gold mineralisation at Mathinna, “A zone of close folding may be traced in a general north-westerly direction from the Tower Hill road cuttings near the Jubilee and Mountaineer sections, through the Horseshoe and New North Eldorado workings. As far as could be determined this is the most closely folded belt in the district, and its occurrence appears to have some significance when the distribution of the ore-bodies is taken into account”. As with the Lefroy and Back Creek areas, the strike of D₂ and D₃ structures in the Alberton–Mangana area is near parallel.

D₃ structures are not everywhere present and without a clear cross-cutting relationship it is not always possible to differentiate between the two events at any one location. The best exposures of D₃ structures typically coincide with mineralised areas, with

refolded D₂ folds best exposed in the Golden Hinges (574 200 mE; 5 406 700 mN) and Hannah adits (566 900 mE; 5 427 800 mN) at Mathinna and Alberton, respectively. In the Golden Hinges mine, tight to isoclinally D₂-folded laminated shale, siltstone and chert beds can be seen refolded into open D₃ folds in the adit wall. A slaty S₂ is folded and crenulated by a spaced to slaty S₃ cleavage.

D₃ faults are recognisable by refolding of D₂ veins, fractures and foliations. D₃ faults appear to have formed preferentially on the steep northeast limbs of D₂ folds and are similar to D₂ faults in appearance. They typically appear as planar zones, normally highly foliated, variably silicified, and commonly enveloped by crackle to mosaic quartz-filled and, more rarely, carbonate-filled breccias. Observations of alteration are confined to silicification near the New Golden Gate mine (574 480 mE; 5 406 600 mN) at Mathinna. Carbonate porphyroblasts formed during D₂ faulting are commonly deformed into a locally weakly developed, spaced to rarely slaty, S₃ cleavage.

Tension gashes and folded S₂ in the West Miami (578 600 mE; 5 396 950 mN) and Argyle (574 940 mE; 5 392 750 mN) mines at Mangana, the Golden Hinges and New Jubilee (575 010 mE; 5 404 550 mN) mines at Mathinna, and the Hannah mine at Alberton all indicate dextral-reverse movement on D₃ faults. Folded S₂-parallel veins at Mangana and reoriented L₀₂ and F₂ adjacent to D₃ fault zones along Walkers Ridge (566 500 mE; 5 419 000 mN) and the Golden Hinges mine also indicate dextral reverse shear during D₃.

KINKING AND MEGAKINKING

Elongate lenticular and monoclinical kink bands to several centimetres wide are common throughout eastern Tasmania. Williams (1989) noted four sets belonging to two conjugate systems, but that the two conjugate sets could be brought to coincidence by rotation of an earlier-formed fanned cleavage into parallelism. Cleavage fanning has been attributed to tightening of earlier formed folds (Powell, 1967; Williams, 1978; Gee and Legge, 1979; Williams, 1989), suggesting kinking was of pre-D₃ age.

Kinking of Mathinna Supergroup rocks in the Alberton, Mathinna and Mangana areas has been described by Threader (1967), Goscombe and Findlay (1989) and Goscombe *et al.* (1992, 1994). In outcrop, kink bands are elongate lenses averaging 20 mm wide by two metres long. Sinistral kink bands are more common and strike to 032°, whereas dextral kink bands strike between 048° and 127°, respectively.

The origin of kinking at Alberton, Mathinna and Mangana is uncertain. Goscombe and Findlay (1989) and Goscombe *et al.* (1992, 1994) noted that kink bands deformed the main foliation and concluded that kinking occurred some time after compressional deformation. A major post-orogenic crustal-scale megakinking event, similar to that proposed for rocks elsewhere in the Lachlan Fold Belt (Powell *et al.*, 1985),

was invoked to account for both outcrop-scale kinking and variations in strike to the regional foliation. Goscombe and Findlay (1989) and Goscombe *et al.* (1992, 1994) did not differentiate between the S₂ and S₃ foliations. Consequently, they did not recognise that variations in the strike of S₂ were not mirrored by similar variations in S₃ (fig. 15). This suggests that kinking occurred late during D₂. There appears to be no relationship between kinking and gold mineralisation.

DEFORMATION AGES

The ages of the upright chevron folds and subsequent crenulation cleavage are constrained by fossils and radiometric ages (fig. 4). Pragian graptolites from the upper part of the turbidite sequence east of the Scottsdale Batholith (Rickards and Banks, 1979) constrain the maximum age for the upright folding to between ca 405 Ma and 400 Ma (using the Young and Laurie (1996) time-scale). Granodiorite emplaced after upright folding, but before the event producing the late crenulation cleavage, has been dated (using Rb-Sr and K-Ar) at 396 ± 4 Ma (McClenaghan and Higgins, 1993). Undeformed adamellite emplaced after development of the late crenulation cleavage (and thrusting west of the River Tamar) has similarly been dated at 381 ± 6 Ma (McClenaghan and Higgins, 1993). These two deformation events are, therefore, Devonian and related to Tabberabberan orogenesis.

In contrast, the timing of the recumbent folding is not well constrained. This event pre-dates the Tabberabberan deformation and post-dates deposition of sediments containing Early to Middle Ordovician graptolites (Bendigonian Be1 to Darriwilian Da3). Recumbent folding like that west of the Pipers River is not present east of the Scottsdale Batholith at Golden Ridge in rocks containing Silurian (Ludlow age) graptolites (Rickards *et al.*, 1993). These rocks are probably equivalents of the Bellingham Formation or Sidling sandstone west of the Scottsdale Batholith (Powell *et al.*, 1993). Although the recumbent event has not been dated directly using radiometric methods, these fossil ages bracket recumbent folding to between 485 Ma and 414 Ma, during the Ordovician and/or Silurian. This timing also coincides with a 423 ± 22 Ma Rb-Sr isochron defined from whole-rock analyses of the recumbently folded Turquoise Bluff Slate, an isochron interpreted as the product of regional metamorphism (Cocker, 1982).

Ordovician to Silurian Benambran orogenesis, dated at between 455 Ma and 424 Ma (Gray and Foster, 1997), has not been previously recorded in Tasmania. The Benambran Orogeny affected turbidites across much of mainland southeastern Australia (Gray and Foster, 1997). There is little reason why turbidites pre-dating the Benambran Orogeny in Tasmania should escape such an event. Although dating of fabrics within the turbidite package in eastern Tasmania is required to better constrain the absolute timing of recumbent folding, the constraints imposed by fossil data show

that this event is most likely a southward extension, across Bass Strait, of the Benambran Orogeny.

A REVISED TURBIDITE STRATIGRAPHY

The contact between the recumbently folded Turquoise Bluff Slate and less-deformed Bellingham Formation west of the Scottsdale Batholith does not crop out. However, the Stony Head Sandstone and Turquoise Bluff Slate experienced an orogenic event not present in younger rocks further east. The contact between the recumbently folded and younger, less-deformed packages cannot, therefore, be conformable (*cf.* Powell and Baillie, 1992; Powell *et al.*, 1993), but instead must be separated by a hiatus in sedimentation during which there was a period of deformation (fig. 4). As such, the Mathinna Supergroup was promoted to supergroup status (Reed, 2001), and existing formations placed in two new groups; the Tippogoree Group and the Panama Group. The Tippogoree Group includes the older and more deformed Stony Head Sandstone and Turquoise Bluff Slate. The Panama Group comprises rocks west of the Scottsdale Batholith and stratigraphically overlying the Turquoise Bluff Slate, including the Bellingham Formation and Sidling sandstone.

The rocks east of the Scottsdale Batholith remain undifferentiated and are here referred to simply as the Mathinna Supergroup. It should be noted that during the course of this study it was possible to recognise distinct packages of rock east of the Scottsdale Batholith, based simply on sand to mud ratios. Unfortunately, it was not the scope of this study to map the along-strike extent of these units.

Igneous and post-Mathinna Supergroup sedimentary rocks

GRANITOID ROCKS

Three roughly NNW-orientated elongate composite I and S-type granitoid batholiths of Late Devonian age

intrude Mathinna Supergroup rocks. These are (from west to east) the Scottsdale, Blue Tier and Eddystone batholiths. The granitoids comprise, in order of decreasing age, hornblende-biotite granodiorite, biotite granite/adamellite and alkali-feldspar granite. Each is surrounded by narrow metamorphic aureoles indicative of intrusion at a high crustal level (emplacement depth of granodiorites range from about one kilometre to twelve kilometres based on hornblende geobarometry; Varne and Fulton, 1994).

Lode and disseminated, possibly granodiorite-related, gold deposits occur in the Lisle-Golconda, Gladstone, Mt Horror and Upper Scamander areas (Klominsky and Groves, 1970; Bottrill *et al.*, 1992; Bottrill, 1994a). These deposits were not examined during the course of this study. Additionally, the younger granitoids, the alkali feldspar granites, contain fluorite, topaz and apatite and are extensively mineralised in tin and tungsten (Taheri, 1992; Solomon and Groves, 1994).

POST-CARBONIFEROUS ROCKS

Mathinna Supergroup and granitoid rocks are unconformably overlain by flat-lying Permo-Triassic rocks of the Parmeener Supergroup, which are intruded by sills of Jurassic dolerite. Exhumation and weathering during the Tertiary was accompanied by basaltic volcanism. The basalt is preserved in lowland areas along the north coast and scattered plateau remnants inland. The Parmeener Supergroup is typically unmineralised, although palaeoplacer cassiterite deposits occur in the Roys Hill area and there is a small quantity of gold in the Mangana area. Lead gold deposits, derived during Tertiary weathering of Mathinna Supergroup rocks, also underlie basalts in the Lefroy and Back Creek areas (McClenaghan, 1994), with extensive granite-derived alluvial cassiterite deposits further east. Pleistocene to Recent sedimentary deposits are largely restricted to valley bottoms and, where proximal to mineralised Mathinna Supergroup, may contain alluvial gold.

Structural setting of gold mineralisation east of the River Tamar

Introduction

Observations of the relationship between structure and gold mineralisation made during the course of this study are restricted to five mineral fields. The Lefroy and Back Creek goldfields lie in recumbently-folded rocks whereas the Alberton, Mathinna, and Mangana goldfields lie further east in upright folded rocks (fig. 1). There are marked differences in reef geometry between upright and recumbent fold domains.

The findings of this study are consistent with those of Powell (1991) and Keele *et al.* (1994) in that gold mineralisation is associated with the latest Tabberabberan deformation (D_3) and is of the same age as that at Beaconsfield. Mineralised structures evident throughout eastern Tasmania and in the Beaconsfield area almost certainly form the upper part of a linked fault system that acted to focus gold mineralising fluids throughout eastern Tasmania and the West Tamar region.

Lefroy and Back Creek goldfields

The Lefroy and Back Creek goldfields are located within the Tippogoree Group at or near to the contact between the Stony Head Sandstone and the Turquoise Bluff Slate (fig. 1). Unlike the Alberton, Mathinna and Mangana goldfields (see below), the Lefroy and Back Creek goldfields are contained within a package of rocks deformed during an orogenic event of probable Silurian age (Reed, 2001).

LEFROY

The Lefroy goldfield (fig. 17) is located approximately at the boundary between the Stony Head Sandstone and the stratigraphically overlying Turquoise Bluff Slate. Gold mineralisation occupies a series of predominantly sub-vertical, planar, east to ENE-trending quartz reefs occupying faults up to 10 km long. Together, these reefs form a northwest-trending ladder-like array, the long axis of which parallels the contact between the Stony Head Sandstone and Turquoise Bluff Slate (Groves, 1965; Gee and Legge, 1979; Powell, 1991; McClenaghan, 1994).

Gold mineralisation is contained entirely within the planar quartz reefs, with little to no obvious alteration of adjacent sedimentary rock. Mineralised veins commonly comprise free gold in vughy quartz, with fine auriferous pyrite increasingly prevalent at depths typically greater than about 30 m (McClenaghan, 1994). Accessory minerals include pyrite, arsenopyrite, stibnite and rare chalcopyrite (McClenaghan, 1994; Keele, 1996). Total production from the Lefroy goldfield is recorded to have been about 5100 kg, with the Au grade averaging about 30 g/t at depths less than about 30 metres. Gold grades

generally decreased with depth as did fineness (Broadhurst, 1935).

Surface exposure in the vicinity of the mineralised reefs at Lefroy is poor, with a subdued topography the result of both Tertiary and Quaternary weathering. Access to the reefs at Lefroy was typically via shafts, most of which are now infilled. The lack of easy access has made assessing the structural controls on gold mineralisation difficult and, with the exception of the Volunteer orebody, it has been necessary to rely on old mine plans and accounts of the geology by previous workers (Thureau, 1882, 1883; Montgomery, 1897; Twelvetrees, 1899; Broadhurst, 1935). Only adjacent to the Volunteer mine are Mathinna Supergroup rocks sufficiently well exposed in road cuttings on the main Bridport to George Town road (fig. 18). Diamond-drill core also intersects the Volunteer Reef and has been logged, complementing the surface geology. Although this core was not orientated during drilling, it has been possible to use the consistent northeast dip of the S_3 cleavage (both in drill core and regionally) to closely estimate the orientation of pre- D_3 structures at depth.

The Volunteer Reef is the largest and southernmost of the mineralised structures in the Lefroy goldfield. It has been worked over a length of greater than 1220 m, with the structure evident in aeromagnetic data (NETGOLD data, 200 m line spacing, Mineral Resources Tasmania) extending over a distance of greater than ten kilometres. The reef was explored to a depth of 380 m with most of the gold extracted at depths of less than about 200 m (Montgomery, 1897; Broadhurst, 1935; Groves, 1965). Reported gold grades were 81.1 g/t for the Volunteer mine, and 122.4 g/t for the West Volunteer mine (these two mines representing the one deposit cut by an old lease boundary) (McClenaghan, 1994). Within the reef, the main Volunteer lode comprises a pipe-like body plunging about 45° to the west (Twelvetrees, 1899). The Chum and Pinafore orebodies also comprise pipe-like bodies plunging west, although these are contained within separate reefs located north of, and paralleling, the Volunteer Reef (Montgomery, 1897).

The projection to surface of the main Volunteer ore body, and the position of the main shaft, coincide with a change from overturned predominantly sandstone beds (?Stony Head Sandstone) in the west, to right-way-up siltstone and mudstone beds (?Turquoise Bluff Slate) 200 m to the east. In diamond-drill core, this transition coincides with a moderately ($\sim 45^\circ$) southwest-dipping highly foliated zone separating overturned carbonaceous siltstone in the hanging wall from right-way-up siltstone in the footwall. S-C fabrics indicate easterly-directed thrusting of the hanging-wall rocks during D_1 (with possible reactivation during D_2). The extent of displacement on this thrust is not known.

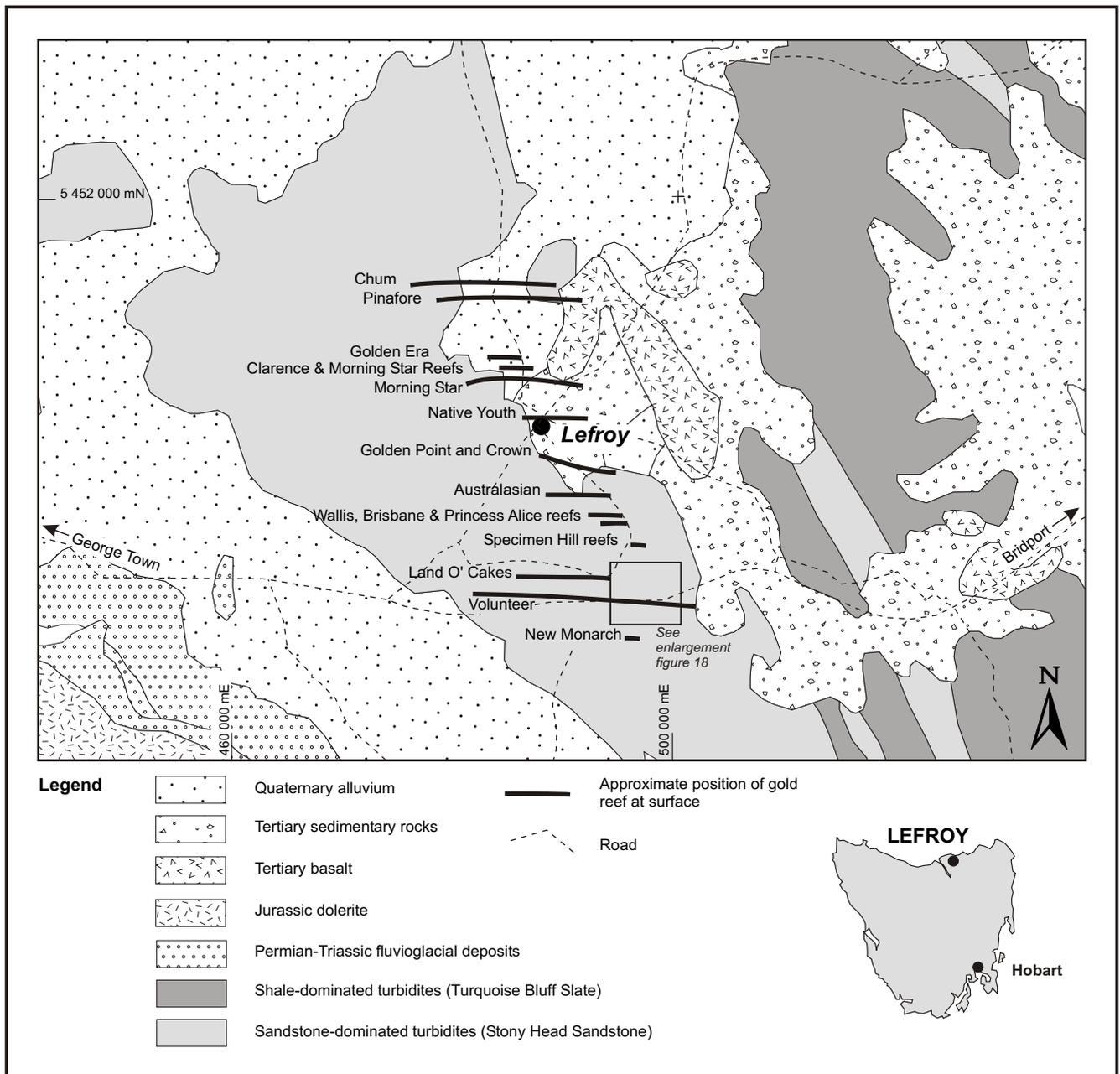


Figure 17

Geology of the Lefroy goldfield [modified from McClenaghan and Calver (1994), with geology compiled from Marshall et al. (1965)]. Transitional boundary between sandstone and shale-dominated sedimentary rock successions corresponds approximately to boundary between Stony Head Sandstone and Turquoise Bluff Slate (Powell et al., 1993). Surface projection of gold reefs from Groves (1965). Structural data from the Lefroy goldfield are illustrated in Figure 4.

Easterly-directed thrusting is consistent with tectonic vergence determined elsewhere in the region from mineral lineations and fold asymmetry (Reed, 2001). Thrusting at or near the contact between the Stony Head Sandstone and Turquoise Bluff Slate is also consistent with D_1/D_2 strain partitioning at the interface between competent sandstone and less competent shale packages. An association between changes in sedimentary composition (and, hence, competency) and locations of gold mineralisation have previously been noted by both Broadhurst (1935) and Groves (1965).

A penetrative to stripy S_1/S_2 cleavage is well developed throughout the Volunteer core and

accompanied development of northwest-striking D_1/D_2 quartz-carbonate-chlorite-(ankerite) veins. These veins are common in outcrop. They carry no detectable gold, are discontinuous in extent, and are normally truncated along bedding planes at the boundaries between sandstone and shale beds.

D_3 structure in the Volunteer core is common but not everywhere developed. Rather, it is evident as localised folding of S_1/S_2 , brecciation and disruption of D_1/D_2 veins, and development of a crenulation cleavage. Auriferous sulphide mineralisation is typically associated with D_3 brecciation and folding of D_1/D_2 structures. This association, and the regional cross-cutting relationship of the reef structures to the

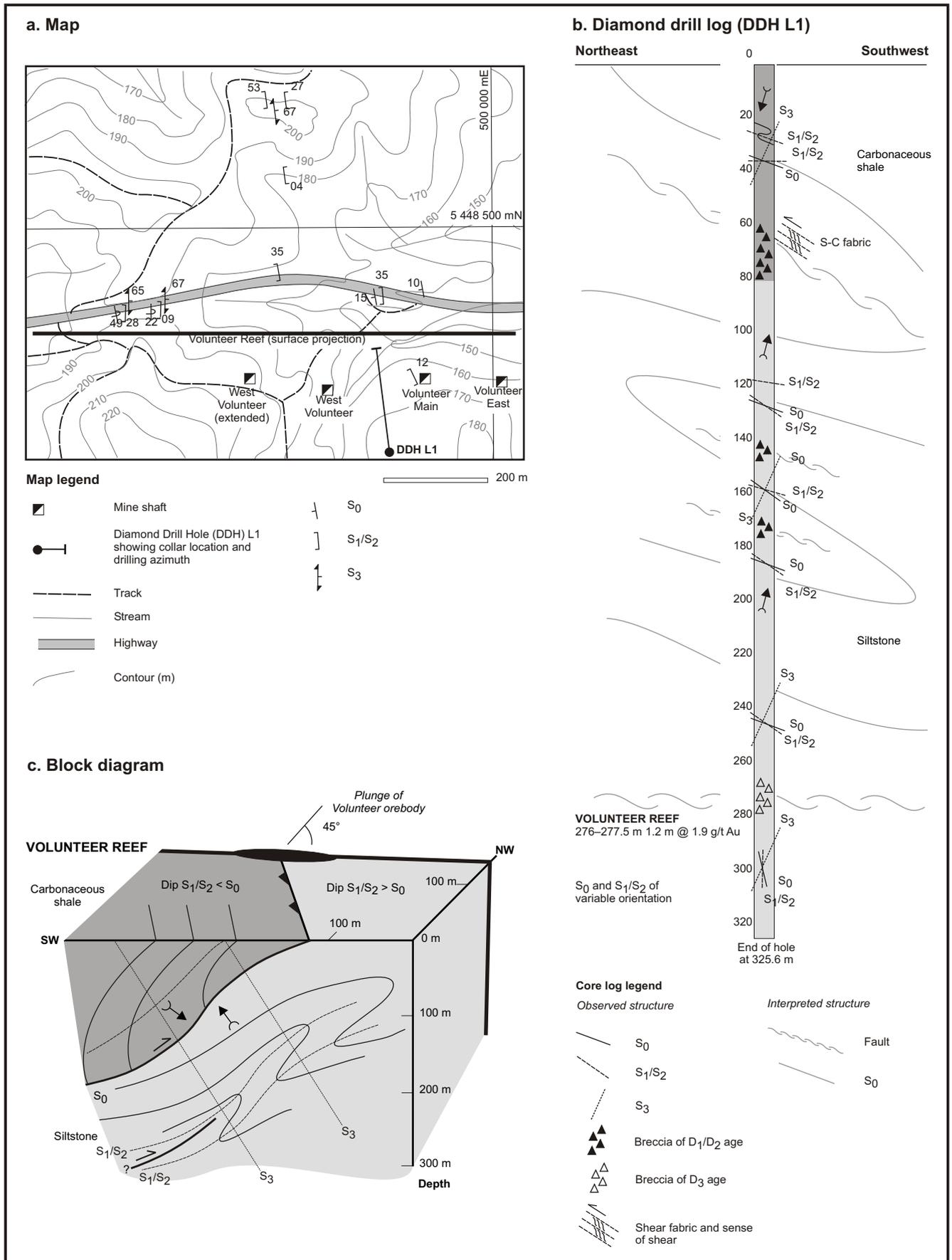


Figure 18

(a) Map of the area in the vicinity of the Volunteer Reef and ore body (St Patricks 1:100 000 scale map sheet (8315), 499 320 mE; 5 448 210 mN). (b) Sketch diamond drill log from drill hole L1, drilled to intersect the Volunteer Reef [detailed logs are contained in Purvis (1998)]. (c) Block diagram showing interpreted structure in the vicinity of the Volunteer ore body, and the coincidence between the plunge of the orebody (in the plane of the reef) and the intersection of a D₁/D₂ thrust and the reef.

D_1/D_2 fold trend, are consistent with previous interpretations (e.g. Powell, 1991) for a D_3 timing for the gold mineralisation at Lefroy.

A westerly plunge to the Volunteer orebody matches the intersection of the thrust in drill core and the ENE-trending D_3 reef. Arching of the ore shoots within both the Chum and Pinafore reefs is also consistent with folding of pre- D_3 structures, resulting in a curvilinear intersection between D_1/D_2 thrusts (and folded sedimentary contacts) and the D_3 reefs.

The mineralised reefs are cut by both northwest-striking and southeast-striking and typically steeply-dipping faults (Broadhurst, 1935). The displacement on these structures is unclear, as is their timing relative to Tabberabberan orogenesis. Sketches showing offsets of the Native Youth Reef (Thureau, 1882) were interpreted by Groves (1965) to indicate downward throw to the northeast and/or dextral strike-slip movement on the northwest-striking faults. Both northeast and northwest-striking structures are typically unmineralised.

Reef offset at Lefroy

Without access to the old workings, the sense of offset across the gold reefs remains uncertain. Determining the movement sense on the fault reefs is important as offset of pre- D_3 contacts could, potentially, duplicate the intersection between the reef and either D_1/D_2 thrusts or stratigraphic contacts either side of the reef and, consequently, high-grade ore shoots within the reef. In determining movement sense, Keele (1996) noted that the Volunteer orebody coincided with 'overstepping' (or overlapping) of the Volunteer Reef relative to the adjacent Land 'o Cakes Reef. He proposed that clockwise rotation of the D_3 stress field resulted in dextral movement on the ENE-trending reefs, thus generating a zone of dilatancy into which mineralising fluids were channelled. There is, however, no direct evidence for dextral movement. Dextral movement also contrasts with apparent sinistral offsets of linear features evident in regional aeromagnetic data (NETGOLD data, 200 m line spacing, Mineral Resources Tasmania). Assuming that the principal compressive stress (σ_1) during D_3 was orientated in the horizontal plane and orthogonal to the strike of the S_3 foliation, at about 060° , then the approximately 090° trend of the fault reefs is best suited to sinistral movement.

A vertically-orientated minimum compressive stress (σ_3) typically accompanied reef formation in the central Victorian goldfields on the Australian mainland (Cox *et al.*, 1991a). If σ_3 was vertical at Lefroy then an increase in either the differential stress ($\sigma_1 - \sigma_3$) or pore fluid pressure (Pf) would have most likely resulted in failure (and reef formation) along bedding, D_1/D_2 thrusts, or the S_1/S_2 foliation (fig. 19), all of which dip predominantly at a low angle to the southwest. In contrast, if σ_3 was horizontal (and σ_2 was orientated vertically), then the optimum modelled

fault orientation is vertical and orientated about 30° to σ_1 , matching the actual orientation of the mineralised reefs at Lefroy. Horizontal σ_3 and subvertical fault development are typical of Andersonian wrench faulting (e.g. in Twiss and Moores, 1992). This means that the Lefroy reefs are likely to exhibit a greater degree of lateral compared to dip-slip movement. Sinistral offset across the fault reefs at Lefroy is most likely given the orientation of the reefs relative to σ_1 . However, if the fault reefs formed in response to variations in net shortening during D_3 compression, with shortening south of any one structure greater than that to the north, then the overall net movement across any single fault might also, in places, be dextral (fig. 20).

BACK CREEK

East of the River Tamar, the Back Creek goldfield is also hosted by recumbently-folded Tippogoree Group rocks, and lies only about 10 km north-northeast of Lefroy. Outcrop in the vicinity of the Back Creek goldfield is extremely poor. Mineralised reefs are of varying orientation and, like the Lefroy goldfield, are probably located near to the contact between the Stony Head Sandstone and Turquoise Bluff Slate. Total production from this field was only about 311 kg (McClenaghan, 1994), small compared to the 5100 kg mined from Lefroy. Lode gold at Back Creek is hosted by veins of varying width, commonly narrow (<50 mm wide), and of varying orientation. These veins are located adjacent to rocks deformed during D_3 . A D_3 age for gold mineralisation at Back Creek thus seems likely. Although of similar orientation and style, lode structures at Back Creek are generally smaller and less well developed than those at Lefroy (Broadhurst, 1935).

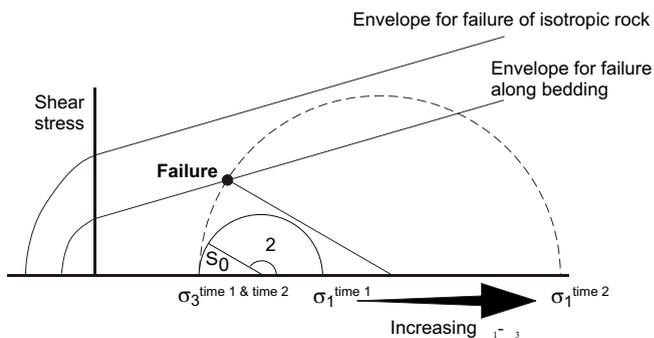
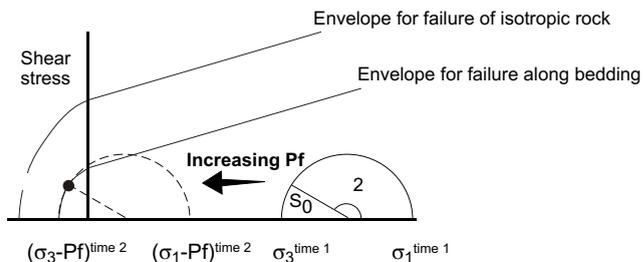
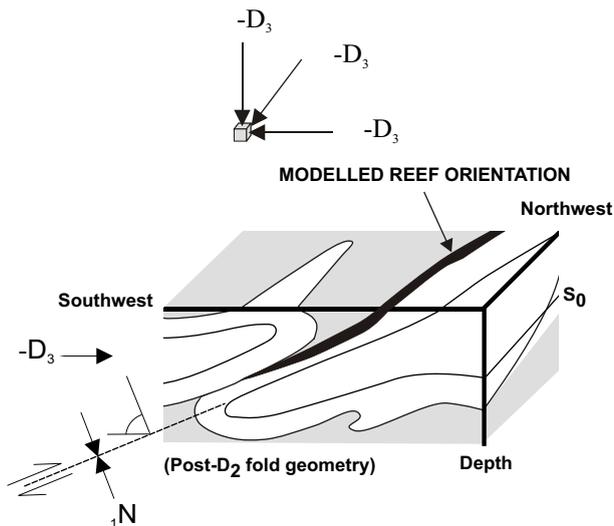
REGIONAL-SCALE STRUCTURES

At the regional scale, mineralised reefs at Lefroy parallel, and in the case of the Volunteer Reef coincide with, a regional-scale lineament evident in aeromagnetic data. The origin of this structure is poorly understood. Parallelism of this structure with the mineralised reefs suggests a common origin.

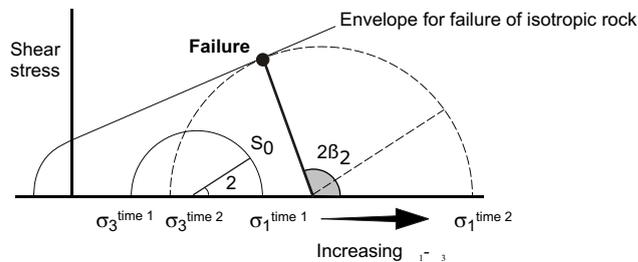
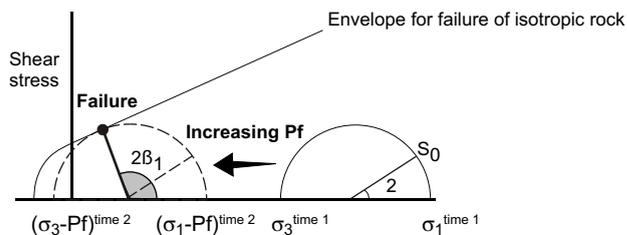
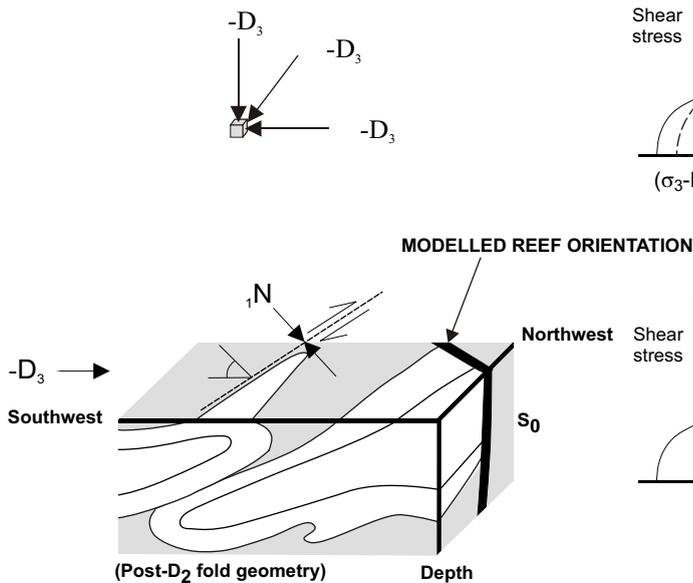
Lode structures at Lefroy can be traced west using aeromagnetic data where they offset northwest-trending linear features, most probably stratigraphic units within the Stony Head Sandstone. With the exception of the Volunteer structure, the lodes cannot be traced east into the shale-rich Turquoise Bluff Slate.

The full strike extent of the Volunteer structure to the east and west is not known. To the east the structure bends to the east-southeast. It cannot be traced beyond the intersection with a prominent northwest-trending magnetic lineament. Much of this latter lineament remains hidden beneath a veneer of Tertiary cover and again it is unclear whether it is a stratigraphic or structural feature. The Back Creek goldfield lies along strike of this northwest-trending aeromagnetic linear.

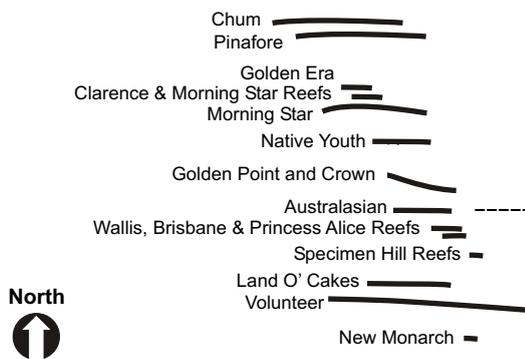
**a. Vertical minimum compressive stress
(i.e. reactivation of bedding-parallel weakness)**



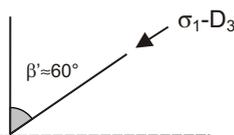
**b. Vertical intermediate compressive stress
(i.e. optimally orientated failure)**



Lefroy Goldfield (from fig. 12)



OBSERVED REEF ORIENTATION (β')



MODELLLED REEF ORIENTATION (β)

$$2\beta_1 = 2\beta_2 \approx 120^\circ$$

$$\beta \approx 60^\circ$$

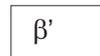


Figure 19

Figure 19

Mohr diagrams modelling reef orientation as a result of changes in effective stress states. σ_1 , σ_2 and σ_3 are the maximum, intermediate and minimum compressive stresses, respectively. P_f is pore fluid pressure.

(a) Modelled reef formation assuming vertical orientation for σ_3 , as modelled by Cox et al. (1995) for Victorian lode gold deposits. Increasing P_f decreases the effective stresses resulting in (in this scenario) tensional failure along either bedding (as shown) or near bedding-parallel D_1 structures. Increasing σ_1 - σ_3 (the differential stress) results in an increase in the shear stress, and also results in failure and reef formation along bedding or sub-parallel structures.

(b) Assuming a vertical orientation for σ_2 (normal for wrench faulting), then bedding no longer contains σ_2 . Increasing P_f results in failure of the intact rock.

Increasing σ_1 - σ_3 (here shown as function of increasing σ_1 and, hence, mean stress) also results in failure of the intact rock. The optimum orientation modelled for reef formation (β) is the same whether failure is the result of either an increasing σ_1 - σ_3 or P_f , and closely approximates the average reef orientation at Lefroy (β').

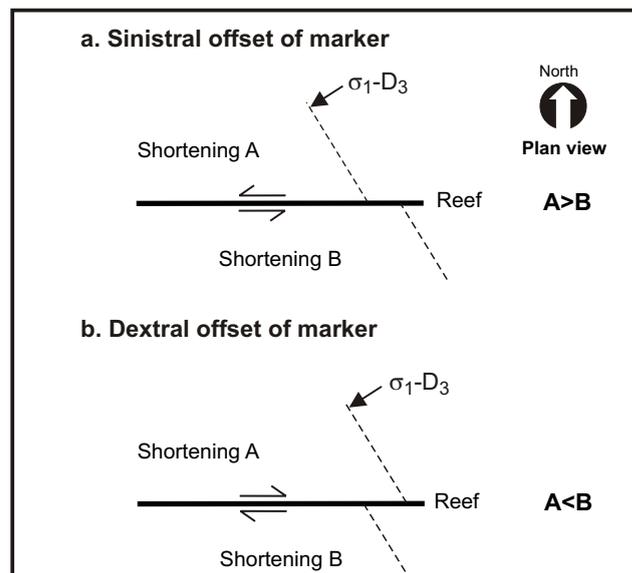


Figure 20

Sketch showing how varying degrees of shortening on either side of the Lefroy fault reefs can determine the apparent lateral movement sense. Movement sense may also vary along the length of any one reef depending on loci and extent of shortening to either side.

Both the Lefroy and Back Creek goldfields coincide with windows through the Tertiary cover. Aeromagnetic data show mineralised structures extending beneath the adjacent cover and it is extremely likely that there is further mineralisation to be found at depths of less than about 30 metres. Potential also exists within the Lefroy goldfield, 250 m to the south of the Pinafore Reef, where an unrecorded ENE-trending structure evident in the aeromagnetics lies buried beneath Quaternary cover.

Alberton, Mathinna and Mangana

The Alberton, Mathinna, and Mangana goldfields all lie along a mineralised corridor that stretches from Lyndhurst in the north to Mangana in the south (fig. 1). The structure within this corridor, historically known as the 'main slide', is dominated by upright folding. The stratigraphy of the area is poorly understood. The results of this reconnaissance study indicate that the stratigraphy can be broadly subdivided into an upward-fining sequence of quartz sandstone, micaceous sandstone, cyclic shale and sandstone packages, and a shale-rich sequence. The thicknesses of these sequences are not known. A more regional approach to mapping is recommended to better define this stratigraphy.

Gold mineralisation is typically restricted to near the contact between micaceous sandstone and cyclic shale-sandstone packages. This transition in sedimentary character is similar to that at Lefroy and, like Lefroy, commonly marks a significant change in the geometry and wavelength of folding and frequency of faulting.

Gold mineralisation is typically hosted by steeply-dipping D_3 or D_3 -reactivated D_2 reefs in faults, and is, therefore, considered to be of D_3 age.

Reconnaissance mapping indicates that each mineral field is located on the northeastern limb of a regional-scale D_1 fold. Unlike the recumbent folds at Lefroy, the geometry of folds at Alberton, Mathinna and Mangana is upright, with bedding on the northeastern limbs normally steep to sub-vertical. The gold-bearing reefs at Alberton, Mathinna and Mangana strike predominantly northwest, parallel to bedding and sub-parallel to the regional fold trend. The plunge of D_2 folds does not appear to have had an impact on mineralisation, with folds at Alberton and Mathinna plunging shallowly northwest whereas those at Mangana plunge to the southeast.

ALBERTON

The Alberton goldfield (fig. 21) can be subdivided into three areas based on reef geometry; these subdivisions are related to regional-scale structures evident in aeromagnetic data (NETGOLD data, 200 m line spacing, Mineral Resources Tasmania) (fig. 22). Mineralised reefs strike predominantly north, NNE, or northwest. The Ringarooma United mine (566 750 mE; 5 427 960 mN) was Alberton's largest gold producer and lies at the junction of the three areas.

NNE-striking reefs predominate south of the Ringarooma United mine and cut across the hinge of the northwest-trending D_1 fold. The reefs are parallel, equally spaced and extend several hundred metres northeast before being truncated by a 200 m to 300 m-wide corridor containing northwest-striking and S_0 -concordant reefs.

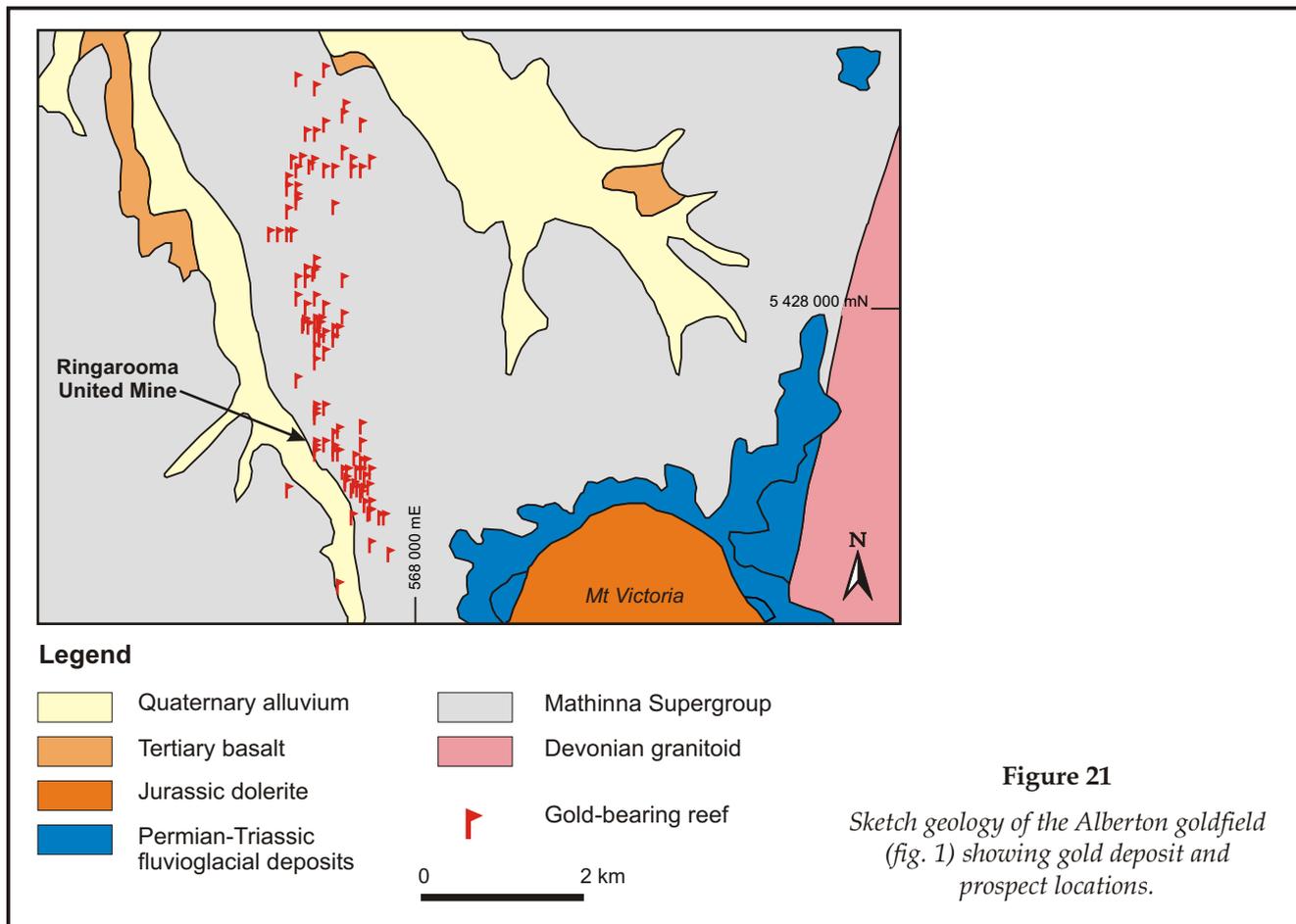


Figure 21
Sketch geology of the Alberton goldfield (fig. 1) showing gold deposit and prospect locations.

The northwest-striking corridor is in turn truncated by a regionally extensive north-striking structure that can be traced using aeromagnetics over a strike length of more than ten kilometres. This structure has been mapped in the Ringarooma United mine and comprises a network of steeply east and west-dipping upwardly branching faults (fig. 23). These are here collectively named the Ringarooma Fault. Data on the internal geometry of the Ringarooma Fault zone is restricted to old mine plans. Lode structures to the north of the Ringarooma United mine are located adjacent to, and parallel to, the Ringarooma Fault.

The upwardly branching fault architecture of the Ringarooma Fault and its north-south orientation oblique to the main northwest trend of the Lyndhurst-Mangana mineralised corridor suggests a component of oblique slip was likely. A transtensional environment is consistent with dextral shear along the main NNW-trending Lyndhurst-Mangana belt (Findlay *in* Taheri, 1992). This potentially created zones of dilatancy into which mineralising fluids would have flowed during D₃. Regardless of movement sense, the Ringarooma Fault appears to form part of a linked fault system probably connecting northwest-trending D₃ faults preferentially developed on the steep northeast-limbs of D₂ folds.

The Ringarooma United mine forms one of a cluster of mines located near the intersection of the northwest-trending fault corridor and the Ringarooma Fault, and near where the contact between the

sandstone-dominated and shale-dominated rocks wrap around the nose of the D₂ anticline. Two smaller clusters of deposits several kilometres north of the Ringarooma United also coincide with the intersection of the Ringarooma Fault with northwest-trending aeromagnetic lineaments. For the Alberton field, at least, the intersections of the Ringarooma Fault with faults developed on the northeast limbs of D₂ folds was important for controlling the flow of the mineralising fluids during D₃.

MATHINNA

Mathinna is located about 20 km SSE of Alberton (fig. 1). The Mathinna goldfield hosts the New Golden Gate mine. This was the largest producer of lode gold east of the Tamar Valley. As at Alberton, Lefroy, and Back Creek, most of the deposits at Mathinna are located on the northeastern limb of a D₂ fold, near the contact between sandstone-rich and shale-rich sedimentary rock successions. Mineralisation resides in a series of northwest-striking reverse faults of D₃ age.

The Golden Gate mine is situated in a locally unique and structurally complex area near where the contact between the sandstone-rich and mixed sandstone-shale units wraps around the nose of the northwest-plunging D₂ fold (fig. 24). D₃ strain increases towards the Golden Gate mine, where a number of mineralised reefs are arranged in an *en echelon* pattern (Finucane, 1935). This pattern is

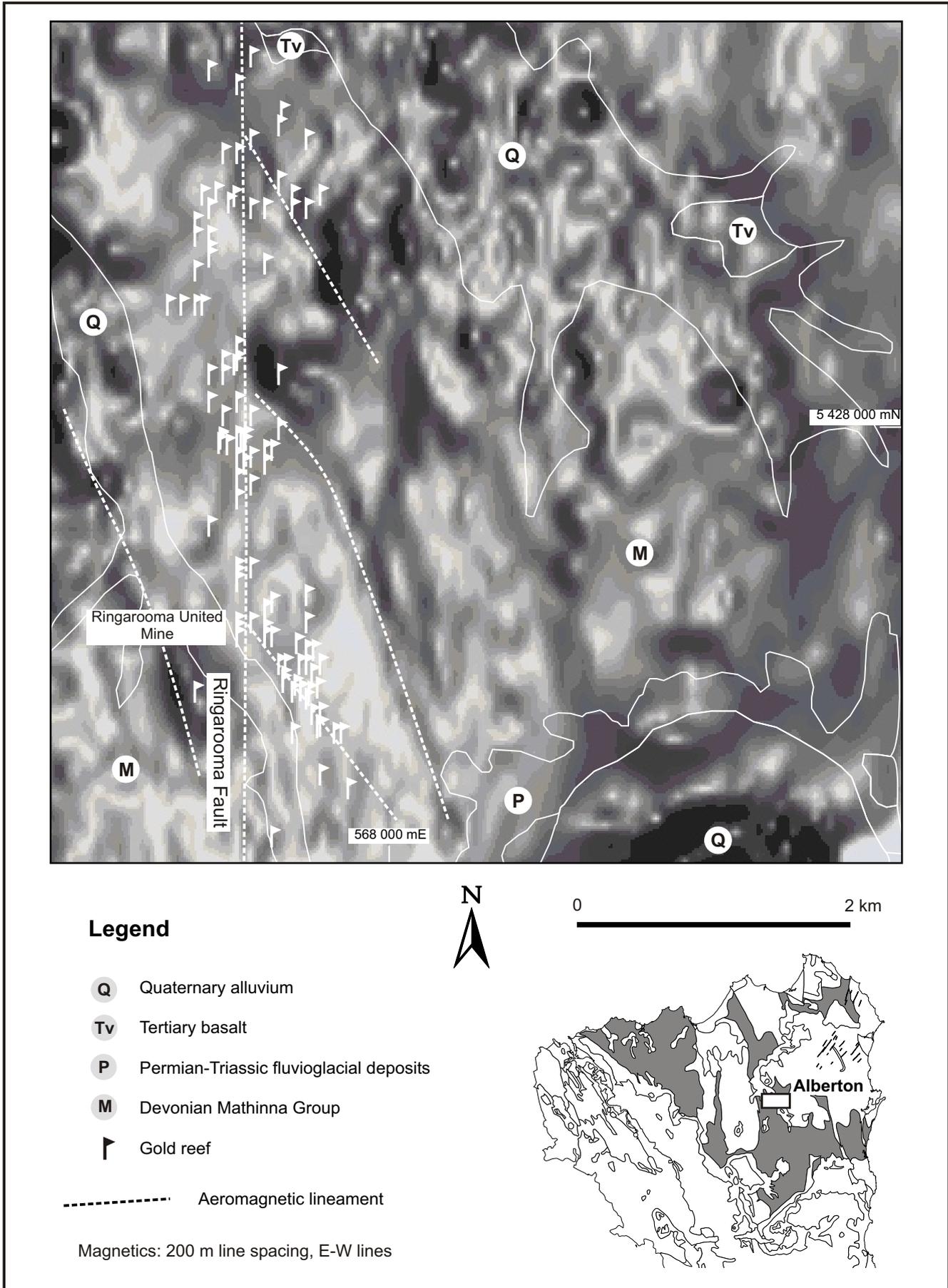


Figure 22

Aeromagnetic image (NETGOLD data, 200 m line spacing, Mineral Resources Tasmania) of the Alberton goldfield showing outline geology, and gold deposit and prospect locations. Dashed lines are mapped faults visible in aeromagnetic data.

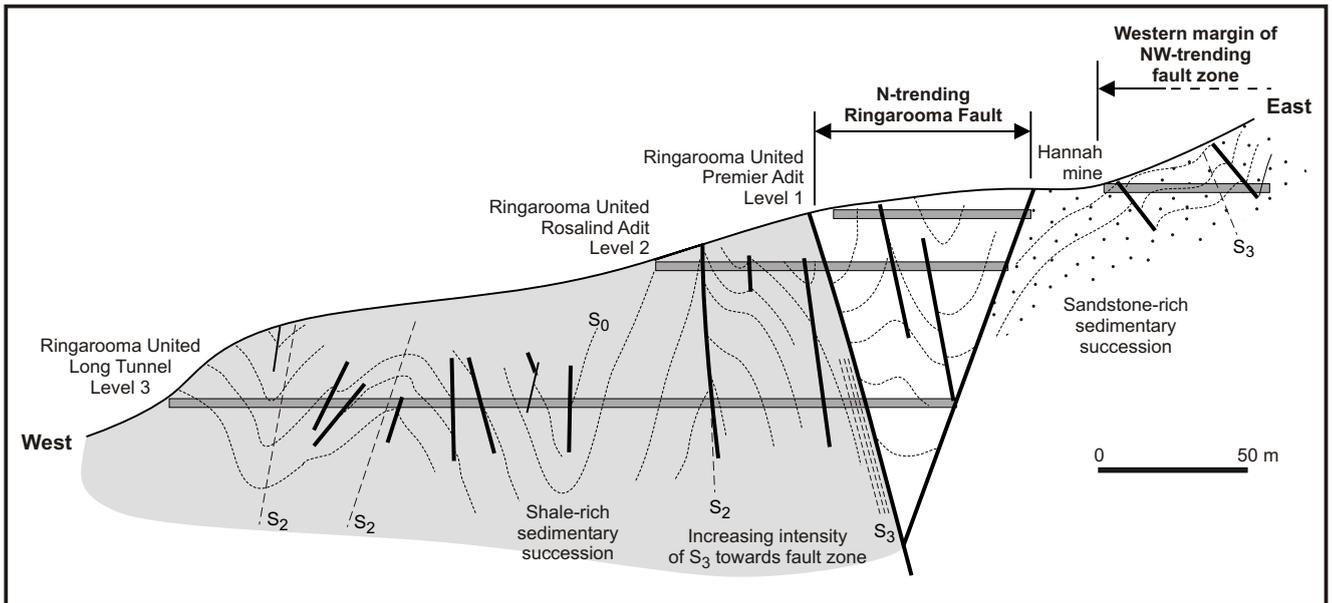


Figure 23

Cross-section through the Ringarooma Fault, as mapped in the Ringarooma United mine, Alberton goldfield (fig. 1). Section has been constructed from adit wall mapping. Mineralised zone is not accessible and has been constructed from various historical plans (Mineral Resources Tasmania).

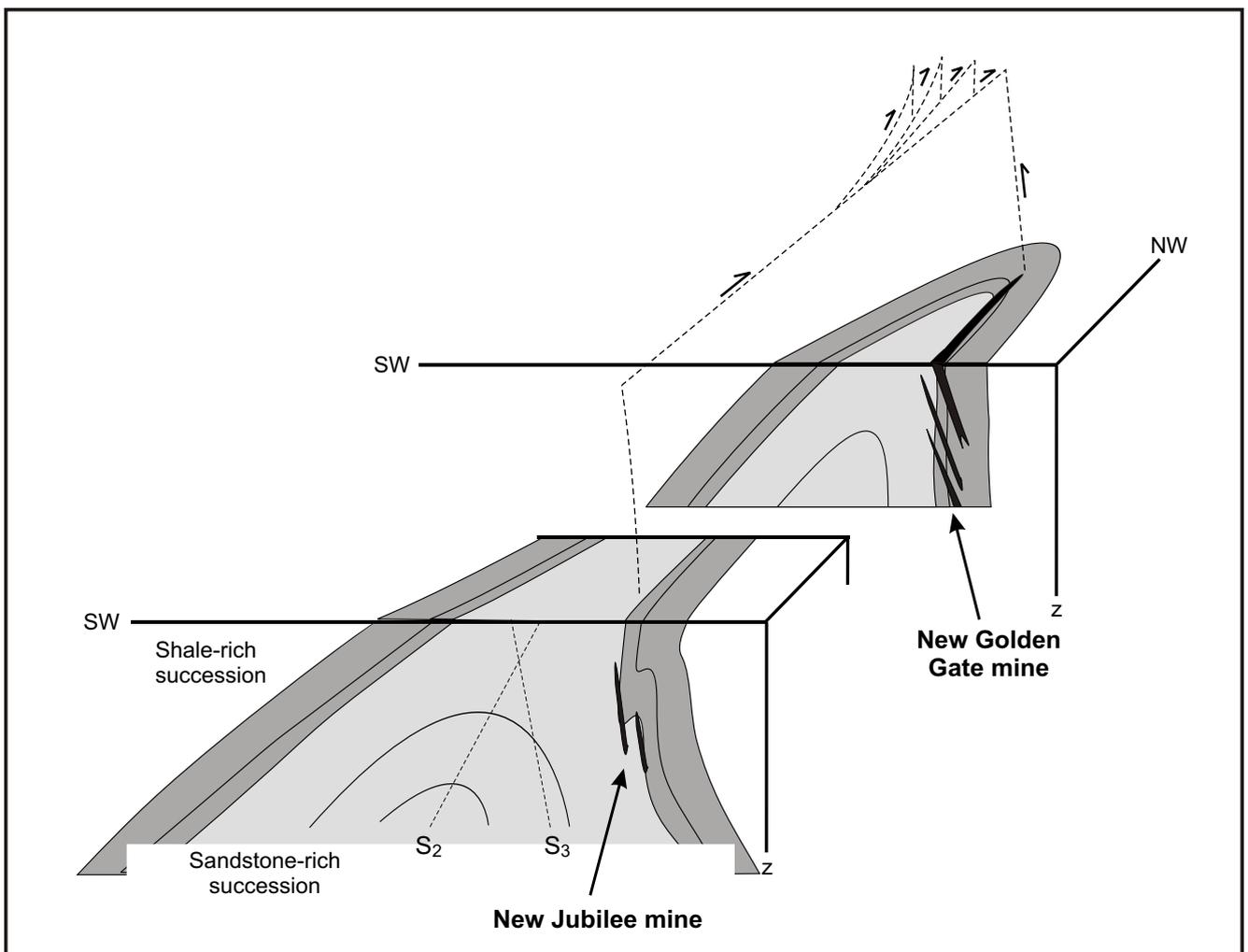


Figure 24

Interpreted structure of the Mathinna goldfield (fig. 1) with locations of the New Golden Gate and New Jubilee mines shown. The New Golden Gate mine comprises a series of stacked reefs arranged in echelon and indicating reverse, east-side-up, movement.

indicative of northeast-side-up movement, consistent with deformation during the southwest-directed D_3 event. Like Lefroy, the mineralised zones at the Golden Gate mine are shoot-like, extending only 50 m along strike but plunging individually to depths of up to 500 m (Taheri, 1992).

The setting of the Golden Gate mine is similar to that of the Ringarooma United mine at Alberton except that no analogue of the Ringarooma Fault has been recognised in the Mathinna area. The coincidence of mineralisation with the nose of a D_2 anticline at the Golden Gate mine, and the shoot-like nature of the orebodies, indicates that the change in strike of bedding may have played an important role in controlling both the ore body shape and location during mineralisation. The steep plunge to the ore shoots may also indicate a strike-slip component to faulting. Regardless, the mine coincides with the location where the relationship between transpressional faults developed on the northeast fold limb and bedding changes from one of concordance to discordance as the strike of bedding changes around the fold nose.

The mineralised corridor extends several kilometres to the southeast of the Golden Gate mine where the cyclic sand-shale package disappears beneath younger Palaeozoic and Mesozoic rocks (fig. 25). An unmineralised corridor of D_3 -deformed rocks continues for a further seven kilometres. Re-emergence of the cyclic sandstone-shale package coincides with re-appearance of mines, including the

Miami (579 400 mE; 5 396 770 mN), West Miami (578 600 mE; 5 396 950 mN) and Hit or Miss (579 000 mE; 5 397 900 mN). Potential for undiscovered gold mineralisation may exist at shallow to moderate depths southeast of Mathinna and coincident with the buried contact between the sandstone-rich and cyclic sedimentary successions.

MANGANA

The Mangana goldfield is located on the northeast limb of a southeast-plunging D_2 fold, but otherwise is similar in form and setting to the Alberton and Mathinna goldfields. Reefs are predominantly subvertical and strike northwest, except in the north of the field at the Fingal mine where they trend north and dip east. The cause of this variation is not known.

CONTROLS ON REEF ORIENTATION

The orientation of bedding prior to D_3 appears to have been particularly important in controlling reef geometry. Mineralised reefs in the upright folded domain are common to the northeast-dipping limbs of D_2 folds. Here, bedding would have been in an orientation conducive to failure during the D_3 event. It is likely that the periodic release of stresses or decrease in P_f caused by faulting along bedding planes meant that the strength of the intact rock was never exceeded (fig. 26). Unlike the Lefroy goldfield, the orientation of the reefs at Alberton, Mathinna and Mangana is consistent with a stress tensor where the minimum compressive stress (σ_3) was orientated vertically.

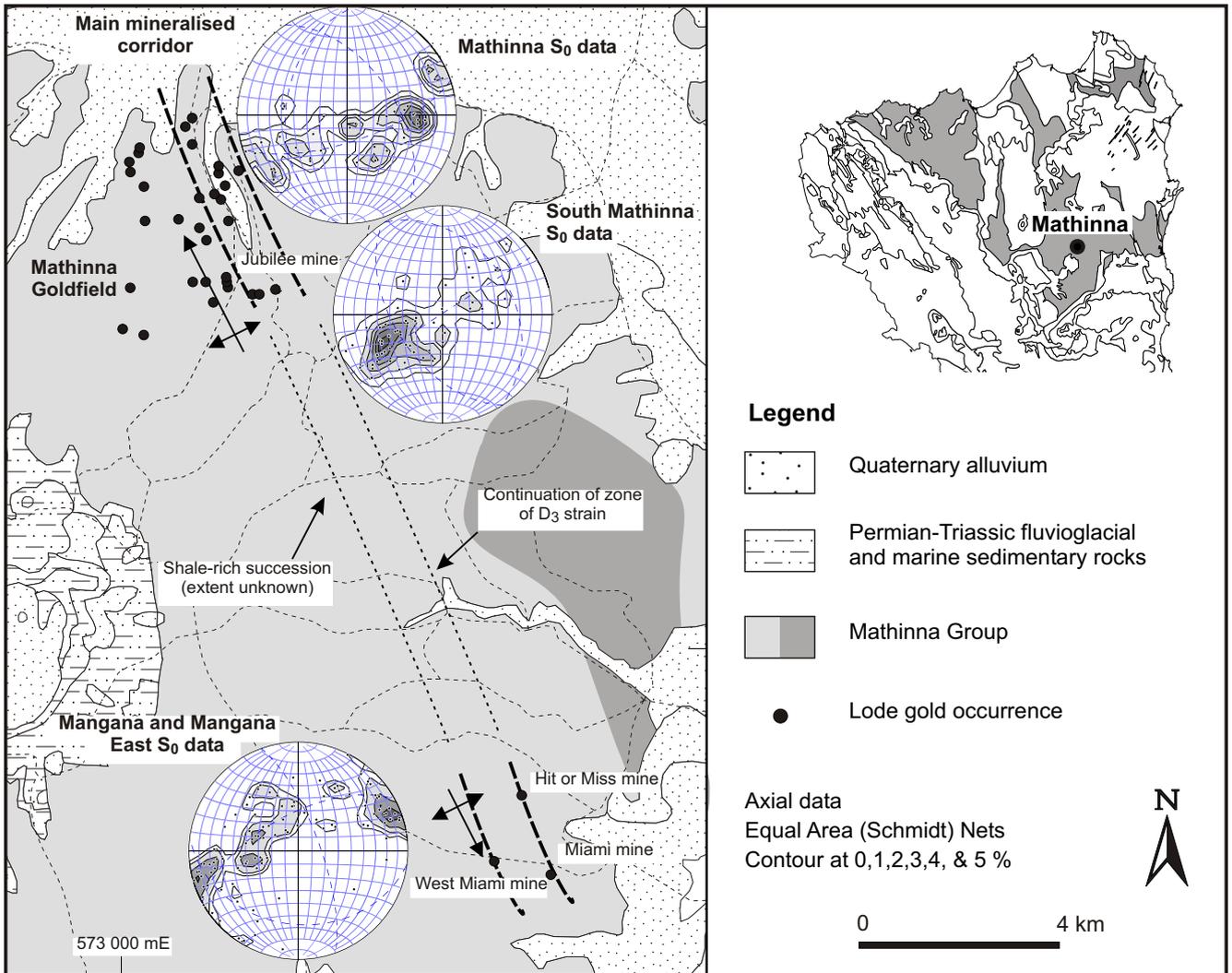


Figure 25

The southeast extent of the Mathinna goldfield coincides with the transition into more shale-rich rocks. Re-emergence of more sandstone-rich rocks about 15 km southeast of Mathinna is accompanied by the appearance of the Hit or Miss, Miami and West Miami mines. D₃ deformation is continuous between Mathinna and mineralised rocks to the southeast.

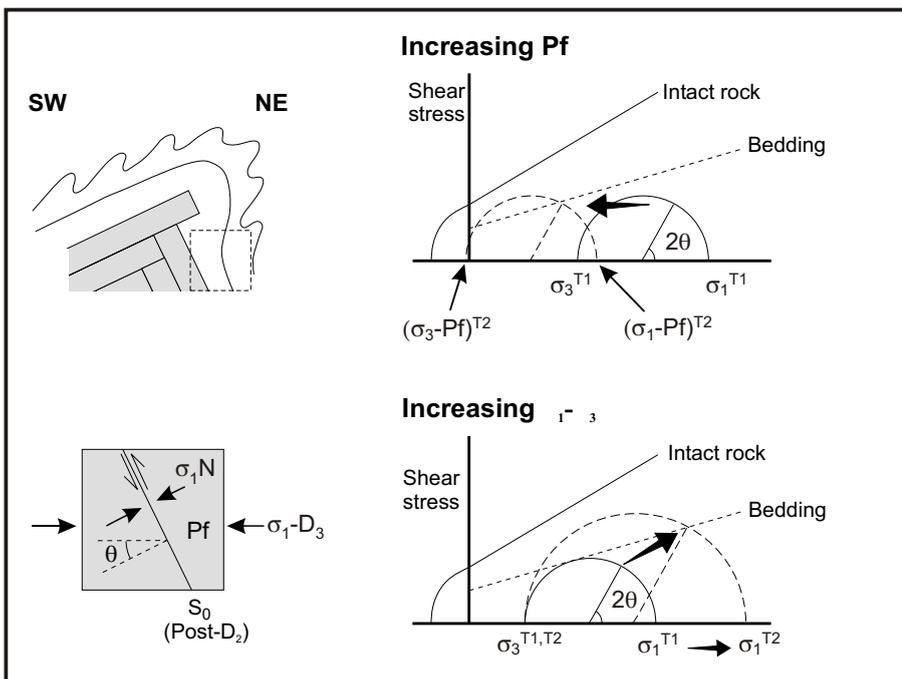


Figure 26

Coulomb-Mohr diagram illustrating the effects of increasing differential stress and pore fluid pressures during D₃ on fault development in the Alberton, Mathinna and Mangana areas. An increase in either Pf or differential stress would have resulted in failure along bedding planes before that of the intact rock, and is consistent with gold reefs in these areas being concordant with the stratigraphy.

Effects of structure on gold mineralisation

Origin of the gold

The origin of the lode-gold in eastern Tasmania and mechanisms of gold transport and deposition are discussed in Taheri and Bottrill (1994). Similarly, deformation and mineralisation processes for lode-style gold deposits in similar-aged rocks in Victoria are detailed in, for example, Cox *et al.* (1991a), Forde and Bell (1994) and Cox *et al.* (1995). In summary, the results of fluid inclusion and stable isotope studies indicate that the gold in eastern Tasmania was derived at depth (fig. 27) through devolatilisation of basalts, ultramafic rocks or greywackes during greenschist to amphibolite-grade metamorphism. An overall mafic source rock for the gold is consistent with the Mathinna Supergroup in eastern Tasmania overlying dense lower crust (basement to the Mathinna Supergroup) that includes rocks of probable oceanic affinity (Reed, 2001). This contrasts with western Tasmania, where basement comprises Proterozoic sedimentary rocks. The surface trace of the proposed boundary between eastern and western Tasmania is located in the West Tamar region (Barton, 1999; Reed, 2001). This forms the likely western extent of autochthonous eastern Tasmanian lower crustal rock. It also coincides with the western extent of most orogenic lode-style gold deposits of known late Tabberabberan age.

Faulting and gold mineralisation

Faults represent sites of high strain and, hence, periodically, low mean stress. Where P_f approximates lithostatic pressure, fluids tend to preferentially migrate to areas of low mean stress (Ridley, 1993; Mair *et al.*, 2000). Fluid inclusion data from gold deposits in eastern Tasmania indicate that the pore fluid pressure (P_f) during gold mineralisation was buffered at close to lithostatic pressure (Taheri and Bottrill, 1994). As such, faults were not just fluid pathways but represented spatial perturbations within the stress

field toward which fluids would have flowed. The extent to which fluids can migrate along faults is related to their permeability. An increase in P_f as a result of fluids moving into the faults results in an accompanying decrease in the effective mean stress, and a tendency towards failure. Faulting thus enhances permeability and further promotes the flow of the mineralising fluid.

Heterogeneities within the regional stress field also affect fault orientation and morphology. Adjacent rocks of overall contrasting competency respond in different ways and at different rates to a regional stress. At the outcrop scale in the Lefroy area, this is commonly evident as folded and well-cleaved shale beds overlying fractured but otherwise undeformed sandstone strata. Shearing, or detachment, between the two beds accommodates these contrasting deformation styles. At the regional scale, faults-reefs evident in the Stony Head Sandstone in aeromagnetic data are typically not as well defined along strike in the Turquoise Bluff Slate. Further east in the Alberton, Mathinna and Mangana areas, more shale-rich units have deformed differently to stratigraphically underlying sandstone-rich sedimentary successions. Cleavage intensity increases and fold wavelength and amplitude decrease in the more fine-grained rock successions. These sedimentary packages have clearly responded in different ways to the regional stresses applied during Tabberabberan orogenesis. Overall, heterogeneities in stress that developed between packages of contrasting composition and, hence, rheology, have been accommodated by faulting at or near the stratigraphic contacts.

At Lefroy, wrench faults intersect the contact between the Stony Head Sandstone and the Turquoise Bluff Slate. Although reactivation of an older structure at depth cannot be discounted, the most likely reason for this coincidence is that wrench faulting facilitated the compartmentalisation of strain otherwise

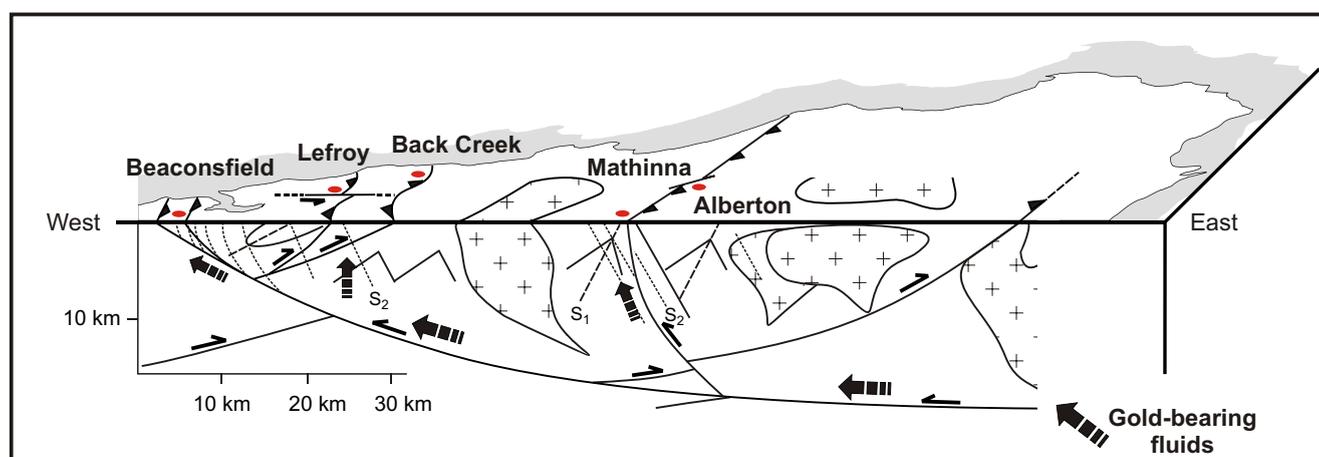


Figure 27

Simplified sketch block diagram of eastern Tasmania showing possible linked fault architecture. These faults provide pathways for the hot gold-mineralising fluids to ascend from depth.

concentrated along the northwest-southeast contact between the Stony Head Sandstone and the Turquoise Bluff Slate. Importantly, variations in the style and rate of deformation either side of this contact would have resulted in heterogeneities in the resulting stresses developed along the length of the fault reefs themselves. Structural complexity at the intersection of the fault reefs with the faulted contact between the Stony Head Sandstone and the Turquoise Bluff Slate would have proven ideal for the formation of, potentially, dilatant jogs or zones of low minimum stress (σ_3). Mineralising fluids would have been focussed into these zones during seismic activity (Sibson *et al.*, 1988), generating the necessary fluid flux to precipitate economic quantities of gold.

The causes of ore shoot development in the Alberton, Mathinna and Mangana areas (where known, e.g. Mathinna's New Golden Gate mine) are less clear. Lateral movement on predominantly concordant faults may have resulted in dilation zones at sites where fault reefs ramp through stratigraphy or, in places like Mathinna, where the overall relationship of the reef to folded bedding changes from one of concordance to discordance.

Fault dilation not only focussed the mineralising fluid but was also likely to have influenced gold solubility. Fluid inclusion data from the lode-gold deposits (Taheri and Bottrill, 1994) have been interpreted to show that gold was transported from depth as a bi-sulphide complex in low salinity CO₂-rich fluids at temperatures of about 300°C. Deposition was primarily the result of pressure fluctuations, instigating rapid decompression, fluid immiscibility and phase separation (Taheri and Bottrill, 1994). This is not uncommon. Similar models for gold deposition have been proposed for orogenic gold belts elsewhere including, for example, lode and stringer-style gold in the Juneau gold belt in southeastern Alaska (Goldfarb *et al.*, 1988) and shear zone-hosted gold mineralisation in the Kautokeino greenstone belt in Norway (Ettner *et al.*, 1993). It is likely that in many deposits in eastern Tasmania, a drop in P_f where fault reefs intersect contacts separating sedimentary rock packages of overall contrasting rheology would have destabilised the gold complexes, thus promoting gold deposition.

Fluid reduction

An association of gold and carbon-bearing rocks was also noted by Twelvetrees (1914), indicating the

possibility that fluid reduction might have influenced gold solubility. There is typical lack of observed wall-rock alteration adjacent to many of the gold mineralised reefs, indicating that reaction of the mineralising fluids with carbonaceous shale was not the primary influencing factor on gold deposition. There is an association of gold with carbonate porphyroblasts in places such as Mangana, where an S₃ crenulation fabric formed around the porphyroblasts indicates their formation either before, or early during, the mineralising event.

The precise timing of mineralisation relative to the second phase of Tabberabberan deformation is not clear. The Lefroy deposits are interpreted to have formed at the same time as the Tasmania Reef at Beaconsfield (Powell, 1991), which is interpreted from field relationships to have formed late during southwest-directed Tabberabberan thrusting (Hills *et al.*, 2001). A late timing for lode-style gold mineralisation relative to the main kinematic phase of orogenesis is common (Kerrick and Cassidy, 1994; Groves *et al.*, 1998). In Victoria, deposits that are considered to have formed late during orogenesis include the Bendigo, St Arnaud, Ballarat and Inglewood deposits (Forde and Bell, 1994). Other examples in older rocks elsewhere include the Sigma mine in the Abitibi Greenstone belt in Quebec (Robert and Brown, 1986), and the Telfer (Vearncombe and Hill, 1993), Mt Charlotte (Ridley and Mengler, 2000), Sunrise Dam and Granny Smith (Mair *et al.*, 2000) deposits in Western Australia.

If gold mineralisation in eastern Tasmania formed late during D₃ then it is unlikely that the porphyroblasts developed adjacent to some of the mineralised reefs are actually associated with the gold mineralisation. An alternative hypothesis is that the porphyroblasts located adjacent to mineralised faults formed during the main D₂ folding and faulting phase of Tabberabberan orogenesis. This is a much more significant event from the perspective of regional shortening. Gold mineralisation then followed ('late' during D₃) and, in places, was associated with reactivation of D₂ faults.

In summary, there may be no direct genetic association between porphyroblast development and gold mineralisation in eastern Tasmania. More work is required to better clarify alteration styles in eastern Tasmania.

Correlations with rocks west of the River Tamar

Correlating rocks on either side of the River Tamar (fig. 4) is complicated by a lack of fossils constraining the timing of turbidite deposition throughout eastern Tasmania. This contrasts with Middle Palaeozoic rocks west of the Tamar in which fossils are common. Here, the post-Delamerian stratigraphy comprises Lower Ordovician Denison Group conglomerate and sandstone unconformably or disconformably overlying Cambrian Dundas Group sedimentary and volcanic rocks. Eldon Group siltstone and sandstone unconformably overlie the Gordon Group and are in turn overlain in the West Tamar region by a poorly exposed turbidite package correlated with rocks comprising the Bellingham Formation and Sidling sandstone in eastern Tasmania (Hills, 1981; MacDonald *et al.*, 2001).

The Stony Head Sandstone is the oldest sedimentary rock unit in eastern Tasmania. It is older than the Middle Ordovician Turquoise Bluff Slate and, like the Denison and Gordon Group rocks west of the River Tamar, was not present during Delamerian orogenesis at approximately 510 Ma (Turner *et al.*, 1998), making it Late Cambrian to Early Ordovician in age. Deposition of the Stony Head Sandstone therefore occurred at approximately the same time as the Denison Group west of the River Tamar (fig. 28). Both the Denison Group and the Stony Head Sandstone are stratigraphically overlain by finer-grained sedimentary successions. These include the predominantly Middle Ordovician Gordon Group limestones in western Tasmania and the similarly-aged Turquoise Bluff Slate east of the River Tamar. Both of these units were deposited in an environment of low sediment input and slow sedimentation.

Silurian to Lower Devonian Eldon Group sandstone and siltstone in western Tasmania are of the same age as Panama Group turbidites east of the River Tamar. Like the Gordon Group limestones, the Eldon Group rocks were deposited in a shelf environment (Baillie, 1989), forming a topographic high relative to the basin into which the Panama Group turbidites were being deposited. Palaeocurrents in the Panama Group indicate sediment derivation predominantly from the northwest and southeast (Powell *et al.*, 1993), consistent with a topographic high located to the southwest and suggesting that the Eldon and Panama groups did not share a common sediment source.

Water depth in western Tasmania had increased by the Early Devonian, with turbidites stratigraphically overlying and possibly onlapping Silurian Eldon Group siltstone and sandstone west of the River Tamar. These turbidites contain Early Devonian graptolites (Banks and Rickards, 1989) and are considered correlatives of the Panama Group turbidites of eastern Tasmania (Hills, 1981;

MacDonald *et al.*, 2001). The lack of transitional Early to Middle Ordovician facies across the River Tamar indicates a degree of shortening between eastern and western Tasmania after Tippogoree Group deposition. Coincident turbidite deposition on either side of the River Tamar by, at the latest, the Early Devonian demonstrates that eastern and western Tasmania were not far removed from one another prior to the Tabberabberan Orogeny.

Despite being separated from Tippogoree Group rocks by less than 20 km, Ordovician sedimentary rocks west of the River Tamar show little evidence of Ordovician to Silurian orogenesis. Duplication of the Palaeozoic stratigraphy on high-angle thrusts west of the Tamar Valley includes Devonian sedimentary rocks and is the product of Tabberabberan-age thrusting. Reactivation of Benambran structures during Tabberabberan orogenesis is unlikely, because the southwesterly vergence to thrusting is opposite that for Benambran deformation east of the River Tamar. Furthermore, the regional angular discordance between Ordovician and Silurian sedimentary rock sequences is less than approximately 10°, which is inconsistent with high-angle thrusting being initiated during the Ordovician or Silurian.

Basement rocks do not crop out in eastern Tasmania. Allochthonous mafic and ultramafic rocks of oceanic origin in western Tasmania were emplaced from the east during Delamerian orogenesis (Berry and Crawford, 1988) and are probably representative of basement east of the River Tamar. A dense oceanic substrate is also consistent with a deep-water environment for turbidite sedimentation and contrasts with the shelf sedimentary environment developed on continental crust further west. Seismic data show the contact between eastern and western Tasmania as a structurally complex zone comprising a series of east-dipping reflectors, probably Tabberabberan thrusts, located west of the River Tamar between the River Tamar and the Port Sorell embayment (Barton, 1999). This zone also represents the eastern extent of exposed Proterozoic continental crust, and it is likely that the contact between western and eastern Tasmania coincides with the boundary between continental and oceanic basement respectively. Recumbent folding east of the River Tamar is inferred to represent the upward continuation of shortening preferentially developed in oceanic basement. Continental basement to Palaeozoic rocks west of the River Tamar did not experience the same shortening event.

Differences in sedimentology and structure either side of the River Tamar can be explained without need for the crustal-scale suture of previous authors (e.g. Baillie, 1985). Some degree of shortening is likely between eastern and western Tasmania, probably during both Benambran and Tabberabberan

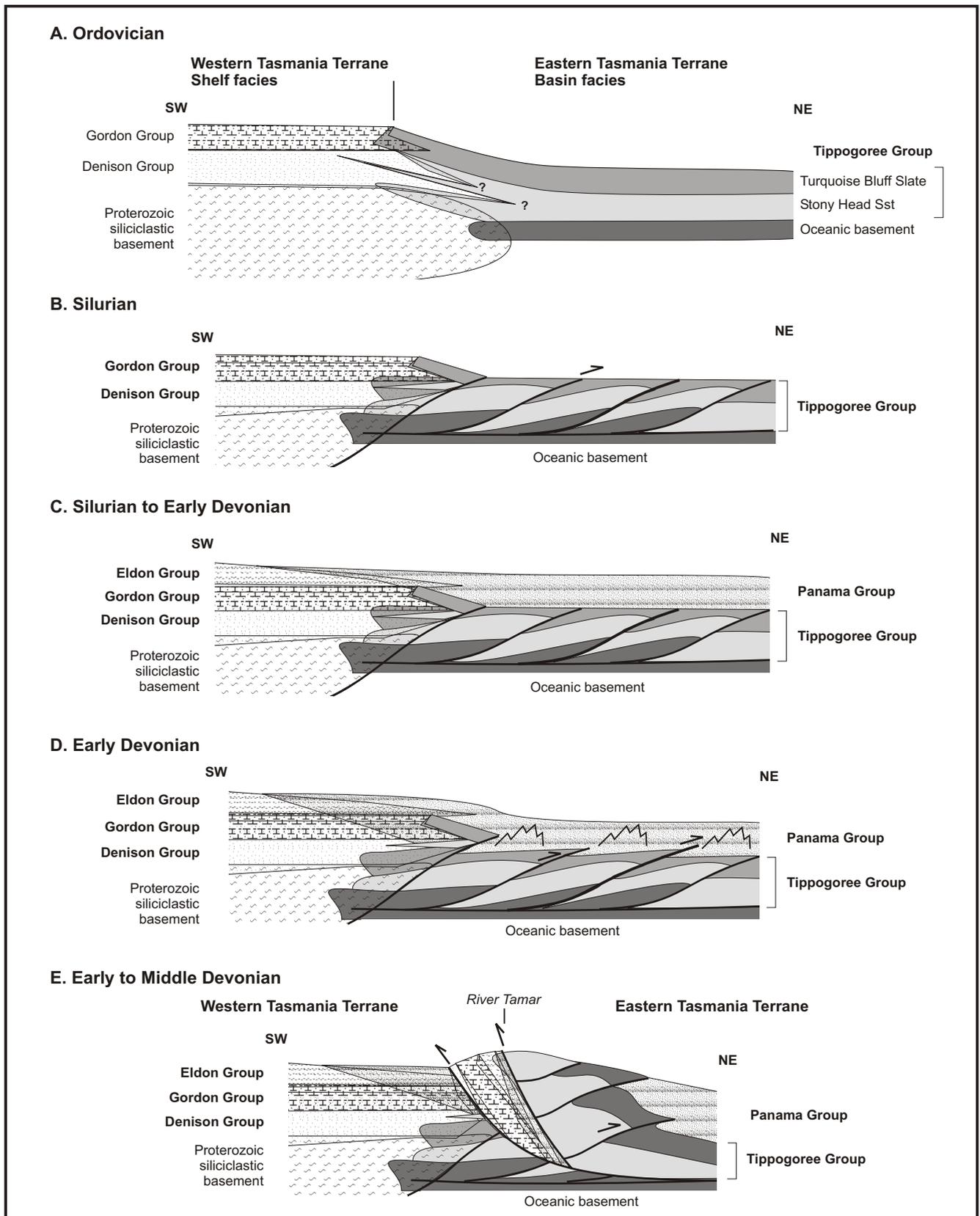


Figure 28

Sketch diagram illustrating possible inter-relationships during middle Palaeozoic orogenesis and sedimentation at the boundary between eastern and western Tasmania. (a) Sedimentary facies in eastern and western Tasmania are consistent with deposition on oceanic and continental crust, respectively. (b) Silurian orogenesis deformed oceanic crust, but not the thicker continental crust. (c) Turbidite deposition during the Silurian and Early Devonian overlapped shelf-facies rocks in western Tasmania. (d) A northeast tectonic vergence during Devonian orogenesis both reactivated and deformed existing structures in eastern Tasmania and produced predominantly upright folds in Silurian and Lower Devonian turbidite successions. (e) A subsequent reversal in tectonic vergence thrust eastern Tasmania southwest against western Tasmanian Proterozoic basement.

orogenesis. The boundary between eastern and western Tasmania, although faulted, is best explained in terms of a change in basement geology. This geology influenced depositional environments and resulted in the contrasting sedimentary facies observed in eastern and western Tasmania. It also appears to have played a critical role in determining the mechanisms and distribution of strain during Palaeozoic orogenesis.

Correlations with mainland Australia

Tasmania has most recently been correlated with the Melbourne Zone (Whitelaw Terrane) in Victoria (Powell and Baillie, 1992; Powell *et al.*, 1993; Cayley *et al.*, 1999), largely on the basis that both regions lack recognised Benambran age structures and both include outcropping Proterozoic rocks. This interpretation is now equivocal, given recognition that eastern Tasmania was deformed during the Ordovician to Silurian and conceivably overlies oceanic as opposed to continental crust. Although rocks exposed throughout western Tasmania may form basement to the Melbourne Zone in Victoria, eastern Tasmania more closely resembles rocks east of the Melbourne Zone in the Tabberabbera Zone (fig. 29). Like eastern Tasmania, the Tabberabbera Zone experienced Ordovician to Silurian orogenesis and is also inferred to overlie oceanic basement (Fergusson, 1998; Cayley *et al.*, 1999; Foster and Gray, 2000).

The Tabberabbera Zone is the westernmost zone in the Benambra Terrane (Fergusson *et al.*, 1986). It differs from rocks further west in the Whitelaw Terrane in that Benambran orogenesis was followed by strike-slip faulting, basin development (Buchan Rift) and widespread magmatism during the Silurian and Early Devonian (VandenBerg *et al.*, 2000). Strike-slip faulting accommodated fragmentation and inferred southward transport prior to accretion of the Benambra Terrane onto the Whitelaw Terrane during the Tabberabberan Orogeny (Willman *et al.*, 2000). In eastern Tasmania, Early Devonian rhyolitic to intermediate volcanism (St Marys Porphyrite) is of similar to slightly younger age and may be of similar origin to felsic volcanic rocks contained in the Buchan Rift in Victoria. In contrast to the Tabberabbera Zone, there is little evidence for strike-slip faulting pre-dating Tabberabberan orogenesis in eastern Tasmania. Some studies (Patison, 1996; Hudson, 1999) have reported foliations pre-dating the first phase of Tabberabberan folding in rocks east of the Scottsdale Batholith. These rocks show none of the characteristics of the recumbently folded rocks west of the Scottsdale Batholith and, although speculative, it may be that the origin of these foliations is related to events responsible for the strike-slip faulting on the Australian mainland.

The oldest turbidite unit in the Tabberabbera Zone is the Pinnak Sandstone, a correlate of the Adaminaby Group in New South Wales (VandenBerg *et al.*, 2000).

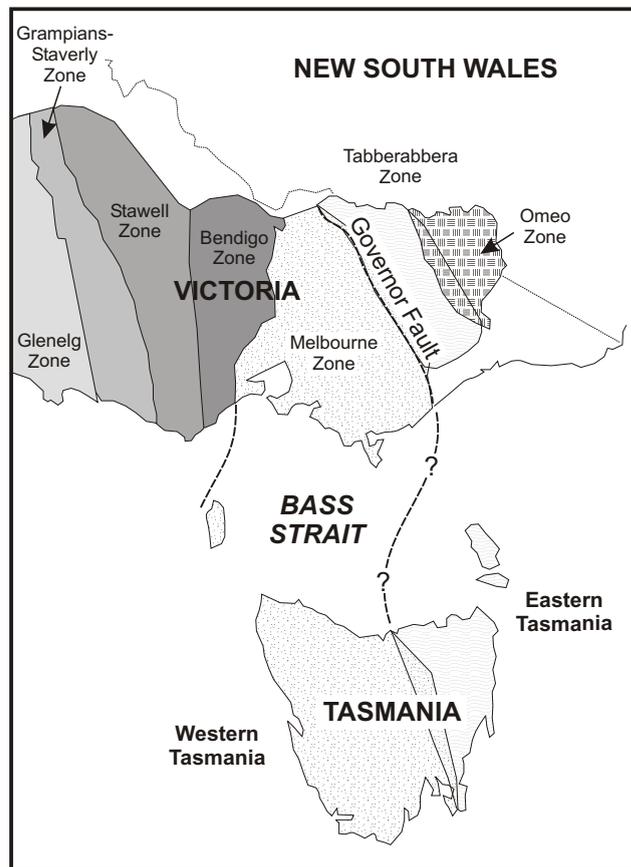


Figure 29

Proposed correlation between Proterozoic rocks in western Tasmania with those underlying the Melbourne Zone in Victoria, and between eastern Tasmania and the Tabberabbera Zone in eastern Victoria.

This Lower Ordovician unit comprises a thick-bedded and poorly fossiliferous sandstone sequence and is of an age and lithology matching the Stony Head Sandstone in eastern Tasmania. The Bendoc Group stratigraphically overlies the Pinnak Sandstone and is lithologically very similar to the Turquoise Bluff Slate. The Bendigonian Be1 to Darriwilian Da3 fossil age for graptolites from the slate shows the Turquoise Bluff Slate to be older than the Bendoc Group, which itself is no older than uppermost Darriwilian (Da4) (A. H. M. VandenBerg, pers. comm., 2001). Slow sedimentation and/or low sediment input commenced in eastern Tasmania several million years before Bendoc sedimentation on the mainland, at the same time that carbonate was being deposited in western Tasmania (Seymour and Calver, 1998). Therefore, the Turquoise Bluff Slate most probably represents an intermediate facies between the Pinnak Sandstone/Adaminaby Group on the mainland and the sediment-starved, platform-carbonate rocks of the Gordon Group in western Tasmania.

The correlation of eastern Tasmania with the Tabberabbera Zone, and of Proterozoic rocks in western Tasmania with the underlying turbidites of the Melbourne Zone, implies that the boundary between eastern and western Tasmania is equivalent to that separating the Tabberabbera and Melbourne

Zones in Victoria. In Victoria, this boundary is the Governor Fault (VandenBerg *et al.*, 2000). The Governor Fault zone includes volcanic, volcanoclastic and ultramafic rocks as well as chert, mudstone and relict blueschist facies metamorphic rocks (Foster *et al.*, 1999). Unlike the mainland, no single structure denotes the boundary between eastern and western Tasmania (Barton, 1999), with Tabberabberan thrusting interleaving rocks of differing character over a corridor width of approximately twenty kilometres. The same type of rocks as those contained within the Governor Fault zone also crop out as basement to Middle and Lower Palaeozoic successions immediately west of the River Tamar (Reed, 2001), at or very near to the boundary between eastern and western Tasmania.

Tectonic vergence does vary between eastern Tasmania and the Tabberabbera Zone. In eastern Tasmania, a northeast transport direction for Tabberabberan thrusting and folding is opposite to

that for the Tabberabbera Zone in Victoria (Fergusson, 1998; VandenBerg *et al.*, 2000). For reasons unknown, but possibly related to deformation in the Tabberabbera Zone and along the Governor Fault, tectonic vergence in eastern Tasmania reversed, with Palaeozoic rocks thrust southwest and up against Proterozoic basement in western Tasmania. The northeast vergence of Benambran structures in eastern Tasmania also appears to be opposite to that shown for rocks in the Tabberabbera Zone (Foster *et al.*, 1999; fig. 4). Comparisons of tectonic vergence across Bass Strait must take into consideration that eastern Tasmania alone experienced reversals of vergence within a single orogenic event. Tectonic vergence also varies for any one event within Tasmania over distances significantly less than that separating eastern Victoria and Tasmania. These variations are probably related to the shape and composition of basement blocks and to the presence and geometry of pre-existing structures and, alone, are not justification for claiming dissimilarity between regions.

Introduction

Nearly all of the more than 600 gold deposits and prospects from throughout eastern Tasmania were original surface discoveries. Given intensive farming, forestry and mining over the last century, the probability of discovering further lode gold deposits intersecting the surface are small.

Targeting lode gold mineralisation at depth can be problematic. Alteration envelopes around individual gold lodes are typically narrow to non-existent, making their detection using conventional rock chip or soil sampling techniques difficult (although partial leach geochemistry appears to be having some success). Understanding the structure of a potentially mineralised area is essential to effective regional-scale and prospect-scale exploration. Predicting reef geometry aids planning and interpretation of geochemical and geophysical programs. It is also critical, when it comes to drilling, to have some idea about the orientation of a reef and possible sites along a reef where grades may be elevated in order to maximise the chance of success.

Historical models for Au mineralisation

Gold mineralisation in eastern Tasmania has previously been discussed in terms of secondary enrichment (Broadhurst, 1935) and also likened to the Victorian mesothermal gold deposits (Keele, 1996).

Gold mineralisation resulting from secondary enrichment was a model originating from observations in the Lefroy and Back Creek areas, where the gold-bearing reefs extended to depths of less than 60 m, coincident with the depth of the supposed water table and hence of an oxidising environment (Broadhurst, 1935). Although some secondary mineralisation was likely, there are a number of reasons why such a model is unlikely to account for the bulk of gold mineralisation throughout eastern Tasmania.

Firstly, gold mineralisation in eastern Tasmania is typically associated with both sulfides and carbonaceous rocks at all depths (Taheri, 1993), suggesting a consistently reduced rather than variably oxidised environment for mineralisation. Secondly, mineralisation is predominantly within veins and rarely occurs on joint planes or disseminations as would be expected if mineralisation was secondary. Finally, secondary enrichment does not account for the high-grade pods of ore at depths of up to 500 m (Groves, 1965), nor does it adequately explain ore located beneath rocks barren of gold. As such, secondary enrichment was unlikely to have resulted in the formation of the high-grade sections of the gold-bearing reefs.

Gold mineralisation in eastern Tasmania has more recently been compared to the Victorian turbidite-hosted mesothermal gold deposits (Keele, 1996). Lode gold in Victoria is also hosted within reefs, although these are interpreted to have formed late during the main folding event, with mineralisation commonly within or near fold hinges and paralleling fold axes (Cox *et al.*, 1991a; 1991b). Fold hinge-related quartz veins in eastern Tasmania are typically unmineralised in gold. Mineralised reefs at Lefroy and Back Creek also cross-cut the main fold trend, inconsistent with models for gold mineralisation in Victoria. Consequently, a Victorian model for mineralisation is inappropriate for gold exploration in eastern Tasmania.

Structural mapping in mineral exploration

Gold lodes in eastern Tasmania are typically constrained to mixed shale and sandstone sequences transitional between sandstone-rich and shale-rich successions, where ductility contrasts have acted to focus strain and, consequently, the mineralising fluids. The juxtaposition of units of varying competency and composition was critical for channelling auriferous fluids and generating the necessary physicochemical traps.

Recognising, and distinguishing between, different generations of structures can be problematic. In particular, identifying zones of D_3 strain for exploration purposes is often difficult at Alberton, Mathinna and Mangana, where structures formed during both D_2 and D_3 are upright and vary in strike by only about 15° . The refractive nature of S_2 also tends to mask any subsequent re-orientation that might otherwise give a clue as to the presence or extent of the D_3 event. Veins formed during both D_2 and D_3 typically occupy multiple orientations, and it is difficult to determine their age without first establishing their context with respect to adjacent structures.

Mapping of bedding–cleavage relationships coincident with observations of stratigraphic younging aids in differentiating between D_2 and D_3 structures in the field. Refolded D_2 folds are an excellent indicator for proximity to D_3 high-strain zones.

Discrimination of the two events is easier at Lefroy and Back Creek where S_1 and S_3 cleavages formed at a high angle to one another. Bedding planes and younging directions are also more clearly defined. Unfortunately, outcrop is poor and it is necessary to utilise trenches and road cuttings to obtain data.

Aeromagnetic data

Aeromagnetic and geochemical data are invaluable when used in conjunction with structural and sedimentological mapping. Aeromagnetic data constrain the location of large-scale structures which may have acted as conduits for mineralising fluids. Utilising geophysical data in conjunction with historical plans, especially those showing the orientation of mineralised reefs, has proven invaluable in identifying large-scale mineralising structures in the Alberton, Lefroy and Back Creek mineral fields. At the goldfield-scale or less, processing of the 2001 Western Tasmanian Regional Minerals Program aeromagnetic data has been used to image the turbidite stratigraphy in the Lefroy area, including discontinuities coincident with reefs and fold hinges.

The regional geophysical setting of gold mineralisation in eastern Tasmania is covered in detail in Roach (1994).

Geochemistry

Rock chip, stream sediment and soil sampling have been used as a regional reconnaissance tool (spacings greater than 50 m by 100 m), but their effectiveness is compromised by poorly developed alteration halos around the gold lodes and typically thin soil profiles. Partial leach geochemical techniques have proven

successful in duplicating known anomalies in the Denison goldfield, where soil cover varies from non-existent to several metres thick. Here, partial leach geochemistry also recognised a metal zonation that may be useful as a vector to ore. The effectiveness of partial leach geochemistry at detecting deep mineralisation at greater depths (>100 metres) has not been tested and further work is required to better constrain the true effectiveness and use of this technique in eastern Tasmania.

Drilling

A comparison of the cost and effectiveness of reverse circulation (RC) as opposed to diamond drilling was conducted at the Morning Star mine in Victoria (Goodz and D'Astoli, 1997) where, like eastern Tasmania, gold is hosted by reefs contained within Palaeozoic turbidites. It was found that diamond drilling provided an intact and complete sample with far less on-costs than RC drilling. More importantly, RC drilling was found to have significantly underestimated the richness of the resource under investigation. When exploring for structurally controlled gold mineralisation, orientated diamond-drill core is also an invaluable source of information that will aid in understanding the structure at the prospect scale.

Conclusions

Mesothermal vein-hosted gold mineralisation in Cambrian to Devonian sedimentary rocks in eastern Tasmania is regionally associated with a third, southwest-directed phase of compressional deformation.

In areas where the pre-mineralisation structure was dominated by upright folds, the gold reefs have formed on steep sub-vertical, predominantly northeast-dipping fold limbs. Here, bedding was in an orientation conducive to shear failure during D_3 and, consequently, the reefs strike predominantly northwest.

Sub-vertical, ENE-striking gold reefs of D_3 age at Lefroy are orientated at a high angle to regional fold trends. This orientation indicates reef formation during wrench faulting when σ_3 was orientated in the horizontal plane and σ_2 was orientated vertically. In contrast, gold mineralisation in Victoria and elsewhere in eastern Tasmania typically formed at a time when σ_3 was vertical. The consistent discordance between the gold reefs and both the strike of the host rocks and fold trends at Lefroy is abnormal compared to gold reefs throughout Victoria and most of eastern Tasmania but similar to that at Beaconsfield.

Ductility contrasts between stratigraphically adjacent units played a critical role in partitioning strain at all scales, with gold mineralisation typically hosted by cyclic mixed sandstone and shale sedimentary rocks

that formed between underlying sandstone-rich and overlying shale-rich successions. Perturbations in the local stress field caused by the partitioning of strain at rock unit boundaries resulted in fluids being focussed into zones of locally higher strain and lower stress.

Most deposits in eastern Tasmania were surface discoveries. However the position of the current erosional surface does not have any causal relationship to the location of gold deposits. Consequently, there is no reason why the present number of deposits should not be indicative of the number still to be found at depth.

Acknowledgments

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