THE UNIVERSITY OF ADELAIDE

THE STRUCTURAL GEOLOGY OF THE RAPID BAY-SECOND VALLEY AREA, FLEURIEU PENINSULA, SOUTH AUSTRALIA.

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THE STRUCTURAL GEOLOGY OF THE RAPID BAY-SECOND VALLEY AREA, FLEURIEU PENINSULA, SOUTH AUSTRALIA.

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Abstract

Whilst the geology of the Rapid Bay-Second Valley area is known to be both structurally and stratigraphically complex, previous workers (Daily, 1963; Evans 1987; Drayton, 1963; Campana and Wilson, 1955) have been unable to agree on many aspects of the area. Neoproterozoic and Cambrian aged sediments were first deposited in an extensional basin, which was formed due to lithospheric thinning, and associated subsidence (Jenkins, 1986, 1990). These rocks have then been subjected to at least one phase of deformation, the Cambro-Ordovician Delamerian Orogeny (Offler & Fleming, 1968 ; Thompson, 1970). Listric extensional faults were formed both before and during sedimentation of the rocks, which has created narrow zones of weakness that the subsequent compressional event has exploited, creating thrust faults (Flöttman *et al.* , 1994).

Structural mapping of the area has revealed that it is transected by two thrust faults, and is intensely folded in places. Structural data has been collected during eight weeks of field work, and has been compiled into a 1:10 000 scale geological map which accurately represents the area. A computer generated three dimensional model has been created for the area, based on this map, and cross and profile sections constructed from the data collected. The model was constructed using Vulcan™ software. Strain analysis has also been conducted on many of the folds in the area.

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1. Introduction

1.1 Regional Geology and Previous Investigations

The Rapid Bay-Second Valley area is located within the Southern Adelaide Fold-Thrust Belt, on the Fleurieu Peninsula South Australia, some 80 km south of Adelaide (see figure 1.1b). The Southern Adelaide Fold Belt is part of a larger structure known as the Adelaide Fold Belt, which extends some 750km from the Flinders Ranges in the north, through the Mount Lofty Ranges in its central portion, to Kangaroo Island in the south, and is approximately 80km at its widest point. It is an approximately north-south trending feature in its northern section, swinging around to a southwest-northeast trending structure to the south, and is comprised of Neoproterozoic to Cambrian sedimentary rocks and rare volcanics sitting on early Proterozoic basement. These rocks were deformed and in some places metamorphosed during the Cambro-Ordovician Delamerian Orogeny (D_1) (Offler & Flemming, 1968; Thompson, 1970)

Clarke and Powell (1989) recognised that tectonic fabrics in the central and southern portions of the Adelaide Fold Belt indicate a westward transport direction during the orogeny. In the Southern Adelaide Fold-Thrust Belt, this deformation has resulted in the formation of a predominant slaty cleavage or schistosity (S_1) (Mancktelow, 1979,1981) and on the south coast of Fleurieu Peninsula, the contemporaneous metamorphism reaches biotite grade (Offler and Fleming, 1968). In the Rapid Bay area the slaty cleavage-forming Delamerian Orogeny (c. 505 Ma) was the major structural event, and only rarely are later, weak crenulations and minor kinking structures present (Mancktelow, 1981).

The theory of thin-skinned tectonics has only recently been applied to the Adelaide fold belt (Jenkins, 1986, 1990; Clarke & Powell, 1989; Jenkins & Sandiford, 1991; Steinhardt, 1991). This theory involves a compressional regime, forming low angle thrust faults, and partial basement influence (providing variable resistance to compression). Jenkins (1986) suggests a cyclical model of lithospheric extension during which sediments of the upper Normanville and lower Kanmantoo groups were deposited, followed by a period of compression (the Delamerian Orogeny). It is further suggested by Flöttman *et al* (1994) that normal faults which were formed during the phase of lithospheric extension were reactivated as reverse faults during the compressive Delamerian Orogeny.

Previous investigations in the Rapid Bay-Second Valley area have been largely concerned with stratigraphic problems (Daily, 1963; Evans, 1987) or were undertaken prior to the development of modern theories of thin skinned tectonics (Drayton, 1963; Campana and Wilson, 1955). While the area is known to be structurally complex, it is important to note that none of the previous authors agreed entirely on the structural history of the region. This thesis is concerned with interpreting the structural Geometry of the Rapid Bay-Second Valley area in terms of modern theories of thin skinned tectonics, and attempting to link this interpretation with previously mapped areas to the south (Rogers, 1991), and areas currently being mapped to the south (Macdonald, 1995) and north (Buhrer, 1995; Szmidel, 1995).

1.2 Location and Physiography of the Rapid Bay-Second Valley Area.

The Rapid Bay-Second Valley area lies on the western coast of the Fleurieu Peninsula, and is bounded to the north by the Second Valley road, to the east by the Adelaide to Cape Jervis road, by Stockyard Creek (or Yohoe Creek) to the south, and by the Coastline to the west (see Map 1).

The lithology of the area consists of the Neoproterozoic Umberatana and Wilpena groups, and the Cambrian Normanville and Kanmantoo Groups. A conformable sequence from the Precambrian Tapley Hill Slate to the Cambrian Carrickalinga Head formation has been established for the Delamere region (Daily, 1963), arising from the discovery of Lower Cambrian fossils in metamorphosed rocks at Delamere

Outcrop within the area is mostly limited to the coastline, and creek exposures, however limited outcrop can be found on some hill sides. In general, quality of the outcrop decreases proportional to the distance inland from the coast.

Figure 1a, Location map of Study Area in Australia

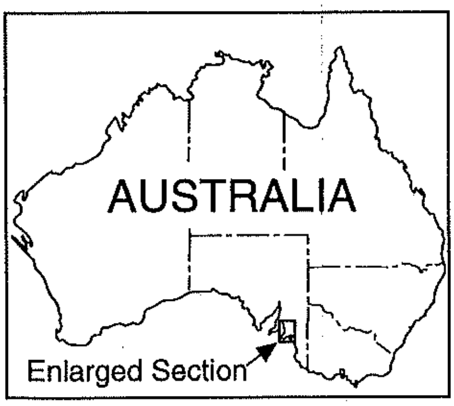
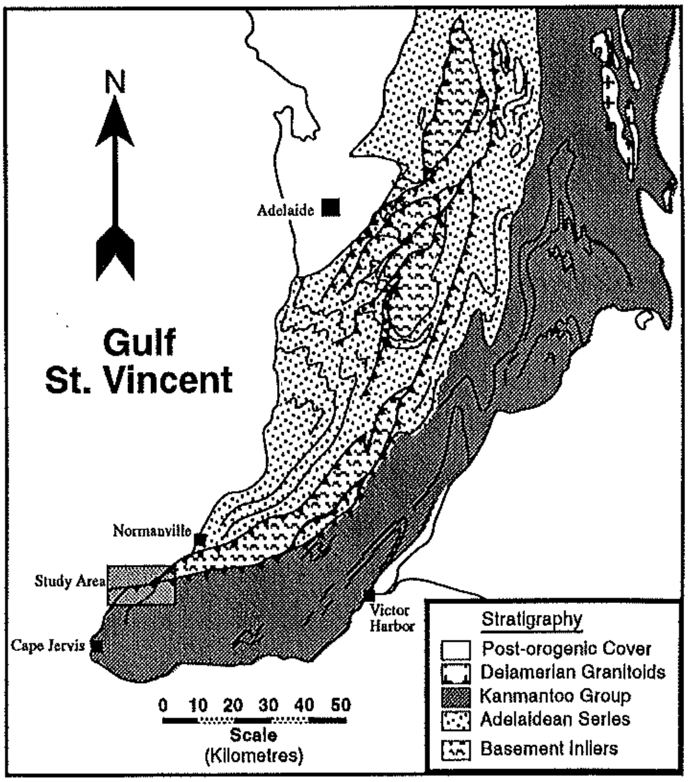


Figure 1b, Location map of Study Area on Fleurieu Peninsula



1.3 Description of lithologies and stratigraphy

As mentioned earlier, previous investigations in the area have been concerned mostly with stratigraphy and as a result, there exists a generally accepted stratigraphic sequence. The most extensive of these studies is that of Daily (1963) and it is his stratigraphic nomenclature which is used as a basis for this study. A complete stratigraphic sequence showing all units of the area can be seen in the Yohoe Creek section on the south eastern boundary of the study area, and has been described by Daily, (1963). Figure 1.2 shows a simple stratigraphic column for the Rapid Bay-Second Valley area, and map 1 shows the distribution of these lithologies over the study area.

Figure1.2 **Stratigraphy Of The Rapid Bay-Second Valley Area.**

Quaternary	Soils	Cover
Cambrian	Kanmantoo Group	Backstairs Passage Fm
		Carrickalinga Head Fm
	Normanville Group	Heatherdale Shale
		Forktree Limestone
		Sellick Hill Limestone
		Wangkonda Limestone
		Mount Terrible Formation
Pre-Cambrian	Wilpena Group	A.B.C. Quartzite
		Brachina Fm
	Umberatana Group	Angepena Fm
		Brighton Limestone
		Tapley Hill Fm

1) Umberatana Group

This group comprises the stratigraphically oldest units found in the area, and are found in the Yohoe Creek section younging to the east. The lower boundary of this group terminates against a major thrust fault in the Yohoe Creek section.

Tapley Hill Formation

This rock is characteristically a fine grained, dark grey, calcareous siltstone. It is very fine grained, and as a result of metamorphism is composed largely of finely recrystallised biotite giving it a phyllitic appearance. Its lower boundary abuts against a thrust fault in Yohoe Creek, and is found along the eastern side of this thrust in most of the mapped area (See Map 1). Bedding and cleavage are very poorly preserved in this unit, with slight changes between phyllitic lithologies and more silicate rich lithologies giving the only indication of bedding. This poor preservation may be partly due to its position near a major thrust plane, as better outcrop does exist in the northern part of the mapped area, near Second Valley. The unit is 30 metres thick in the Yohoe Creek section, and the upper contact is gradational into the highly calcareous Brighton Limestone.

Brighton Limestone

The Brighton Limestone consist of a series of alternating blue grey limestones and calcareous shales, which weather to a flaggy, buff coloured rock, of fine grain size. The unit is not very thick, around 25 metres in most places, but provides the most recognisable marker unit in the area and can be mapped reasonably accurately from interpretation of aerial photographs. Near Second Valley the unit has been tightly folded and stratigraphically thickened.

Angepena Formation

Conformably overlying the Brighton limestone is a sequence of blue calcareous siltstones interbedded with less calcic, silica rich siltstones and metasandstones, which Preiss (1987) has recognised as a southern equivalent to the Angepena Formation near Arkaroola. Near the top of the unit a gritty marble, which is overlain by a grey metasandstone is present, and easily recognisable by a characteristic orange-brown weathering colour. The calcareous siltstones are around one centimetre thick, whilst the siltstones and metasandstones are tens of centimetres thick. Overall this unit is approximately 50 meters thick in the Yohoe Creek section, and is a similar thickness in the No Where Else Creek. It is therefore assumed to remain a reasonably constant thickness throughout the field area, however the unit is mostly covered by Permian glacial deposits or Quaternary soils.

2) Wilpena Group

The units of the Wilpena Group conformably overly the Umberatana Group in the Rapid Bay, Second Valley area. This group is found throughout the Flinders Ranges, and has been recognised by Plummer (1978) to be further divided into two coarsening upward cycles. The lower of these two cycles has been further subdivided into five distinct lithozones, however the Nuccaleena dolomite, which is the lowermost lithozone, is not present in the study area. Evans (1987) describes this unit as becoming lenticular and sometimes absent in the Southern Adelaide Fold Belt.

Brachina Formation

The Brachina Formation consists of alternating quartz rich sandstones and less competent shaly units. The shaly units are often calcareous, becoming less calcareous towards the top of the Formation. The sandstone units are generally poorly sorted or massive and tens of centimetres thick, whilst the shaly units are almost always thinner and rarely exceed ten centimetres thick. The unit is found extensively throughout the area both east of Rapid Bay, and again in Yohoe Creek and No Where Else Creek.

A.B.C. Quartzite

This is a massive quartzite unit, which is separated in places by thin, fine grained interbeds. Ripple marks can be seen in some of the massive units, however bedding is often poorly defined. The massive units are well sorted in some parts, however iron minerals are abundant throughout most of the unit, which have weathered to give the rock a red colour. The unit is extremely hard, and forms a prominent ridge when it outcrops. Good outcrop of this unit is easily observable in a road cutting on the road into Rapid Bay (see appendix A, location 127).

3) Normanville Group

The Normanville Group comprises the lowermost units of the Cambrian sequence in the area. It appears to be a mostly conformable sequence, with the exception of the Heatherdale Shale, which is observed in only one area near Rapid Head, but is absent from all other areas. The units of this sequence are :

Mount Terrible Formation

The Mount Terrible Formation is a clastic sequence, composed of sandstones and siltstones. The lower portion of the unit is phyllitic and has a light grey colour, with bands of arkosic grits. The unit becomes gradually coarser grained towards the top, with the topmost unit being a coarse grained sandstone. The unit is approximately thirty metres thick in the Yohoe Creek section, and is a similar thickness in the Yatagolinga Creek section.

Wangkonda Limestone

At its base, the Wangkonda Limestone appears as a blue argillaceous limestone, which has a mottled appearance in parts. It progresses upwards through a brown coloured band, to a pink coloured uppermost portion. Bedding is not obvious in all parts of this limestone, however it can be discerned in some sections by thin sandy bands. Thickness of the unit ranges from around thirty to forty meters thick throughout the study area.

Sellick Hill Limestone

This unit lies conformably above the Wangkonda Limestone, and consists of alternating bands of lenticular limestone within argillaceous material. The argillaceous material contains muscovite, biotite and quartz. The rock is blue grey in colour, but often weathers to a buff colour. According to Daily (1963) the "lower two feet" of the formation contains hyolithids which were found by X-ray methods to be siliceous. The unit is approximately twenty to thirty meters thick in the Yohoe Creek section, and occurs as the core of an overturned syncline in the Yatagolinga Creek.

Forktree Limestone

This limestone outcrops throughout the study area, but has been significantly thickened due to tectonic folding in the area south of Rapid Head. A large quarry is currently being mined in this area by the Brighton Limestone Cement company, and provides excellent exposure. The unit consists of a massive marble member, and a mottled argillaceous limestone member, which for the purpose of this study have been mapped as one unit. The marble unit is a blue colour, with white bands throughout, whilst the limestone unit is a blue grey limestone with bands of grey brown argillaceous material.

The unit has been intensely deformed in the Rapid Head area, however remnants of bedding are still observable (see plate 1.a). In the south eastern section of the area, the unit is significantly less deformed, with bedding and cleavage more readily observable.

Heatherdale Shale

The Heatherdale Shale is only found as a thin band, and a large exposure in the core of an overturned syncline, just south of Rapid Head. It consists of grey carbonaceous shales, and is characterised in its lower units by black phosphatic nodules. It has been intensely deformed at Rapid Head, however bedding and cleavage are still easily observed in this area.

The unit is absent from all other areas within the study area, where the Kanmantoo group lies unconformably on top of the Forktree limestone. This contact has been described by Campana and Horwitz (1956) as being tectonic, and by Jenkins and Sandiford (1992) as erosional. Jago *et al.* (1994) suggest that "where a sedimentary contact is preserved on Fleurieu Peninsula it is an unconformity with marked vertical relief." (Jago *et al.*, 1994, pg 446) The latter statement seems be the correct interpretation for the Second Valley, Rapid Bay area.

4) Kanmantoo Group

The contact between the base of the Normanville Group and the Kanmantoo Group is sharp, and possibly unconformable.

Carrickalinga Head Formation

The Carrickalinga Head Formation is the lowermost unit of the Kanmantoo Group, and outcrops extensively in the Yohoe creek section closest to the coast. It is a sequence of alternating thin phyllitic and massive blue grey metasandstones of low biotite grade metamorphism (see plate 1.b). This type of sequence is characteristic of the Madigan Inlet Member of the Carrickalinga Head Formation.

The Blowhole Creek Siltstone, and the Campana Creek Member of the Carrickalinga Head Formation, which normally overlie the Madigan Inlet Member in the stratigraphic sequence (Gatehouse *et al.* ,1990) seem to be absent from the stratigraphy of the Rapid Bay, Second Valley area.

Backstairs Passage Formation

The contact between the Carrickalinga Head Formation and the Backstairs Passage Formation is sharp, and thought to be unconformable in the Yohoe Creek Section. This is consistent with Rogers (1991), who recognises a sharp, unconformable contact between the Carrickalinga Head and Backstairs Passage Formations in the Talisker area. This is suggested to be an erosional or depositional feature rather than structural, as the nature of the contact between the Backstairs Passage Formation and the subjacent Madigan Inlet Member appears sharp and conformable (Rogers, 1991).

The unit consists of a series of grey and brown sandstones with some limited cross bedding. It is the youngest unit mapped in the area, and occurs only in the western part of the area, terminating at the top at a major thrust. Good outcrop exists in Yohoe Creek, where the unit is approximately eighty meters thick.

1.4 Aims of the Study and Method of Investigation.

The study area was chosen specifically in order to link maps produced by previous workers to the south (Rogers, 1991; Johnson, 1991), and current mapping being done to the north (Buhrer, 1995; Szmidel, 1995) and south (Macdonald, 1995). The area is located on the inner section of the Fleurieu Arc, which Mancktelow (1981) has recognised as a possible reason for the anomalous nature of the structures in the region, compared to surrounding areas. The objectives of this study are:

- to produce a detailed geological and structural map of the area,
- to document and illustrate the structural geometry of the area, in particular to investigate the continuity of structural features (such as thrust faults and fold axes) across the area, and into adjoining areas.
- to construct balanced cross-sections of the area,
- to create a three dimensional computer model of the area,
- to determine the strain history of the area,
- to describe the microstructure of the area,
- to create a feasible model for the geometric and kinematic evolution of the area based on results from all of the previous mentioned aims.

The methods used in this investigation included mapping of the area at 1:10,000 scale, using aerial photographs as a base in the field. This mapping consisted of the collection of data representing the major fabrics of the area (ie. bedding, cleavage, lineations) and the tracing of lithologies, faults and shear zones.

The data collected in the field was then overlain onto orthophoto maps to produce a quality detailed structural map (See Map 1). Stereographic projections of the different types of data, in the various structural domains of the area, were then created to represent the general orientations of the structural elements.

The creation of balanced cross sections and profile sections was carried out using the data measured in the field, and the orthophoto maps. Three dimensional modelling was carried out using a Silicon Graphics Indigo 2 microcomputer, running Vulcan (Maptek™, 1995) three dimensional mapping software. The cross sections, profile sections and maps mentioned previously were used as a guide for the creation of the model.

Determination of finite strains were made using the Hudleston method on various folds in the area. A detailed description of microstructural kinematic indicators, folds and fabrics has been made through the examination of thin sections cut from oriented hand specimens from the area, and the use of a transmitted light microscope. The kinematic model of the evolution of the area is based on the results of all the methods mentioned above.

2. Structural Geometry

2.1 Introduction

Map 1 is the geological map which has been produced of the area, and shows the general distribution of lithologies, geological boundaries, major faults, folds and fabrics. Orientations of bedding (S_0), cleavage (S_1), intersection lineation ($L_1{}^0$) and elongation lineation (L_1) were collected from various localities throughout the mapped area and are represented in the structural maps 2,3 and 4, and the accompanying stereographs.

The area is transected from southwest to northeast by two major thrusts, which divide the area into three zones that are characterised by different styles of deformation. The stereographs shown in maps 2,3 &4 give the average orientations of fabrics in the area, and in each tectonic zone. Unfortunately, these do not give a true indication of the differing deformation styles because the nature of the deformations has led to all of the measured fabrics being oriented in the same general direction. The following is a description of the three tectonic zones in the area.

2.2 Tectonic Zones

As previously mentioned, the area has been divided into three tectonic zones, 1) The Rapid Head Sheared Zone, 2) The Mount Rapid Folded Zone and the Yohoe Creek Thrust Sheet. The zones are separated by two shallowly dipping thrust faults, which trend NE-SW and dip 20°-30° towards the east. The two thrust faults, hereafter referred to as the Rapid Bay Thrust (RBT), and the Yohoe Creek Thrust (YCT) extend across the full length of the mapped area, with the Rapid Bay Thrust deviating offshore briefly between Rapid Bay and Second Valley (see chapter 2.3).

Zone 1) The Rapid Head Sheared Zone (RHSZ)

This zone is located mainly on the coast, and is characterised by intense deformation, which includes shearing and major folding. The most abundant lithology of this zone is the Forktree Limestone, which (partly due to its low competence) has been intensely folded and sheared, resulting in significant tectonic thickening of the lithology (see map 1). This zone is also the only region in the mapped area where the Heatherdale Shale outcrops. This unit has also been tectonically thickened due to repeated stratigraphy in the exposed core of a major synform at Rapid Head. The lowermost unit of the Kanmantoo Group, which is the Carrickalinga Head Formation, also outcrops in this zone. However in contrast to the Forktree Limestone, the Carrickalinga Head Formation has behaved more competently during deformation. This high competence is partly responsible for the

Plate 1.a Remnants of sedimentary bedding in the highly deformed Forktree Limestone found at location 90 (see appendix A). Bedding is horizontal, Cleavage is dipping east to west.

Plate 1.b Outcrop of Carrickalinga Head Formation, displaying inverted graded bedding. The outcrop was found at location 13, and is interpreted to have been overturned.

Plate 1.c Thrust fault surface found in old diggings at location 30.1. A fault breccia has formed, defining the thrust surface.

Plate 1.d Exposed thrust fault, found near the jetty at Second Valley. A sense of displacement of south over north can be deduced from minor bending of the bedding layers upwards in the footwall, and downwards in the hangingwall of the fault. This photograph was not taken perpendicular to the regional movement direction, and therefore conflicts with the overall interpretation of a SE over NW sense of vergence for the whole area.

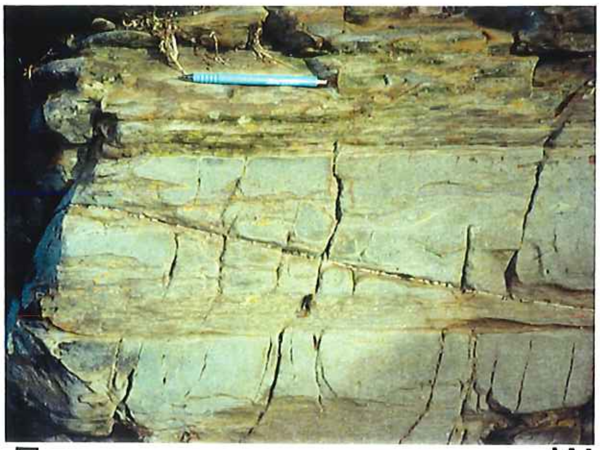
Plate 1.e Intense folding in marble bands at Second Valley. This outcrop is in the footwall of the Rapid Bay Thrust.

Plate 1.f Microfolds in a thin section of the Forktree Limestone. Field of view is approximately 2 mm, and picture was taken under plane polarised light.

Plate 1.g σ type porphyroclast indicating east over west vergence. Field of view is approximately 0.6mm in, and picture was taken under cross polarised light. Sample is number 90, cut in the X/Z section of the finite strain ellipsoid.

Plate 1.h High angle between horizontal cleavage and folded bedding, in the Heatherdale Shale. Picture taken at location 59 (see appendix A). Note the black phosphatic nodules (parallel to bedding), which are characteristic of the Heatherdale Shale.

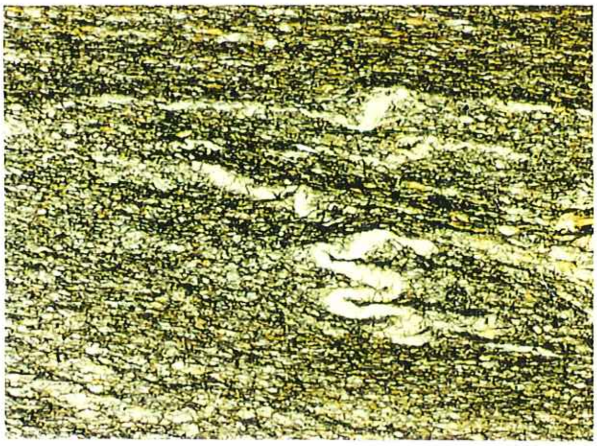

E 1.a W

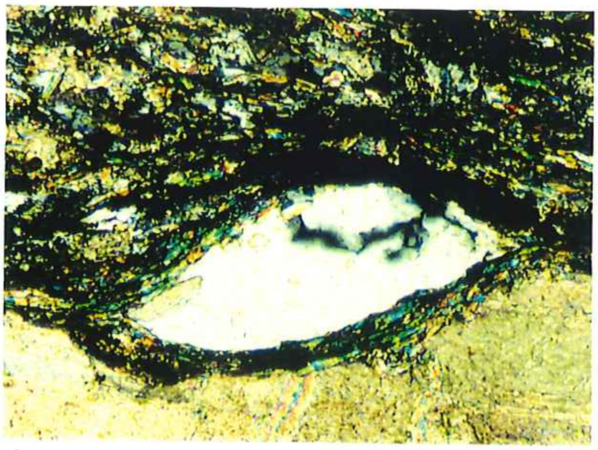

E 1.b W


NE 1.c SW

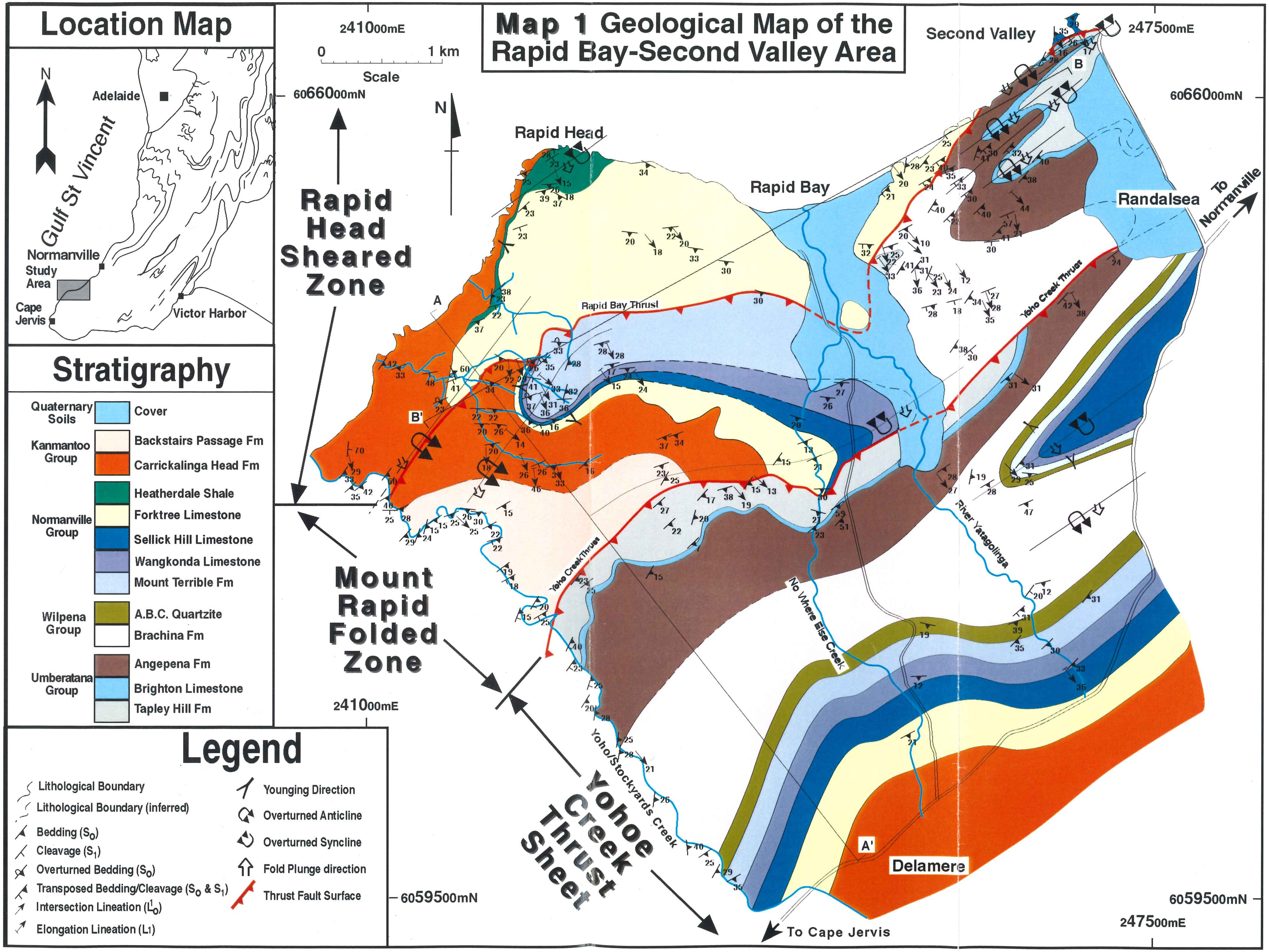

SW 1.d NE


N 1.e S

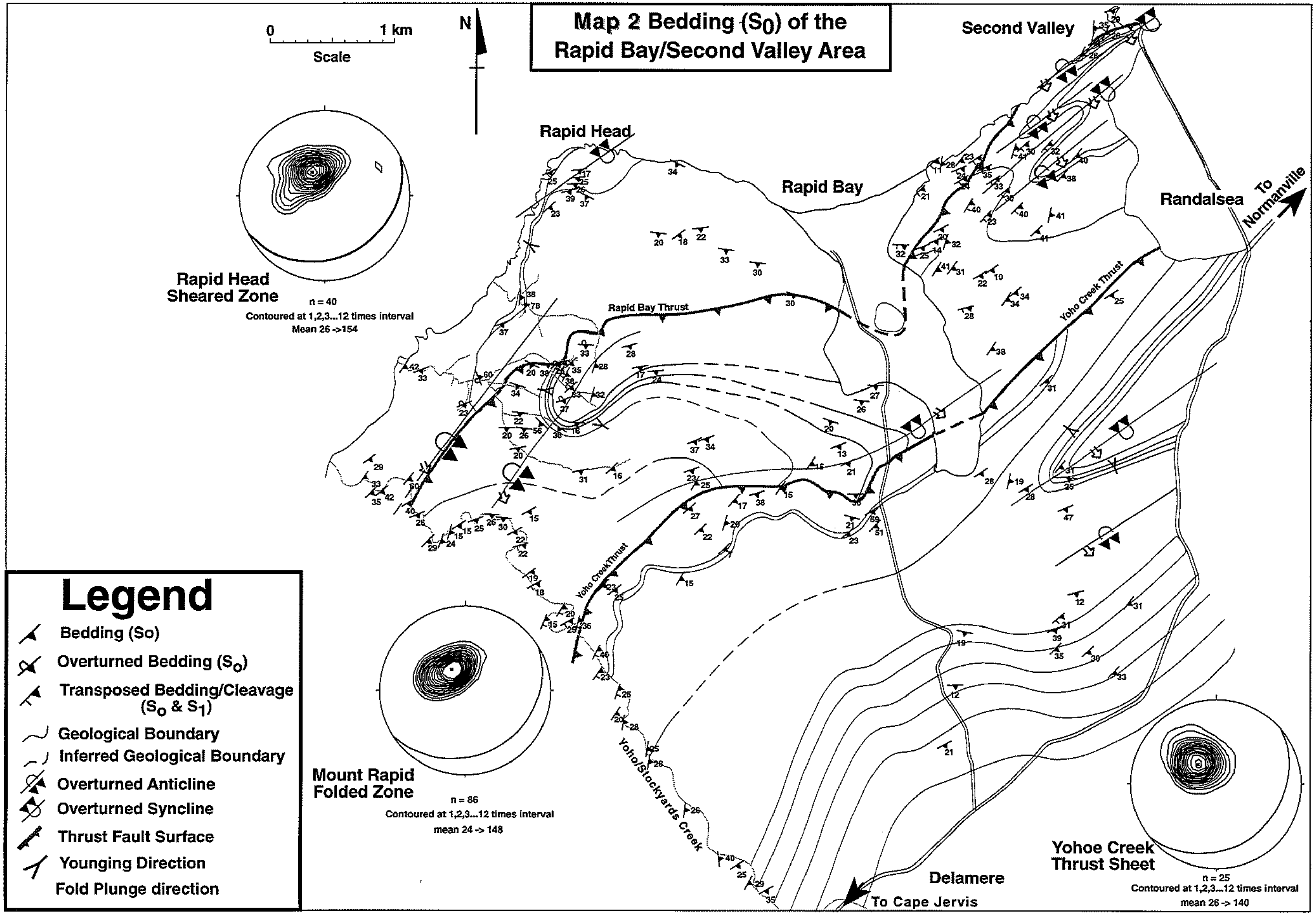

1.f


E 1.g W

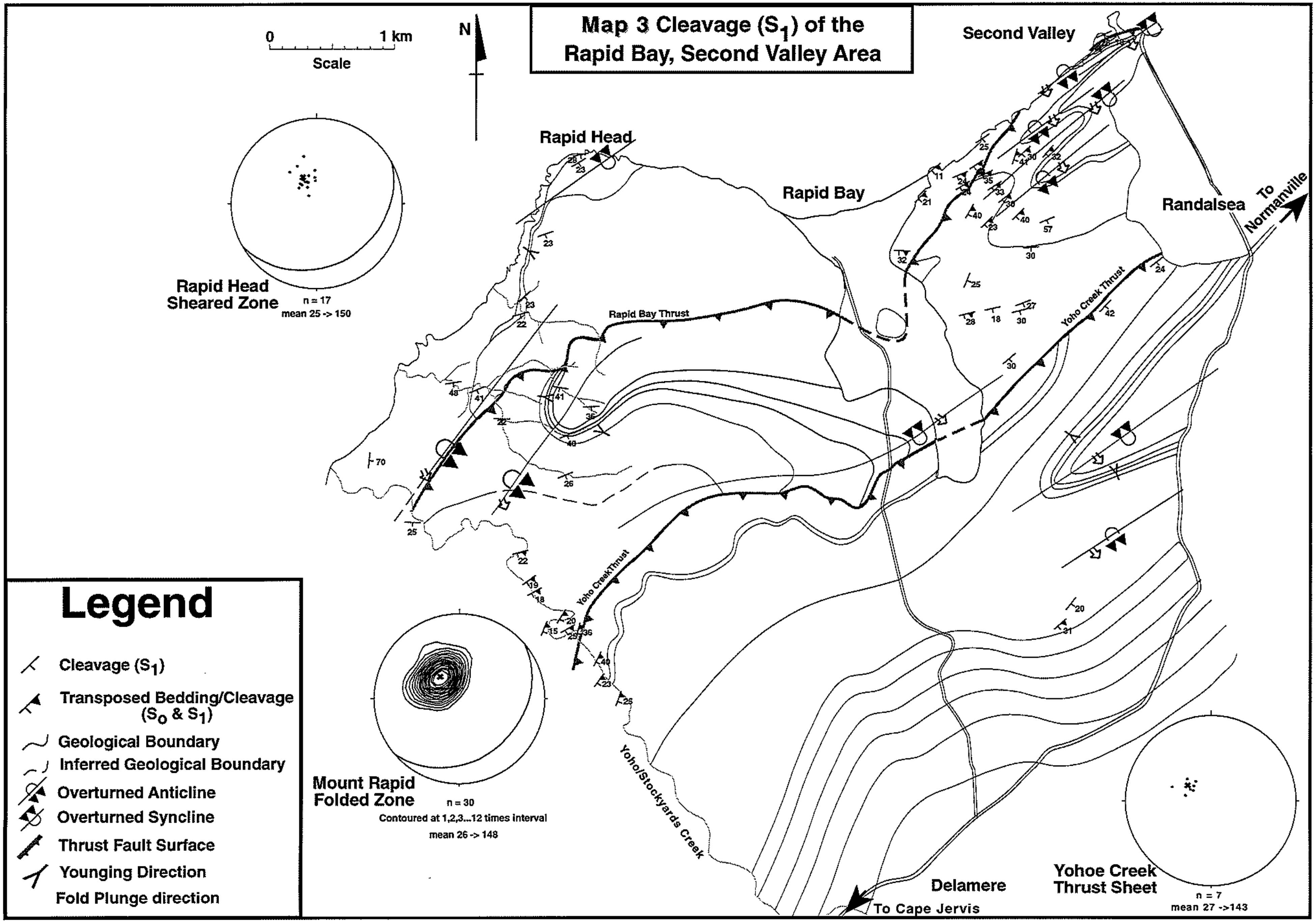

E 1.h W



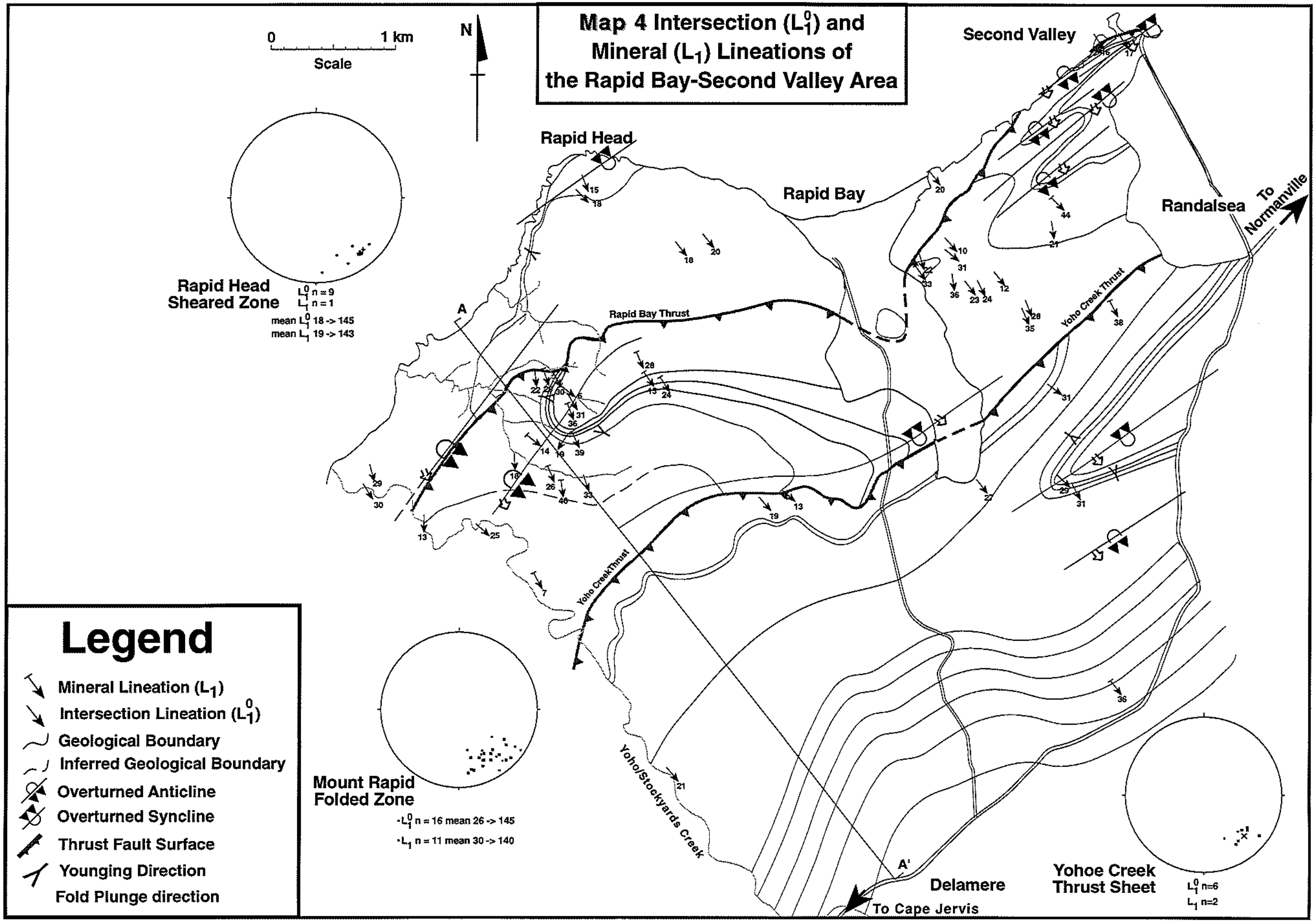
Map 1 Geological Map of the Rapid Bay-Second Valley Area
Location Map
N
Adelaide
Gulf St Vincent
Normanville
Study Area
Cape Jervis
Victor Harbor
Stratigraphy
Quaternary Soils
Cover
Kanmantoo Group
Backstairs Passage Fm
Carrickalinga Head Fm
Normanville Group
Heatherdale Shale
Forktree Limestone
Sellick Hill Limestone
Wangkonda Limestone
Mount Terrible Fm
Wilpena Group
A.B.C. Quartzite
Brachina Fm
Umberatana Group
Angepena Fm
Brighton Limestone
Tapley Hill Fm
Legend
Lithological Boundary
Lithological Boundary (inferred)
Bedding (S_0)
Cleavage (S_1)
Overturned Bedding (S_0)
Transposed Bedding/Cleavage (S_0 & S_1)
Intersection Lineation (L_0^1)
Elongation Lineation (L1)
Younging Direction
Overturned Anticline
Overturned Syncline
Fold Plunge direction
Thrust Fault Surface
241000mE
0 1 km
Scale
6066000mN
N
Rapid Head Sheared Zone
Mount Rapid Folded Zone
Yohoe Creek Thrust Sheet
241000mE
6059500mN
Rapid Head
Rapid Bay
Rapid Bay Thrust
Second Valley
247500mE
6066000mN
Randalsea
To Normanville
Yoho Creek Thrust
River Yatagolinga
No Where Else Creek
Yoho/Stockyards Creek
Delamere
To Cape Jervis
6059500mN
247500mE
A
A'
B
B'


Map 2 Bedding (S_0) of the
Rapid Bay/Second Valley Area
0
1 km
Scale
N
Rapid Head
Rapid Bay
Second Valley
Randalsea
To Normanville
Rapid Bay Thrust
Yoho Creek Thrust
Yoho Creek Thrust
Yoho/Stockyards Creek
Delamere
To Cape Jervis
Rapid Head Sheared Zone
n = 40
Contoured at 1,2,3...12 times interval
Mean 26 ->154
Mount Rapid Folded Zone
n = 86
Contoured at 1,2,3...12 times interval
mean 24 -> 148
Yohoe Creek Thrust Sheet
n = 25
Contoured at 1,2,3...12 times interval
mean 26 -> 140
Legend
Bedding (So)
Overturned Bedding (S_0)
Transposed Bedding/Cleavage (S_0 & S_1)
Geological Boundary
Inferred Geological Boundary
Overturned Anticline
Overturned Syncline
Thrust Fault Surface
Younging Direction
Fold Plunge direction

Map 3 Cleavage (S_1) of the Rapid Bay, Second Valley Area



Map 4 Intersection (L_1^0) and Mineral (L_1) Lineations of the Rapid Bay-Second Valley Area



Carrickalinga Head Formation appearing to be relatively undeformed at the outcrop scale.

Zone 2) The Mount Rapid Folded Zone (MRFZ)

Tight, reclined to upright, minor and major folds plunging 25°-35° towards 145° SE, characterise this zone. In the north eastern section, the folding has a higher frequency and lower wavelength than that of the southwestern section, suggesting that folding is likely to be disharmonic between the different lithologies. All lithologies which are present in the study area (with the exception of the Heatherdale Shale) can be observed in this zone, however due to the intense folding these lithologies are often repeated when transected across strike.

Zone 3) The Yohoe Creek Thrust Sheet (YCTS)

In the western section of this zone, reasonably uniform homoclinal bedding occurs, dipping between 25° and 40° to the ESE, and younging to the south east. Similarly to the MRFZ, a complete stratigraphic sequence (with the exception of the Heatherdale Shale) can be observed in a transect from NW to SE. However, the eastern section of this zone is dominated by a major reclined anticline/syncline pair, whose axial planes trend NE-SW, and axial traces plunge approximately 30° towards 150° SE.

2.3 Major Thrusts

The Rapid Bay and Yohoe Creek Thrusts have been interpreted from average elongation lineation orientations (see Map 4), and measurements taken from minor fault planes near the thrusts to dip at a shallow angle (RBT dips ~ 25° SE, YCT dips ~ 30° SE) and trend northeast to southwest across the region. In addition, another major fault has been interpreted from seismic surveying in the near offshore environment of Rapid Head (Flöttman, *pers com.*), and a further thrust has been mapped by previous workers to the south east of the study area (Evans, 1987). It is suspected that the RBT and the YCT are part of the lower levels of a larger scale imbricate fan near to the major basal décollement. Both the RBT, YCT and the two other previously mentioned faults are suspected to root into the décollement surface at depth.

The faults have been recognised as zones of intense strain, from discordant contacts between lithologies, lineaments detected on aerial photographs and remotely sensed images and minor faulting at outcrop scale. (See plates 1.c & 1.d). Minor faulting tends to increase in areas near to the fault planes, as do calcite or quartz filled veins. Limited mining of silver and lead rich deposits of galena, which is associated with fault related calcite veins in the limestone units, has taken place in the past (Madigan, 1925). The old diggings from these ventures often provide excellent exposures of fault surfaces, particularly at locations 30 and 30.1 (see

Plate 1.c)(See appendix A). On the coastline between Rapid Bay and Second Valley, numerous examples of minor faulting can also be observed (See plate 1.d).

A southeast over northwest vergence has been deduced for these faults from investigations of small scale kinematic indicators (See chapter 3) however a quantitative value of displacement cannot be attained due to the lack of characteristic markers. An attempt has been made to tectonically restore the area, using three dimensional modelling techniques and strain analysis, in an effort to unravel the tectonic evolution of the area. (See Chapters 4&5)

2.4 Folding

Introduction

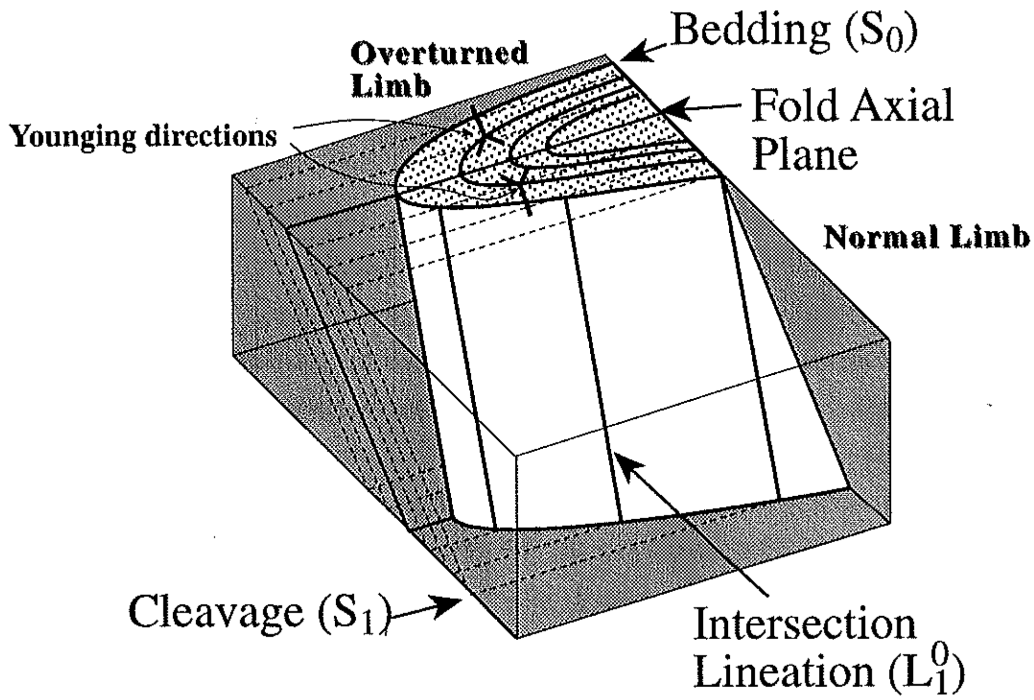
The orientation of sedimentary bedding varies greatly throughout the area, in particular in the Mount Rapid Folded Zone, and to a lesser extent in the Rapid Head Sheared Zone. However, due to the tight, reclined nature of the folds in these zones, the dip and strike of bedding does not appear to fluctuate greatly. The Yohoe Creek Thrust Sheet displays reasonably uniform bedding in its southern section, however to the north tight overturned folding has again occurred, making bedding in this section similar to that of the other two zones. Orientations of bedding in the three tectonic zones are illustrated in map 2.

Mancktelow (1981) recognised the existence of reclined folds in the area, and stated this as one of the reasons why the area is significant in the tectonic evolution of the Southern Adelaide Fold Belt. This area (between the townships of Rapid Bay and Second Valley) is anomalous, compared with the rest of the fold belt, where first generation folds have generally sub-horizontal to gently plunging axes and moderately to steeply inclined axial surfaces (Mancktelow, 1981).

Particular attention was given to mapping the folds in the area, because of their anomalous occurrence. Previous workers have mapped a single major anticlinal structure dominating the structural geometry of the area (Anderson, 1975; Mancktelow, 1979; Evans, 1986). This study has also recognised a large anticlinal structure, however closer inspection reveals that it is in fact made up of two reclined antiforms, separated by the Rapid Bay Thrust.

Because folding in the area ranges from reclined to overturned, and hence both limbs of the folds dip in approximately the same direction, it was necessary to use the relationship of bedding and cleavage to determine vergence delineating the upright from the overturned limbs of the major folds. This relationship is illustrated in figure 2.1.

Figure 2.1 Sketch showing the relationship between bedding, cleavage and intersection lineation in an idealised reclined fold.



Samples of minor folds were collected throughout the mapped area, including hand specimens, microfolds (observed in thin section) and also photographs of folds in profile and plan view at outcrop scale. In addition to these samples, map scale folds were classified using a profile projection which was constructed perpendicular to the plunge of major folds in the area. The methods for classification of folds, and strain analysis from these folds is discussed in chapter 5.

The Rapid Head Sheared Zone

Folding within the RHSZ is tight to near isoclinal and reclined, being represented at the mapping scale by a major anticline syncline pair, hereafter referred to as the Rapid Head Anticline Syncline Pair (RHASP). At outcrop scale, many folds were observed with wavelengths ranging from tens of metres (see plate 1.e) to centimetres and again folding is represented at the microscale with wavelengths of a few micrometres (see plate 1.f).

The RHASP is characterised by steeply dipping (37° to 60°) north westward younging overturned limbs, and more shallowly dipping (17° to 26°) south eastward younging normal limbs. Investigation of intersection lineations measured around the RHASP, in association with measurements taken from small scale folds, reveals that the plunge of the overturned anticline is approximately 25° towards 150° SE, and the plunge of the overturned syncline is approximately 15° towards 145° SE (see map 4)

The Mount Rapid Folded Zone

In this zone folding is the predominant deformational feature, and consists of large scale anticline syncline pairs which are tight, reclined and plunging around 25°-30° towards 145° SE. Again folding occurs at all scales from regional mapping scale to micro scale. The wavelengths of mapping scale folds seems to increase from approximately 25 metres in the north eastern section to 1 km in the south western section. The plunge of folds throughout this zone appears to be uniform, with an average intersection lineation of approximately 25° towards 140 (see map 4).

The existence of a major anticline in the southwestern section has not been recognised by previous workers, and was detected during this field study largely by evidence found in one creek section north of Yohoe Creek (locations 11, 12 and 13, appendix A). Two near perpendicular cleavages were measured in this section, one parallel to the regional axial cleavage (~25° towards 150° SE.) and another approximately 47° towards 230° SW. This situation can be indicative of the hinge zone of a major fold whose fold axes have been rotated during deformation. Further evidence to support the existence of a reclined structure is overturned bedding in the Carrickalinga Head Formation (see plate 1.b) which was found at location 13.1 (see appendix A). A profile section has been constructed across this zone, which shows the interpretation of these folds at depth. (See Figure 2.2b)

The Yohoe Creek Thrust Sheet

Due to poor outcrop, no samples of minor or microscale folds were collected, however a major anticline syncline pair, both of which plunge at around 30° towards 145 SE.. was mapped in the north eastern section. The fold was detected due to lithological variations, and the relationship between bedding and cleavage as described in figure 2.1. Intersection lineations indicate that both of these folds plunge approximately 30° towards 145° SE.

2.5 Cross and Profile Sections

A cross section has been constructed using traditional methods, such as those described by Marshak and Mitra (1988, pg 303-332). The method involves the projection of structural data measured at ground level onto a vertical section trending across the strike of bedding. This method assumes that the thickness of layers remains constant at depth, and that the folds are cylindrical or cylindroidal. The resulting cross section is a deformed state cross section, and is represented in figure 2.2a.

The position of the section line for cross section A-A' was chosen based on two main considerations. Firstly the amount of information which the section contains depends on the amount of data which was measured near to the section line. The interpretation of the cross section must also be feasible based on the

Figure 2.2a Cross Section A-A'

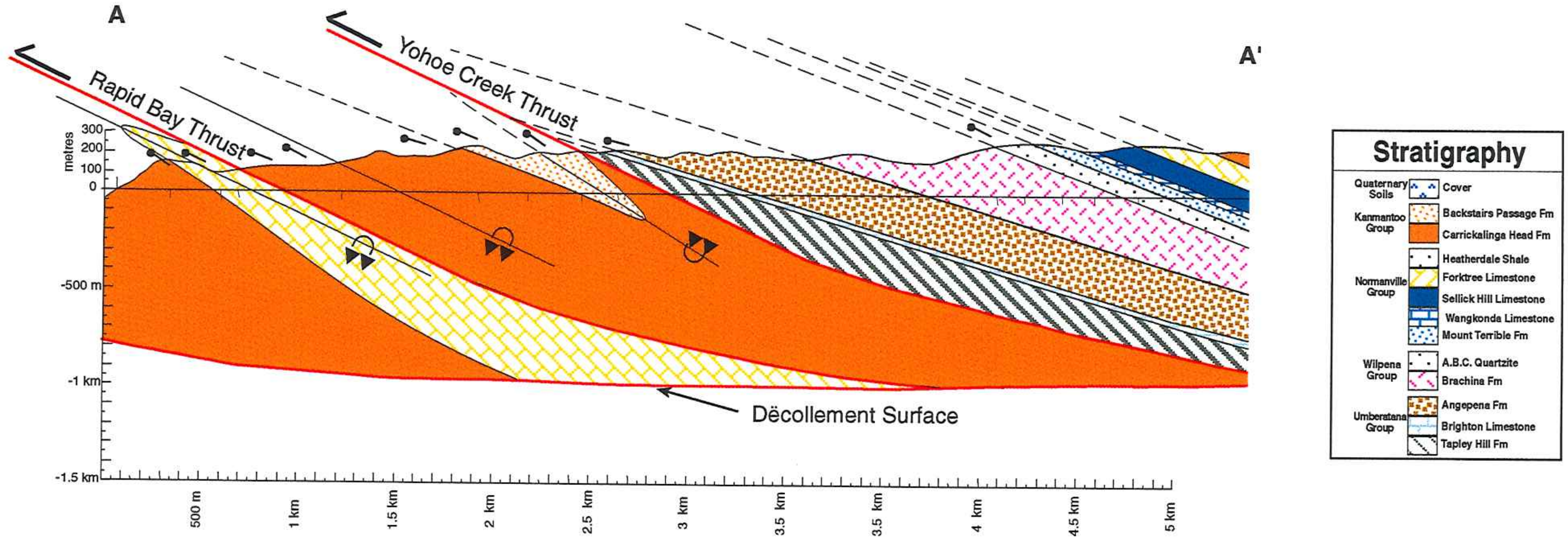
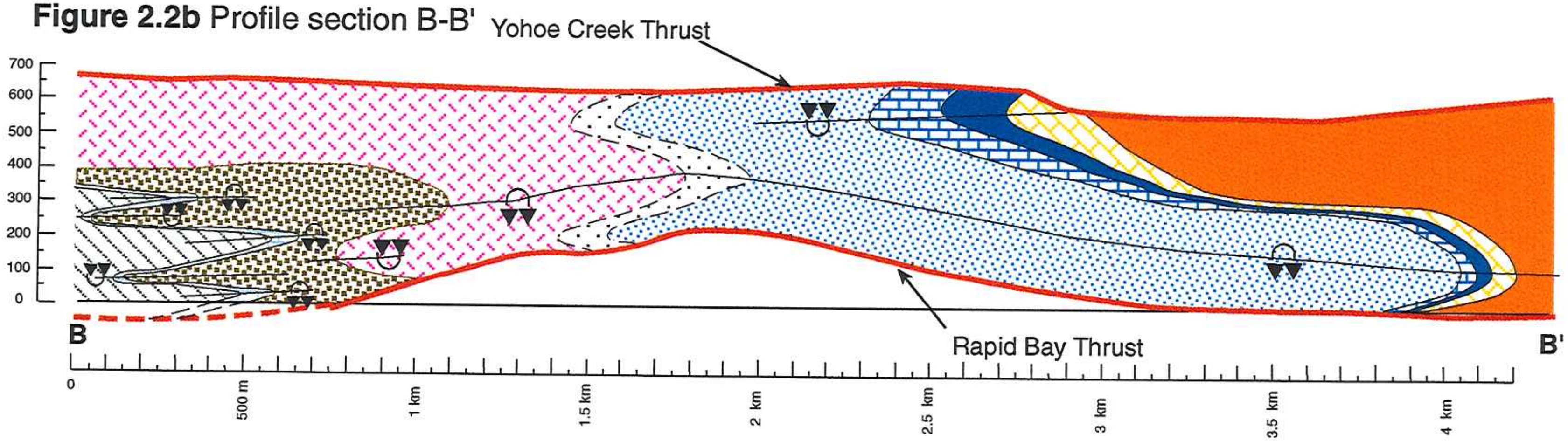


Figure 2.2b Profile section B-B'



geology at outcrop scale. It is felt that section line A-A' best satisfied both of these considerations.

Figure 2.2b shows a profile projection of the Mount Rapid Folded Zone. This projection is based on methods described by McClay (1987), and Marshak & Mitra (1988), and takes into account the steep topography of the area. The section line B-B' is considered to be at sea level, and the projection plane is projecting upward at 65° towards 150° SE. (perpendicular to the plunge of the major fold axes). Data measured within the Mount Rapid Folded Zone has then been projected onto the profile plane, to create a "slice" through the area.

The orientation of this profile plane was chosen to give a view of the folds in the Mount Rapid Folded Zone, looking down the plunge of the major fold axes. This is effectively a cross section along the strike of bedding in the area, and provides more information on the structural geometry of the Mount Rapid Folded Zone than the cross section A-A'. The decision to construct a profile section rather than multiple cross sections was made because it was felt that more information would be provided by the profile section.

Because of the nature of folding in the area, restoration of cross sections and profile sections is difficult. Further analysis of strain (See chapter 5) is necessary before any attempt can be made to restore these two sections.

3 Structural and Metamorphic fabrics

Introduction

Oriented samples which displayed a variety of minor structures in hand specimen were collected at various locations throughout the study area (see appendix A). Samples were collected from most of the lithologies present in the region, however some lithologies which did not display a range of structures were only rarely sampled.

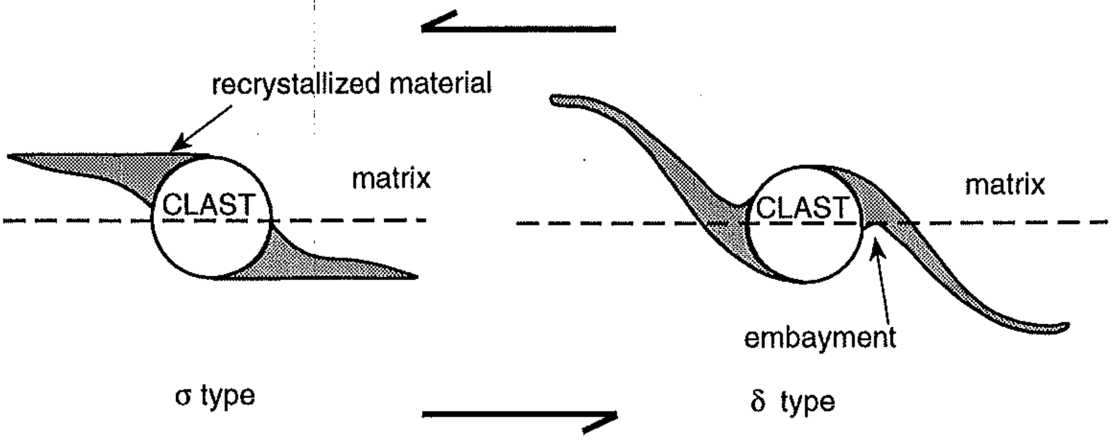
Most samples displayed an elongation lineation and near layer parallel foliations. The hand specimens were cut, firstly parallel to their elongation lineation and perpendicular to their foliation (XZ section of the finite strain ellipsoid), and secondly perpendicular to both elongation lineation and foliation (YZ section of the finite strain ellipsoid). Thin sections were made in both the XZ and YZ plane, which were used to describe the fabrics of the area.

The fabrics examined in thin section include all of those measured at outcrop scale in the field, these being bedding (S_0), cleavage (S_1), elongation lineation (L_1) and intersection lineation ($L_1{}^0$). The orientation and nature of these fabrics varied greatly across the study area, due to variations of lithologies, strain magnitude and their positions relative to major structures such as faults and folds. The fabrics described in this chapter are those which are believed to have developed during one major D_1 (Cambro-Ordivician) Delamerian deformation (Thompson, 1970).

Very few kinematic indicators were found in the study area, however those that were found provided reasonable evidence of contractional movement verging east over west. Most of the indicators were found in carbonate lithologies. The indicators were looked for in thin sections which were cut parallel to the elongation lineation and perpendicular to the S_1 foliation (XZ plane of the finite strain ellipsoid). Passchier and Simpson (1986) suggest that this plane will contain any evidence of kinematic movement depicting the style of the deformation. The classification system of Passchier and Simpson has been used to determine the types of kinematic indicators found in the study area (see figure 3.1)

Plate 1.g shows a thin section cut in the XZ plane of sample 90 which was collected at location 90 (see appendix A). This plate is an example of a σ type porphyroclast according to the classification of Passchier and Simpson (1986) (see figure 3.1). A general contractional east over west vergence has been deduced from samples which display similar indicators.

Figure 3.1 Classification of porphyroclast systems with a sinistral sense of movement. Modified from Passchier & Simpson (1986).



3.2 D_1 Fabrics

A penetrative slaty cleavage (S_1) developed over the whole study area, which is mostly axial planar to the major folds. Mancktelow (1979), noted that in areas of low grade metamorphism (e.g. the western side of Fleurieu Peninsula) S_1 is readily recognised as a penetrative cleavage strongly developed in pelites, and weakly to moderately developed in the psammites and carbonate rich units. Refraction of S_1 between pelitic and psammitic layers can be marked, particularly in regions of shallowly dipping S_1, occasionally with angles greater than 40° between the two orientations (Mancktelow, 1979). Slight variations of S_1 in the area could also be due to minor fanning associated with parasitic folds which are abundant in the R.H.S.Z. and the M.R.F.Z.. The S_1 foliation is mainly a slaty cleavage, but can also be a schistosity in quartz rich rocks. Due to the intense, tight folding of the region, S_1 and S_0 are near parallel and transposed in the limbs of folds making the distinction between the two very hard to distinguish. It is only within the hinge zones of folds that a significant difference between the two is apparent (See plate 1.g).

A bedding/cleavage intersection lineation (L_1^0) is developed throughout the region, which is expressed as either the trace of S_0 on the S_1 surface, or the trace of S_1 on the S_0 surface (see Figure 2.1). The lineation has been used to define the plunge of folds within all regions of the mapped area, based on the assumption that the S_1 fabric is axial planar.

A mineral lineation (parallel to an elongation lineation) was also measured throughout the study area, this lineation being defined by the preferred orientation of minerals (e.g. biotite) within the S_1 plane. The mineral lineation is better defined in the siliceous rocks than the limestones and marbles. Mancktelow (1979) described the angle made between L_1 and L_1^0 in the S_1 plane as varying constantly across the Southern Adelaide Fold Thrust Belt. Rogers (1991) recognised a high angle between the two lineations in the Talisker area, south east of Rapid Bay, however in the Rapid Bay-Second Valley area, the two lineations are near parallel. Mancktelow (1979, 1981) suggested that this feature, and the presence of reclined folds in the area (which is anomalous to surrounding regions), may be due to the areas' position on the inner part of the Fleurieu Arc.

The mean orientations of S_1 in the three tectonic zones is 25° towards 150° SE in the RHSZ, 26° towards 148° SE in the MRFZ, and 27° towards 143° SE in the Yohoe Creek Thrust Sheet. This appears to indicate that S_1 is increasing in dip, and tending to trend more north-south as the area is transected from northwest to southeast. This change in orientation would be consistent with the interpretation that the fold axes have rotated due to the area's position on the inner section of the Fleurieu Arc (see chapter 6). However a definite conclusion cannot be made because the variation is only slight, and error margins involved when taking measurements are reasonably high. Further investigations of S_1 to the southeast would be necessary to substantiate the theory of fold axis rotation.

Mancktelow (1981) also used the relationship between L_1 and L_1^0 on the S_1 plane, as an indicator of vergence in the western portion of the Stockyard Creek section. Although Mancktelow detected a change in vergence along this section, he suggested that the stratigraphic sequence maintains an eastward younging direction. Based on the work in this thesis, and previous work (Mancktelow 1979, 1981; Evans, 1987) to the north of Stockyard (or Yohoe) creek, in addition to contemporary work being undertaken by Macdonald (1995) to the south of Stockyard Creek, it has been established that a major thrust fault (the Rapid Bay Thrust) and a major anticline are responsible for the change in vergence recognised by Mancktelow (1981). This has been established based on the continuous nature of the Rapid Bay thrust across the mapped area (see map 1), the existence of the "Plough Creek Thrust" (Macdonald, 1995) to the south (assumed to be the continuation of the Rapid Bay Thrust) and by a small zone of intense folding in the area corresponding to Mancktelow's change in vergence in Stockyard Creek.

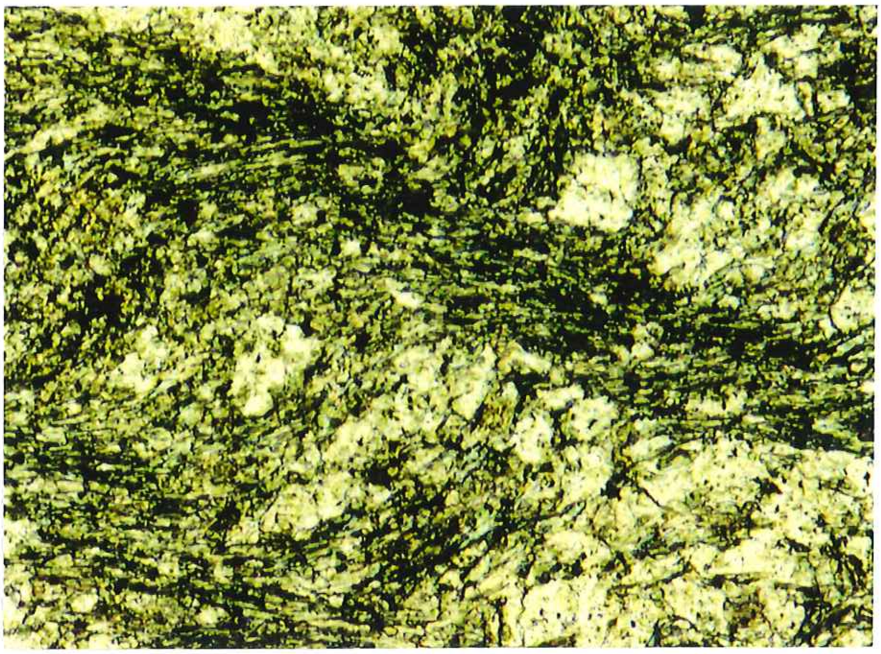
<u>3.3 Evidence For a Possible D_2</u>

Crenulation cleavages and minor kink folds (see plates 2.a 2.b &2.c), which could be associated with a second weaker deformation event than D_1 are present within the field area. The crenulation cleavages can only be observed at microscale (see plates 2.a & 2.b) but display a very marked difference in orientation to S_1 (between 10° and 45° difference). The irregularity in orientation, and limited occurrence of such crenulations and kink folds makes the determination of a direction of maximum compression difficult. It is for this reason that a correlation cannot be made between the D_2 of Offler & Flemming (1968) or Mancktelow (1979), which is developed in other areas of the Southern Adelaide Fold Thrust Belt, and the D_2 described in this chapter.

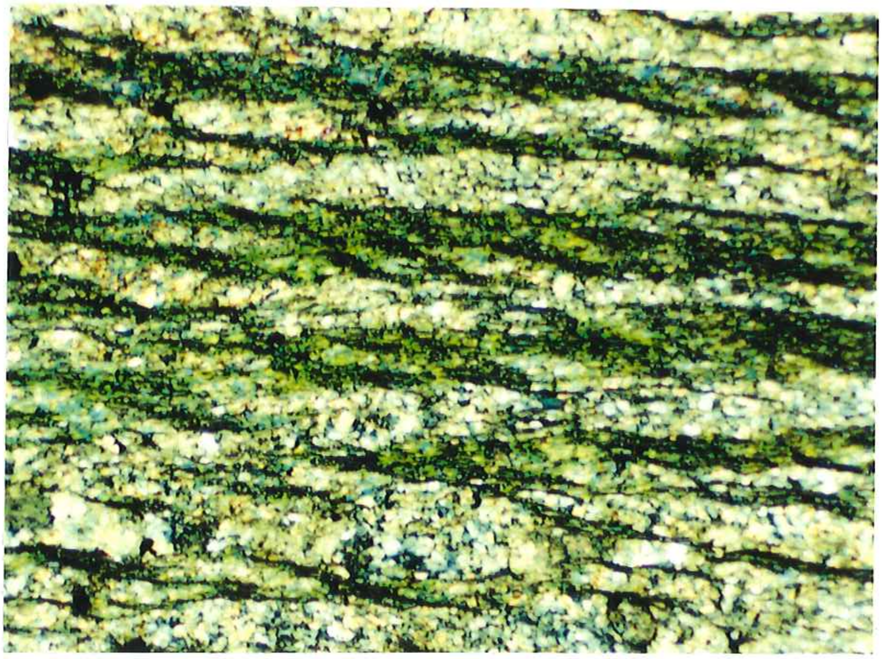
Plate 2.a Crenulation cleavages in Forktree Limestone, sample 90, Y/Z plane of the finite strain ellipsoid. Field of view is approximately 0.6mm, and picture was taken under plane polarised light.

Plate 2.b Crenulation cleavages in Forktree Limestone, sample 90, Y/Z plane of the finite strain ellipsoid. Field of view is approximately 2mm, and picture was taken under cross polarised light.

Plate 2.c Kink fold in the Forktree Limestone. Picture taken at location 119 (see appendix A).



2.a



2.b

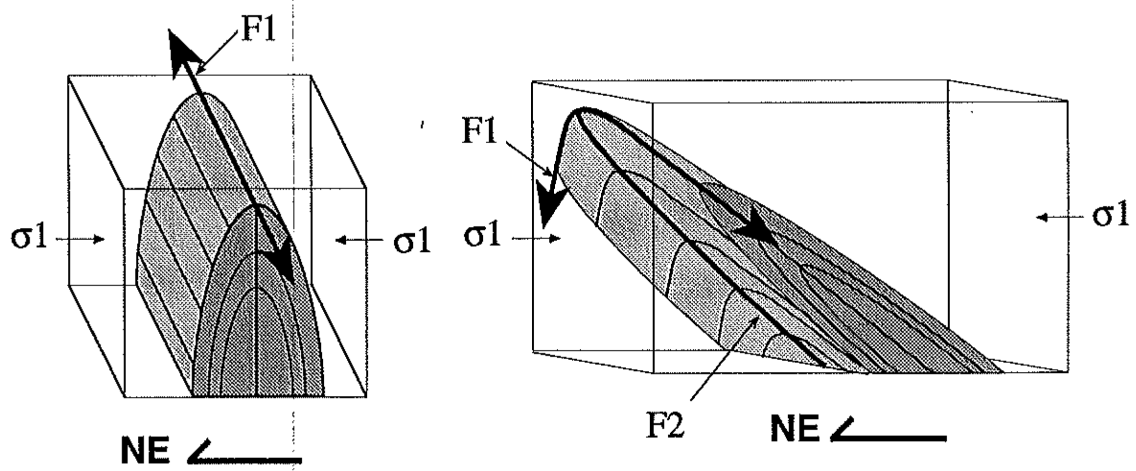
2.c

NE SW

3.4 Formation of Fold Axes

The possibility that the area may have undergone some rotation (producing the reclined folds discussed in chapter 2.4) could provide a scenario whereby irregular and isolated evidence for a second deformation (D_2), could exist. However, the so called second deformational event would in fact be the result of one prolonged period of deformation (D_1) overprinting its own previous effects as the area rotates, and the direction of maximum compressive stress stays constant (see Figure 3.2).

Figure 3.2 Sketch diagram showing a scenario whereby one continuous deformation could result in the formation of structures which look like the result of two deformations (i.e. a sheath fold). The rotation of the F1 fold axis is due to continued strain (σ1) in a constant direction. The second part of this sketch is directly comparable to the structure shown in plates 3.a, 3.b & 3.c.



Work by Sanderson (1973) has suggested a theoretical mechanism whereby reclined folds may be formed due to increasing strain in the XY plane. According to this mechanism, the rate of rotation of any individual fold axis will depend on the original angle between that fold axis and the Y direction. Mancktelow (1979,1981) has used the theoretical work produced by Sanderson (1973) in a comparison with data measured in the Rapid Bay, Second Valley region. The results of this comparison between a computed model and the actual measured data are illustrated graphically in figures 3.3a and 3.3b. The measured data appear to correspond very closely with the computed curve 5 of figure 3.3a.

Plates 3.a, 3.b & 3.c Three different views of a small scale sheath fold, found at location 11 (see appendix A). A structure of this type could form due to the region being subjected to two separate deformation events, or one prolonged deformation, during which the first fold axis was rotated.
See also figure 3.2.

NW 3.a SE

3.b
SW NE

NE
3.c
SW

Figure 3.3a Computed frequency-distribution (θ') curves, after normalisation, for X/Y from 1 to 5, standard deviation of fold orientation = 20° and,original angle between fold orientation mean and Y=10°. From Sanderson (1973).

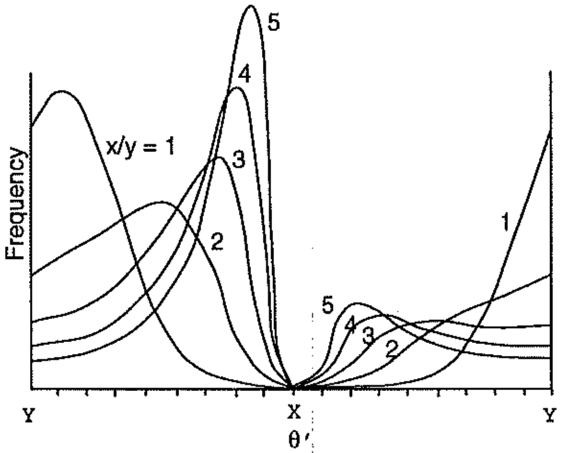
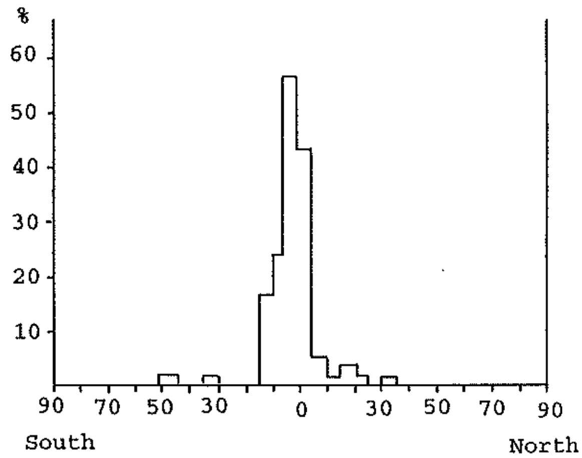


Figure 3.3b Frequency distribution histograms of the pitch angle difference between intersection lineations and elongation lineations in the Rapid Bay-Second Valley area (Mancktelow's Zone A). From Mancktelow (1981).



Mancktelow (1979) describes the consequences of this rotation including the possibility of two minor folds on the same limb of a major fold displaying opposing vergences. Evans (1986) further elaborates on Mancktelow's original observation by illustrating the possibility of sheath fold formation, which could produce the same opposing vergences on the same limb of a fold. Plates 3a, 3b & 3c show a structure found in the mapping area, in the creek immediately north of Stockyard Creek (location 11, appendix A) which appears to be a small scale sheath fold such as that described by Evans (1986). Another locally developed cleavage S_2, (oriented 40° towards 230°) approximately axial planar to the second fold axis (F_2) appears to have developed at this locality, and is measurable up to 100 metres to the west (location 13) (see appendix A). Between locations 11 and 13, the two cleavages are equally as well developed, creating a spectacular "pencil cleavage" within the Carrickalinga Head Formation. This S_2 is only developed in this small area, which has been mapped as the closure of the major anticline of the Mount Rapid Folded Zone.

4 Three Dimensional Computer Modelling

It has always been an inherent problem in the mapping of geological structures that the structures mapped are three dimensional, whereas the completed map of geological structures is limited to two dimensions. It is therefore sometimes difficult for information to be conveyed accurately from the author of the map to the reader. Methods such as the use of structural mapping symbols, and the construction of cross sections and profile sections can be used to help the reader visualise the map in three dimensions.

A cross section and a profile section have been produced for the mapped area, (see chapter 2) however due to the complex nature of the structural geometry of the region, it is still difficult to visualise the area in three dimensions. It is for this reason that a computer generated model has been constructed, representing a portion of the mapped area in three dimensions. This method has the advantage of allowing the user to view the model from any angle, either above, below, or even within the model. In addition, sections and block diagrams can be produced quickly and simply by creating slices through the model in any orientation required.

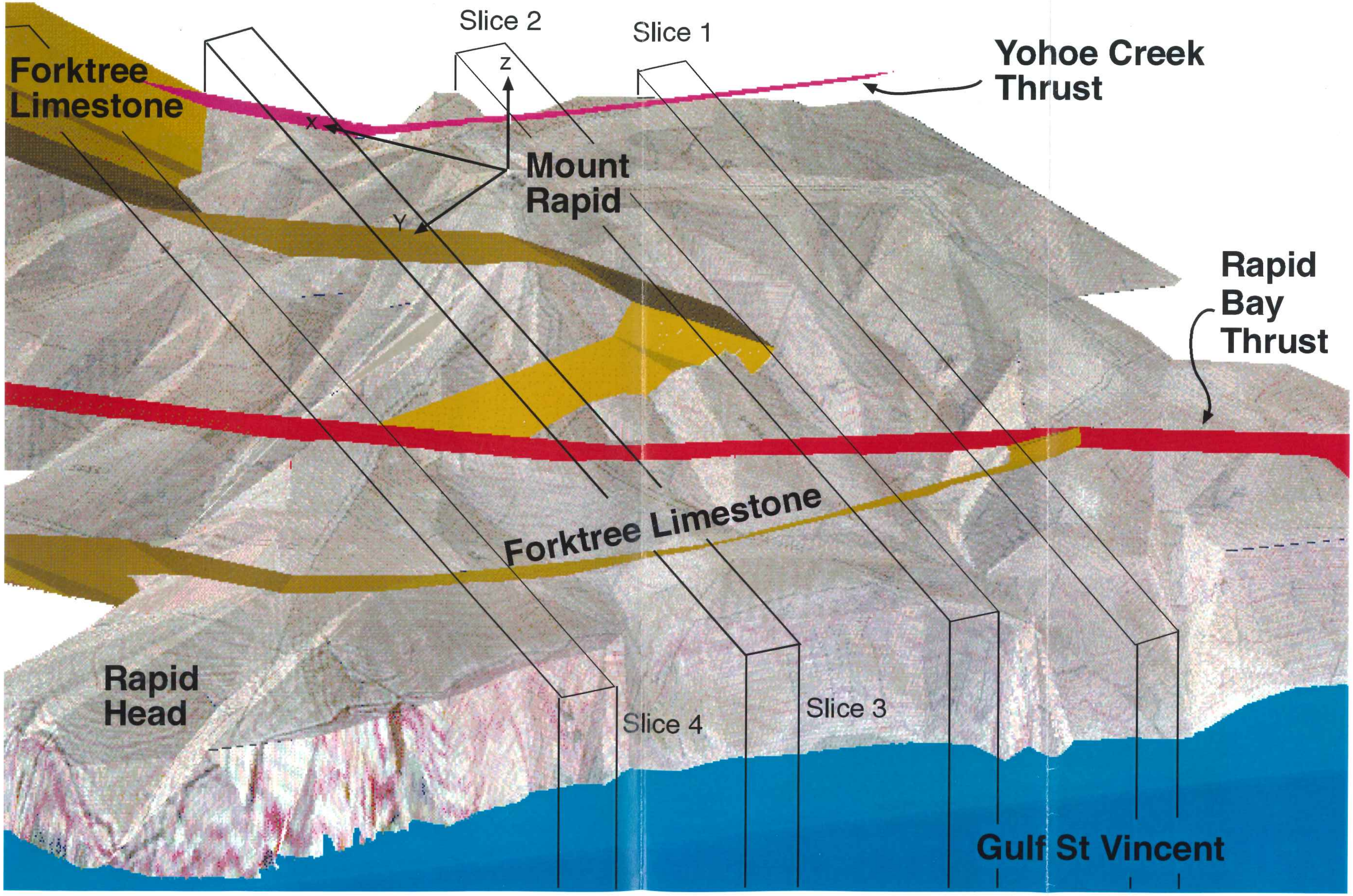
4.2 Methods of Modelling

The equipment used in the construction of this three dimensional model includes one Silicon Graphics Indigo 2 computer, running the Vulcan package of mapping software, which is produced by Maptek™. The computer program Envisage is the core of the Vulcan package, allowing the use of Vulcan's many individual programs.

A geological map, a cross section, and a profile section (See chapter 2.4) were prepared prior to construction of the three dimensional model, and provide the basis for this model. All of these conventional methods of representation were produced firstly by hand, and then scanned into computer format using a colour scanner, and a Macintosh 8100 Power PC running the Adobe Photoshop 3.0 and Aldus Freehand 5.0 software. These diagrams were then converted to a format that could be read by the Silicon Graphics machine, and recognised by Envisage.

Within the Envisage program, the map, cross section and profile section were positioned in their correct orientation, and used as underlays, guiding the construction of the model. An orthophoto map was also used to reproduce the topography of the region, which is very important in this area due to the steepness of the topography and significant relief. The orthophoto map was then draped over the topological surface, in order to better represent the true appearance of the landscape. The contours of the orthophoto map should theoretically be parallel to each other on the modelled topography surface, however because the topography

Figure 4.1 Computer generated model of the Mount Rapid/ Rapid Head Area



Northeast Southwest

surface was built based on a contour interval of 50 meters, slight variations of topography are not shown, resulting in the contours being distorted in some areas.

Lines, polygons and arcs were then constructed over the underlays, in order to represent the two thrust faults and various folded stratigraphy. The resulting model is illustrated from various points of view in figures 4.1, 4.2 & 4.3.

4.3 Results of modelling

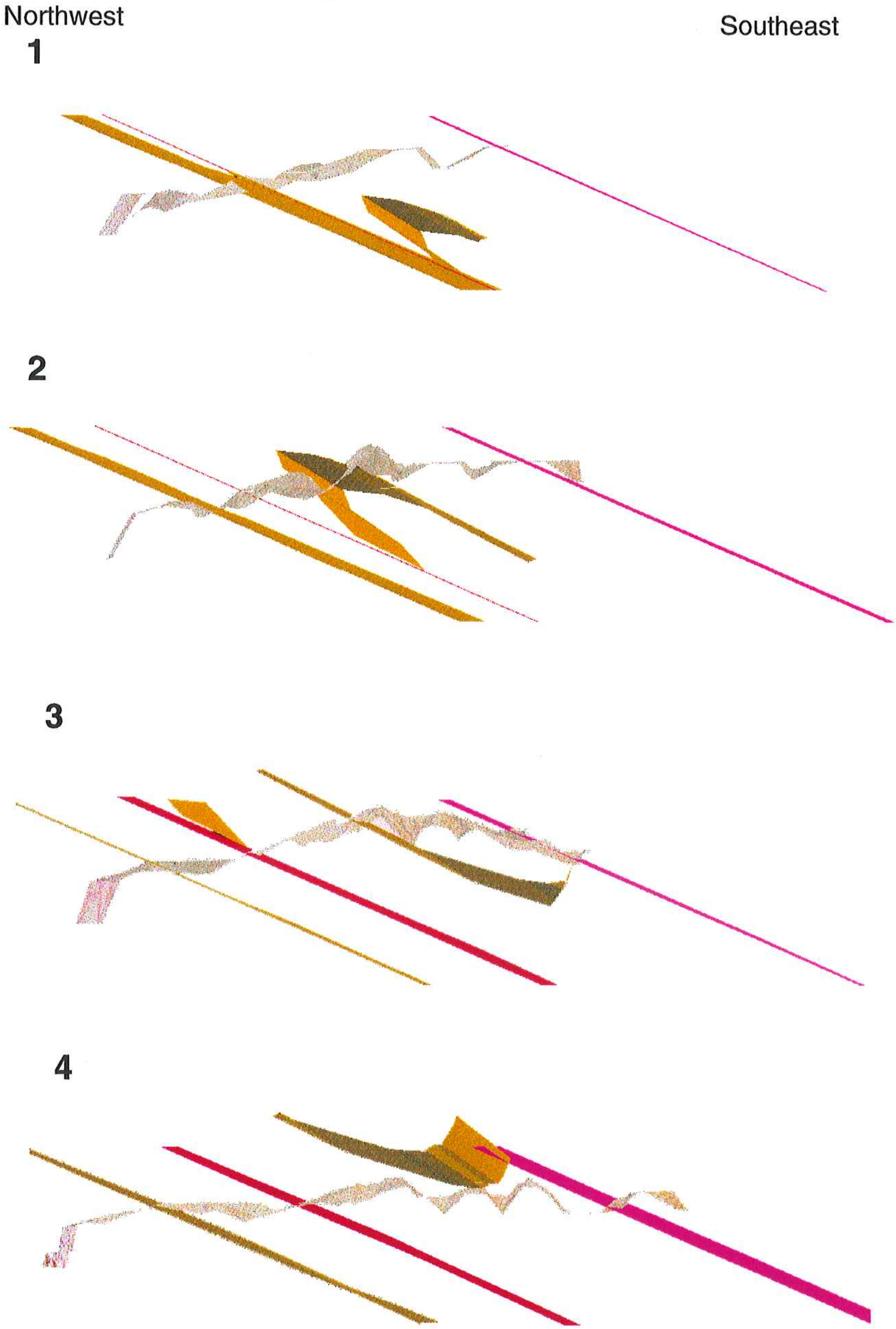
The model produced is best viewed on the computer screen, for several reasons. The Silicon Graphics Indigo 2 computer, which was used, has been specifically designed to display three dimensional graphics, and as such the resolution of the image produced on the screen is far superior to the resolution which most colour printers are capable of. This contributes to the viewer being able to perceive the third dimension of the model more easily on the screen than on paper. Changing the angle which the model is viewed at can be done in real time, allowing the viewer to rotate the model, pick a point from which to view the model, choose a path for the computer to "walk" within the model or even to "fly" in and around the model. Close up views can also be made using zoom tools, as can changes of vertical exaggeration.

One limitation of a solid three dimensional model is that because the objects are solid, they can obscure the view of other objects. This problem can be overcome by three different methods. An object such as the local topography, which prevents the viewer from seeing the geology underground, can be changed to a "wire frame" object, effectively making the surface translucent. This allows the viewer to keep track of where the ground surface is, while still allowing the sub surface to be viewed. Slices, which are effectively equivalent to cross sections, can be made with ease, allowing the user to view a limited part of the model (see figures 4.2.1 to 4.2.4).

Figure 4.1 shows the model, viewed from northwest of Rapid Head, looking towards the southeast. This is a view slightly oblique to looking down the plunge of the region's folds, which are represented by the trace of the outer surface of the Forktree Limestone. This marker bed is projecting outward from the page, and has a negligible thickness. If the model were viewed directly down the plunge of the folds, the Forktree Limestone would have no thickness.

The importance of topography when mapping shallowly dipping structures is illustrated by the contact between the Forktree Limestone trace and the topographic surface, southwest of the Rapid Bay Thrust. This contact is undulating, and when viewed from above would appear as a wavy line rather than a straight line. A good example of this in Map 1, is shown by the way in which the Rapid Bay Thrust appears to deviate markedly at Rapid bay, due to a severe change in topography along the trend of the Thrust. This allows the inclusion of a reasonably large outcrop

Figure 4.2 Slices through the computergenerated model of the Rapid Head-Mount Rapid area.



of Forktree Limestone (within Quaternary cover) to be included in the Rapid Head Sheared Zone.

Figures 4.2.1 through 4.2.4 show vertical slices through the model, looking towards the northeast. The positions of these slices are indicated on figure 4.1. Each slice has a thickness of 100 meters, and is viewed at an angle slightly oblique to the regional strike of bedding and cleavage (see map 3). The reason for presenting this view again is that the structures would not be properly represented if they were viewed perpendicular to strike.

Folding of the Forktree Limestone, in both the hangingwall and footwall of the Rapid Bay Thrust is well represented in figure 4.2.1, and figure 4.2.2. In figure 4.2.3, no folding is visible , and the trace of the Rapid Bay and Yohoe Creek thrusts and the Forktree Limestone are near parallel. Figure 4.2.4 shows a syncline in the Forktree Limestone in the footwall of the Yohoe Creek Thrust. The folding within the Forktree Limestone, between the two thrusts, is a representation of the Mount Rapid Anticline Syncline Pair, which was discussed in chapter 2.3.

Figure 2.3 shows a slice taken through the model, perpendicular to the plunge of the Mount Rapid Anticline Syncline Pair. The trace of the Forktree Limestone in this figure is directly comparable to the profile section (figure 2.2b) which was discussed in chapter 2.4.

4.4 Discussion of modelling

Because this model is based on the profile and cross sections discussed in chapter 2.4, it must be stressed that this is only one interpretation of the subsurface geology. The assumptions have been made that the folds are cylindrical, and that the fault surfaces maintain the same orientation at depth as they do at the surface. The model is also very simplified in that it does not take into account the possibility of a décollement surface at depth, which would be expected in areas which have deformed via methods of thin skinned tectonics.

The Vulcan modelling package is extremely powerful in the way it allows the user to display and interpret a map area in three dimensions. It is however limited by the significant time taken in learning how to operate it. This model was constructed over several months. However, the length of time spent constructing the model was minimal compared to the time spent learning to use the software. A detailed description of how the model was made has been included in appendix B, in the hope that subsequent users may benefit from the experience gained in installing and using the software for this project.

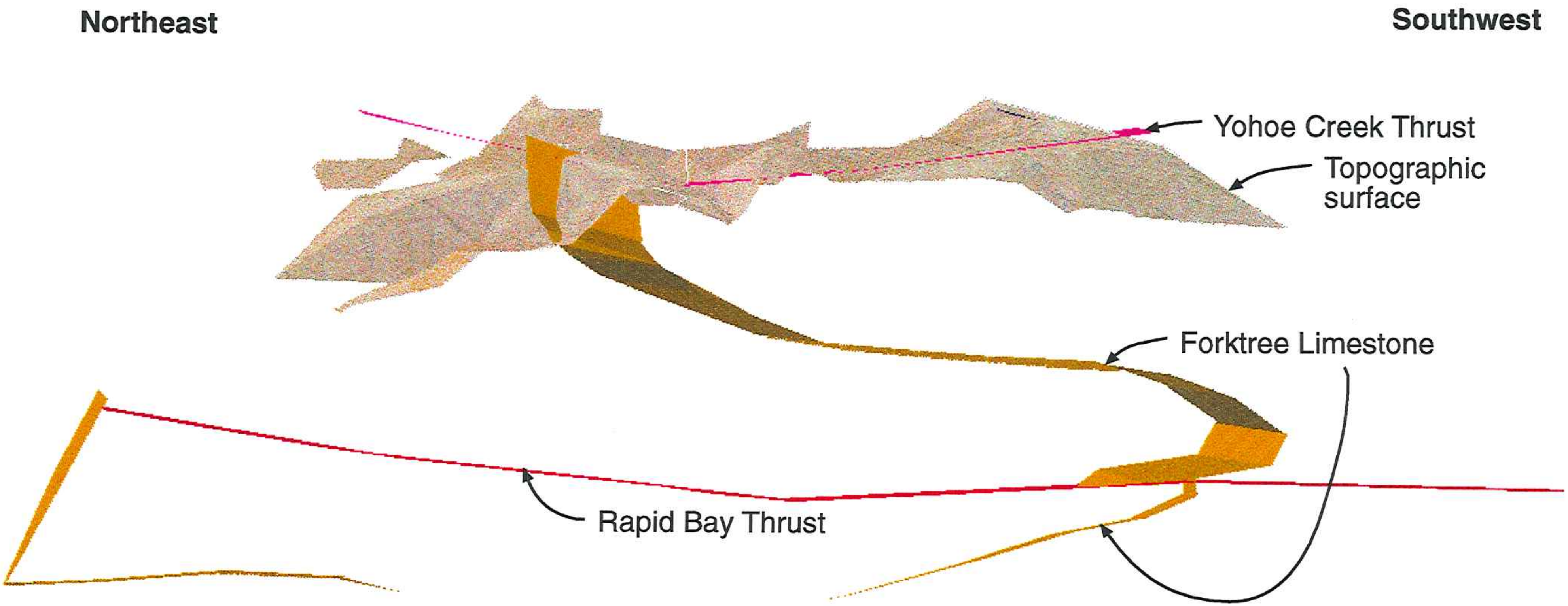
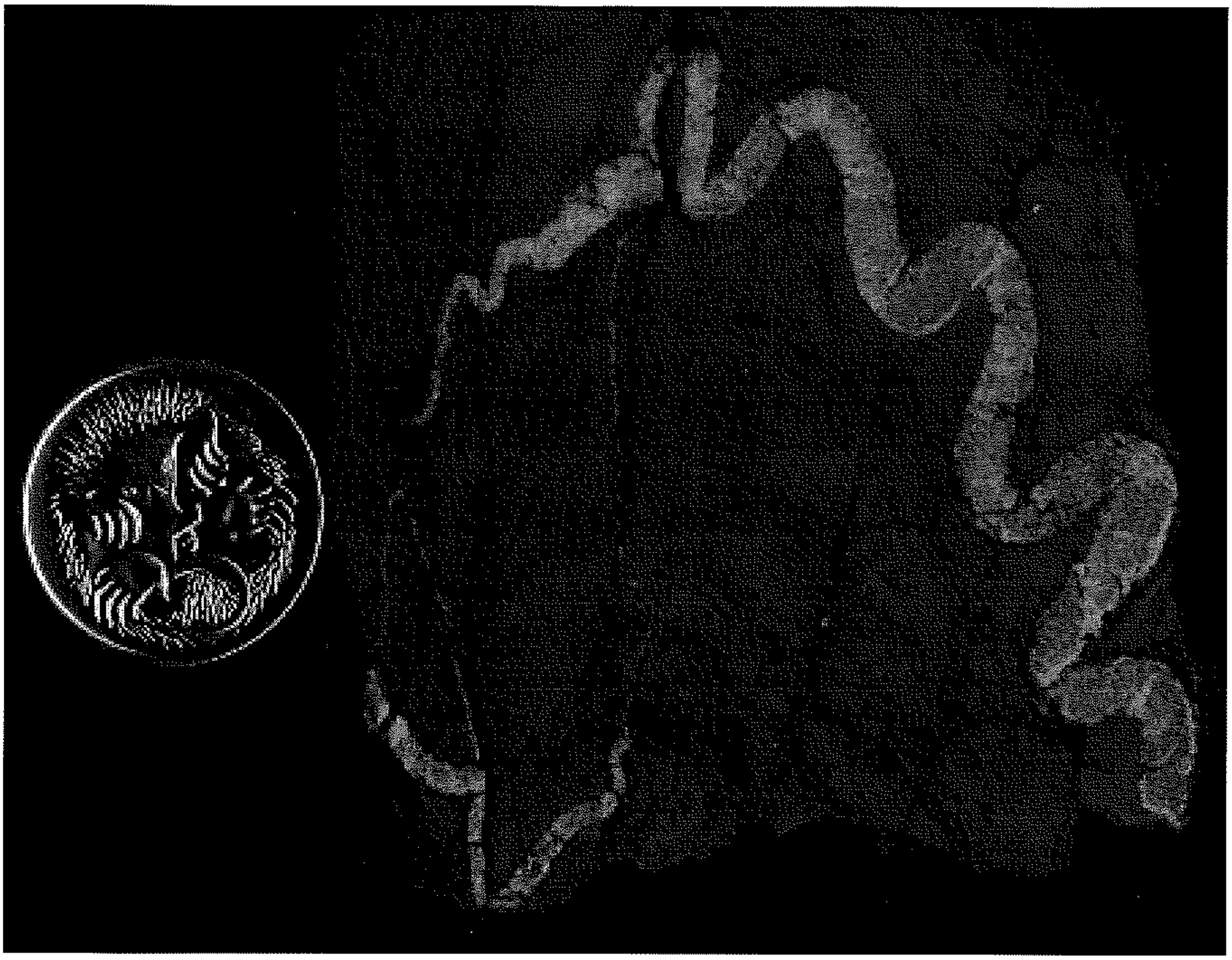
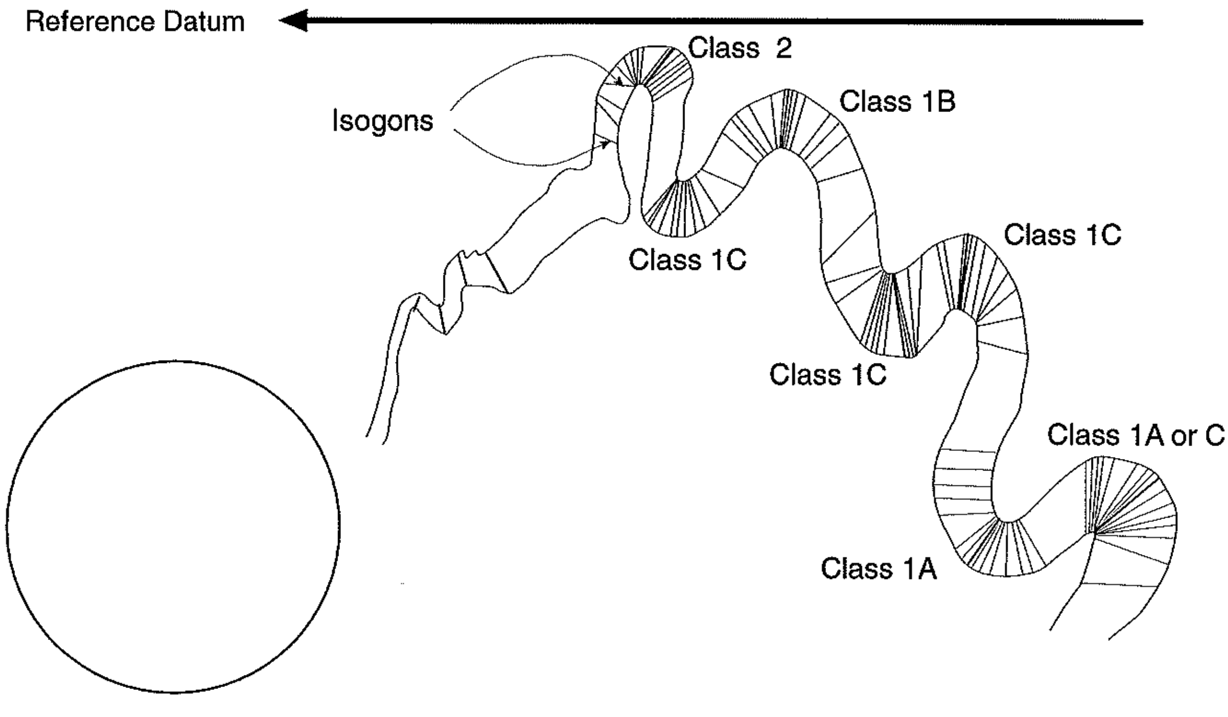


Figure 4.3 Profile slice through thecomputer generated model, looking down the plunge of the regional fold axes. Note that this figure is directly comparable to southwestern part of profile B-B' in chapter 2.4 (figure 2.4b)

Figure 5.1 Fold classification on a ptygmatically folded calcite vein using the dip isogon method. Classification is based on the patterns which the isogons make, e.g. convergent, divergent, or parallel in the sense of tracing the isogons from the outer to inner arc.





5 Quantitative Strain Analysis

Introduction

Strain analysis in the Rapid Bay-Second Valley area was undertaken using methods which involved the analysis of folded layers. Traditional methods such as analysis of deformed conglomerates and ellipsoidal objects was not possible due to the lack of relevant samples. Some conglomerate samples were found, however further analysis revealed that little deformation of the clasts had occurred due to the nature of the materials involved. These samples consisted of quartz clasts within a limestone matrix, the clasts of which deform very little due to their high competence contrast with the surrounding limestone matrix.

5.1 Fold Classification

Classification of folds which were observed in the area was carried out firstly using the dip isogon method described by Ramsay and Huber (1987). A dip isogon is a line joining points of equal dip on adjacent boundaries of the folded layer. The patterns which dip isogons make gives an indication of the rate of curvature of the outer surface of the layer, compared to the rate of curvature of the inner surface. These patterns can then be used to give a qualitative classification for the fold (see figure 5.1).

Layer thickness variations of the folds were then considered in order to establish a classification for the folds under the scheme devised by Ramsay (1967). The method is based on a description of the changes in layer thickness (t_α) with angle of dip (α), these measurements being expressed as a proportion of the layer thickness (t'_α) at the fold hinge (Ramsay & Huber, 1987). Figure 5.2 defines the parameters α, t_α, t_0, ϕ which are referred to extensively throughout this chapter.

Figure 5.2 Sketch of an idealised fold, defining the parameters α, $t\alpha$, to, and ϕ.

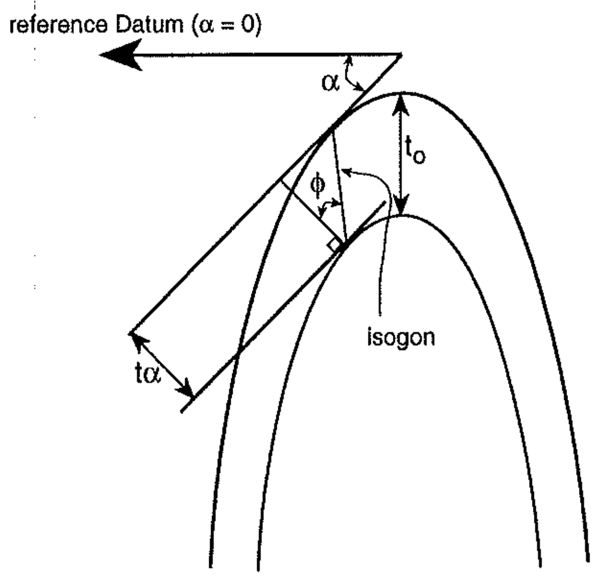
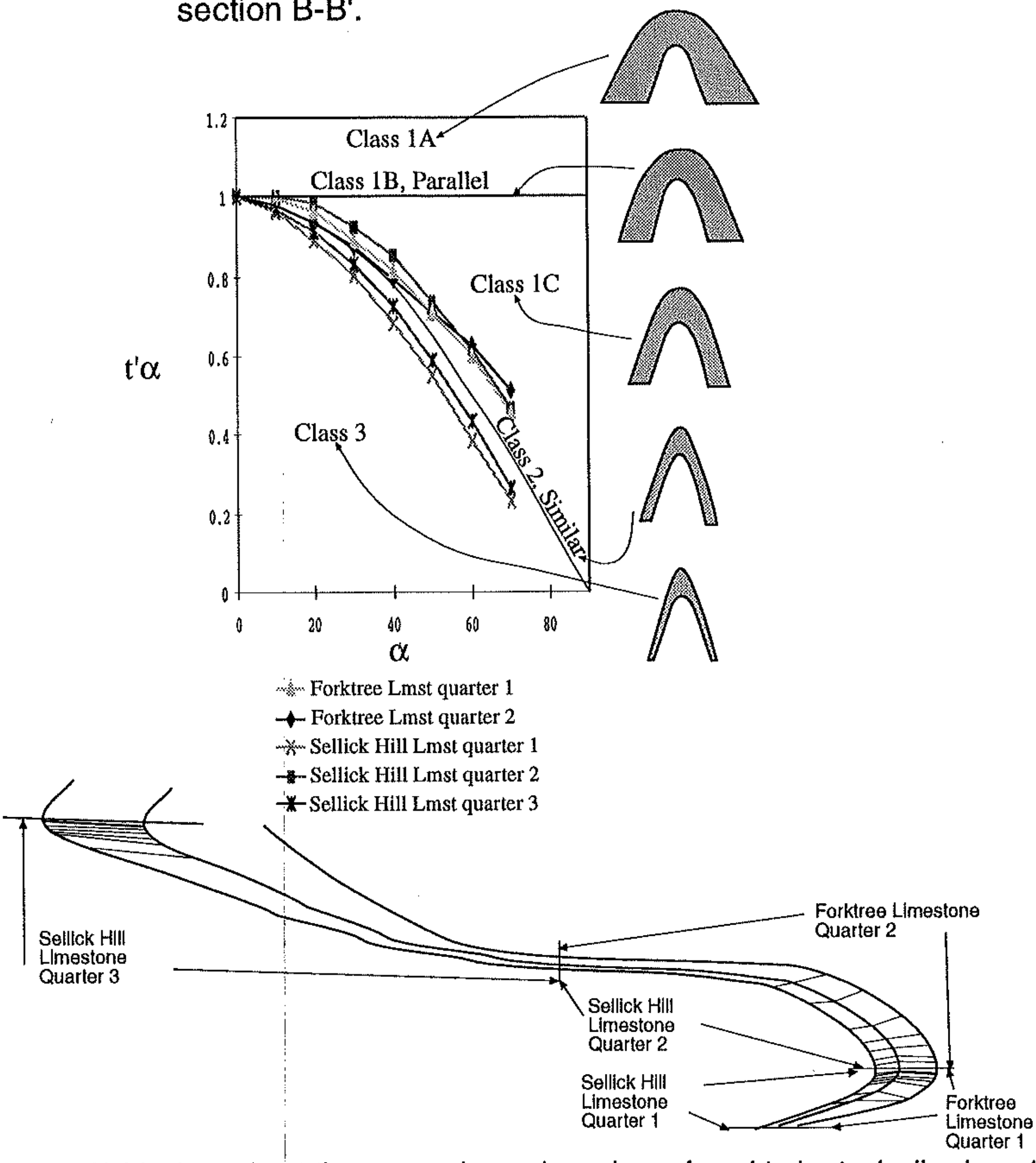


Figure 5.2 shows the method for determination of orthogonal layer thickness (t_α) at angle of dip α, on an idealised fold trace. The standardised orthogonal thickness (t'_α) was then obtained for each value of α, using the trigonometric relationship $t'_\alpha = t_\alpha / t_o$, where t_o is the thickness of the layer at the hinge line. A plot of α vs t'_α can then be constructed and compared to a template in order to determine the class of the fold. This method is superior to the dip isogon classification method in that it gives a quantitative description of the fold.

Figure 5.4 illustrates the α vs $t'\alpha$ curves for a portion of the profile section B-B' (see figure 2.2b and chapter 2.5) which was constructed perpendicular to the plunge of the folds in the MRFZ. From this diagram it can be deduced that whilst the Sellick Hill limestone in quarter one (SH1), and the Sellick Hill limestone in quarter three (SH3) are both of fold type class 3, limb thinning of SH3 is greater.

Figure 5.3 α vs t'α plots for a part of the profile section B-B'.

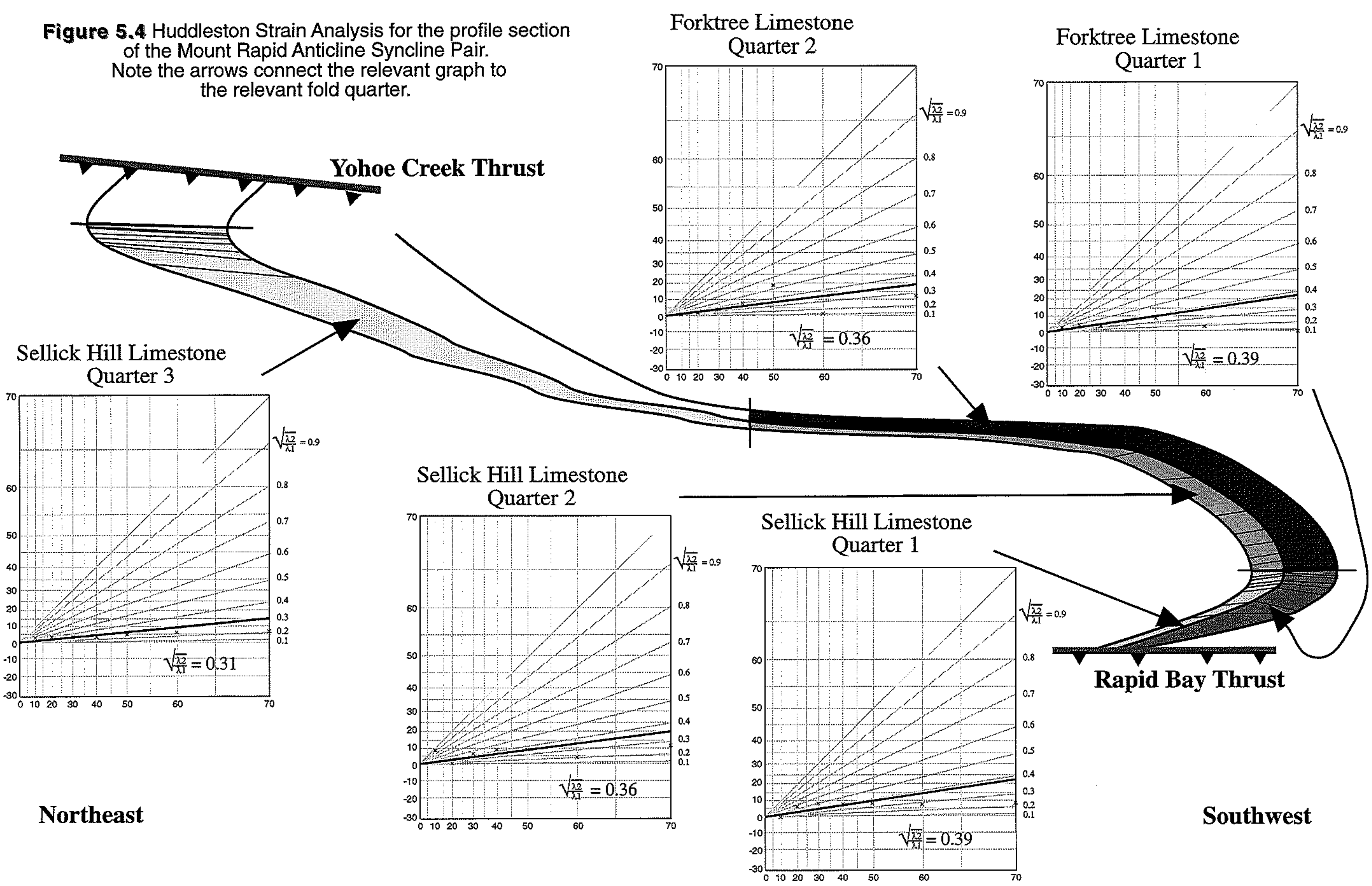


Folds throughout the mapped area have been found to be typically class 1c to class 3 after Ramsay & Huber (1987).

5.2Hudleston Strain Analysis

The method of strain analysis from folded surfaces described by Hudleston (1972) is a graphical method to determine the apparent X/Z strain ratio of the finite strain ellipsoid. This method makes use of the parameter f which is defined as the angle between the dip isogon and the normal of parallel tangents to the inner and outer arc of the folded surface at dip angle a (see figure 5.2). The relationship α–ϕ versus a is then plotted on a logarithmic chart and given a best fit line. This line is then compared to a mathematically derived set of lines to give the apparent strain ratio $\sqrt{\lambda 2}/\sqrt{\lambda 1}$ (Z/X apparent reciprocal strain ratio) (see figure 5.4).

Figure 5.4 Huddleston Strain Analysis for the profile section of the Mount Rapid Anticline Syncline Pair. Note the arrows connect the relevant graph to the relevant fold quarter.



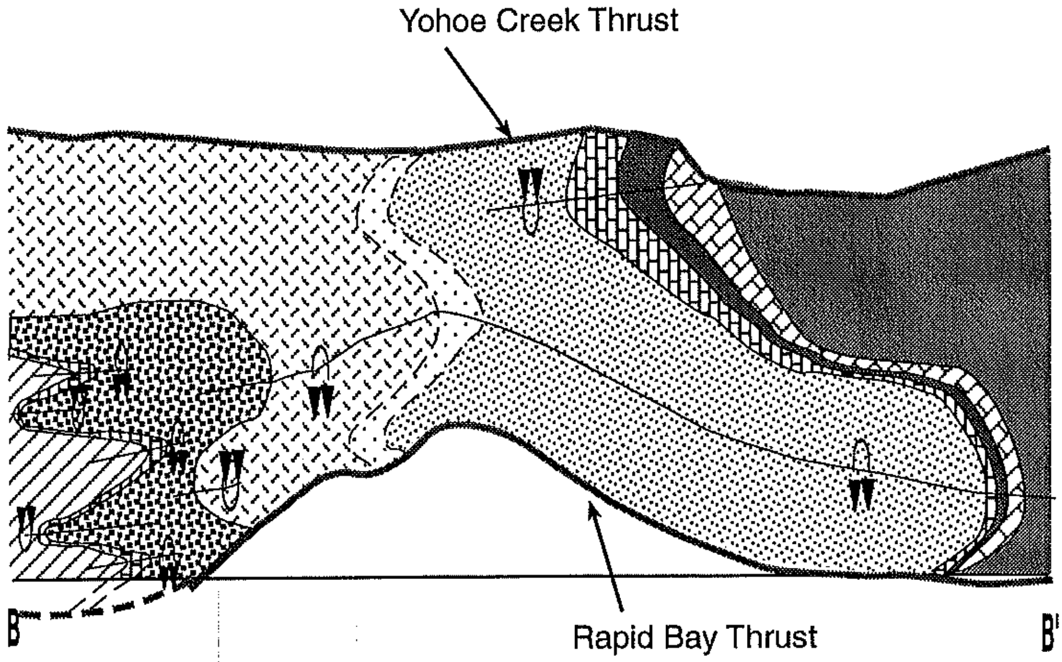
The method assumes that the folds were initially class 1b, and have been subjected to a bulk flattening strain under homogeneous, pure shear conditions. It seems likely that where the ductility contrast is low an actively folding layer will deform by a combination of a buckling and flattening process (Hudleston, 1972). The method used in this chapter is however useful in describing the relative variation in magnitude of strain in the X and Z directions of the finite strain ellipsoid.

The Hudleston method has been applied to the Sellick Hill Limestone and Forktree Limestone in the profile section (fig 2.4b) of the Mount Rapid Folded Zone. This has been done in an effort to restore this profile section.

The results of the Hudleston method of strain analysis are displayed in figure 5.4. The two adjacent folded layers of the Sellick Hill Limestone and the Forktree Limestone have been analysed for each quarter wavelength (between the hinge line and the point of inflection on the limbs). Though the best fit line for each quarter was obtained from data which fluctuates greatly, the fact that the apparent strain ratios obtained for each of these quarter wavelengths are very consistent gives some indication that the values may be valid. The resultant Z/X reciprocal strain ratios were then averaged to give an overall apparent strain ratio of 0.362 (equivalent to X : Y : Z = 1.66 : 1 : 0.602) for the Mount Rapid Folded Zone.

An equal area "unflattening" of the Mount Rapid Anticline Syncline Pair was then done by first constructing a strain grid with the dimensions of the apparent strain ratio over the Mount Rapid Folded Zone. Restoration was then done by restoring the strain grid to dimensions of equal length in the X and Z directions. The resultant unflattened profile is shown in figure 5.5.

Figure 5.5 Unflattened profile section B-B'.



5.3 Shortening

A line length shortening was then calculated for the Mount Rapid Anticline Syncline Pair, giving a value of 76 % shortening. This value is directly comparable to a value of 62% shortening obtained from line length methods on a buckled vein (figure 5.1) which was found within the Mount Rapid Folded zone. This buckled vein has apparently not been subjected to the flattening which the MRASP has experienced, either due to its emplacement after flattening, or its high competency contrast with surrounding lithologies.

With the effects of both flattening and shortening now both having a quantitative value, it is then possible to restore the profile to the undeformed state (see chapter 6.1).

6.1 Construction of Cross and Profile Sections

Mancktelow (1981) recognised the difficulty associated with structural mapping of the area due to the lack of sedimentary younging features, the indistinct lithologies and tendencies of small scale folds to display opposing vergences on the same limb of a major fold. Restoration of the cross and profile sections which are discussed in chapter 2.4 is difficult in the Rapid Bay-Second Valley area for the same reasons. This is also due to the reclined nature of the folds in the region, and the similar orientations of all fabrics. Analysis of apparent strain ratios and shortening values for the folds in profile section B-B' does however allow a schematic restoration of this section.

Two possible scenarios are suggested of the deformational history of the Mount Rapid Folded Zone (see figures 6.1.a & b). Figure 6.1a is a cartoon describing the first scenario, which consists of bedding being oriented oblique to the maximum compressive stress prior to the D1 Delamerian Orogeny. During D1, an oblique wrenching component of stress best explains how bedding reached the deformed state which exists at present.

An alternative scenario is illustrated in figure 6.1b, whereby the bedding was originally oriented parallel to the maximum compressive stress. No wrenching component is necessary in this scenario to reach the buckled state, and homogeneous strain would also be created perpendicular to the direction of maximum compressive stress, giving the necessary conditions for flattening of the folds.

Neither of these scenarios explains sufficiently the way in which originally horizontal bedding has become tilted prior to folding. The former scenario is favoured to explain the tilted bedding because the wrenching component involved in the deformation could have previously caused the beds to become tilted. Alternatively, tilting of the beds may have occurred simultaneous to deformation.

6.2 Extension Prior to D1

Jenkins (1990) described the evolution of the Adelaide Fold Belt as consisting of a cyclical lithospheric extension and thermal sag prior to D1. He suggests that the deposition of the Heatherdale Shale and the Carrickalinga Head Formation mark the beginning of the compressional phase of the formation of the Fold Belt. In the south, transition to a euxinic shale facies (Heatherdale Shale) and a thick turbidite succession (Carrickalinga Head Formation) are suggested to mark a renewed lithospheric attenuation. He also suggests that this is further substantiated by the close association of the Truro Volcanics with Early Cambrian sediments in the northwestern part of the Kanmantoo Trough.

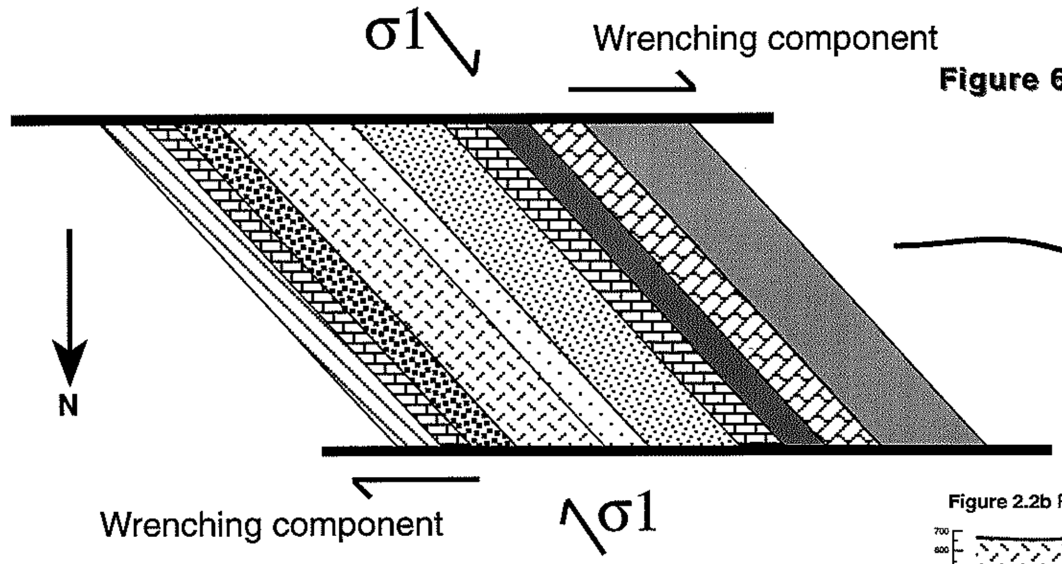
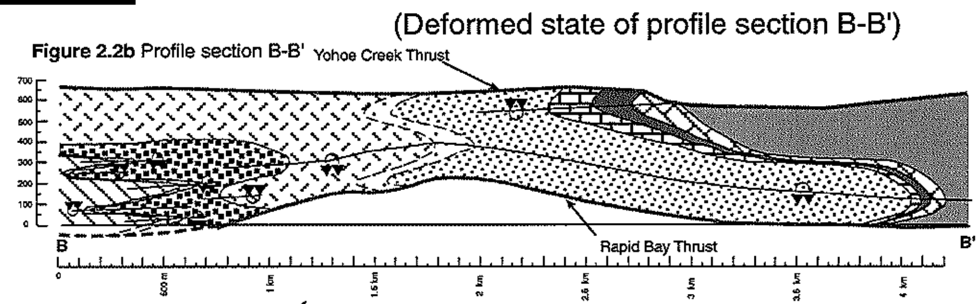


Figure 6.1a First scenario for the formation of the profile section B-B'. A wrenching component of stress is involved in the deformation of beds, originally dipping towards the southwest.



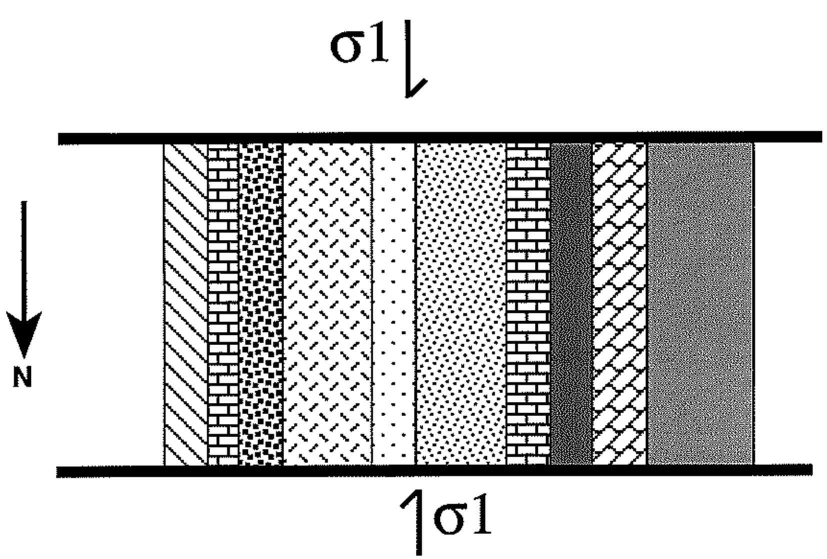


Figure 6.1b Second scenario for the formation of the profile section B-B'. A maximum compressive stress (σ1) is applied in a direction parallel to beds which are originally dipping towards the west.

Rogers (1991) noted a general thinning of these lithologies towards the west and a sharp change in thickness of the Talisker Calc-Siltstone across reverse faults in the Talisker area. He suggested that this change in thickness could be due to listric extensional faults being generated during extensional basin formation.

In the Rapid Bay-Second Valley area, the Heatherdale Shale outcrops as a thinned unit on the overturned limb of the Rapid Head anticline, and has been tectonically thickened in the core of the Rapid Head Syncline. The unit is however absent from the remainder of the mapped area, resulting in the Carrickalinga Head Formation lying apparently unconformably above the Forktree Limestone.

Two main arguments have been proposed as to the nature of the contact between the Normanville and Kanmantoo Groups. The contact has been described by Daily (1963), and Gatehouse *et al.* (1990) as being conformable, although Campana and Horwitz (1956) had previously described it as a tectonic unconformity. Jenkins and Sandiford (1992) described the contact as erosional while Jago *et al.* (1994) have described the contact as an unconformity with marked vertical relief, indicating a preserved sedimentary contact and erosional surface.

The contact between the Normanville and Kanmantoo groups is mostly unconformable in the Rapid Bay-Second Valley area, however very few of the contacts observed show signs of tectonic involvement. The favoured explanation for the sparse outcrop of Heatherdale Shale in the study area is therefore that of Jenkins and Sandiford (1992) & Jago et al. (1994), this explanation being that the contact between the Heatherdale Shale and the Carrickalinga Head Formation is erosional. It is further suggested that in places, this erosion has cut through the Heatherdale Shale and begun to erode the Forktree Limestone.

6.3 Conclusions

The Rapid Bay-Second Valley area has been subjected to one major deformational event, the Late Cambrian-Early Ordovician Delamerian Orogeny. This event has resulted in the formation of tight reclined folds which plunge shallowly southeast, a prominent northwest-southeast trending foliation, and up to 76% crustal shortening. The formation of shallowly dipping, east over west verging thrust faults have also formed either post, or more likely syn folding.

The existence of reclined folds in this area is anomalous to surrounding areas in the Southern Adelaide Fold Thrust Belt. Mancktelow (1981) suggests that based on experimental work by Sanderson (1973), these reclined folds may have formed due to a continued maximum compressive stress in one direction. This suggestion assumes that the fold axes were originally oriented oblique to the maximum compressive stress. This scenario seems plausible, and can also explain how minor fold axes can display opposing vergences on the same limb of a major fold. The presence of a small scale sheath fold in the study area gives evidence that complex methods of folding have occurred in the area.

The position of the area on the inner section of the Fleurieu Arc could be the reason why complex folding has occurred in the area. Mancktelow (1981) also suggests this as a possible reason for the near parallel nature of mineral and intersection lineations in the area. An alternative reason for the parallelism of these lineations could be their close proximity to the Gawler Craton, compared with the outer section of the Fleurieu Arc. Mancktelow (1979) recognised the mineral lineation invariably becomes shallower across the fold belt in the direction of the Gawler Craton, and the parallel nature of the two lineations could be due to this.

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My sincere thanks must firstly go to my supervisor Dr. Pat James, without whom this year would not have been possible, in more ways than one. Special thanks also to Thomas Flöttman and Peter Haines for assistance in field work. Most of all I would like to thank all of my fellow honours students, and in particular my fellow structuralists Andrew, Danny, Dave and Rebekah. Thank you to all of the staff that I've hassled throughout the year, Fran Parker, Gerald Buttfield, Sophie, and John Willoughby to name just a few. Sherry Proferes deserves a special mention, as do Geoff, Rick and Murray for the endless help they have provided in drafting of maps, cutting of thin sections and getting the computers to do what I wanted them to. Thank you also to Steve Sullivan and all the people at Maptek for their technical support with the Vulcan software.

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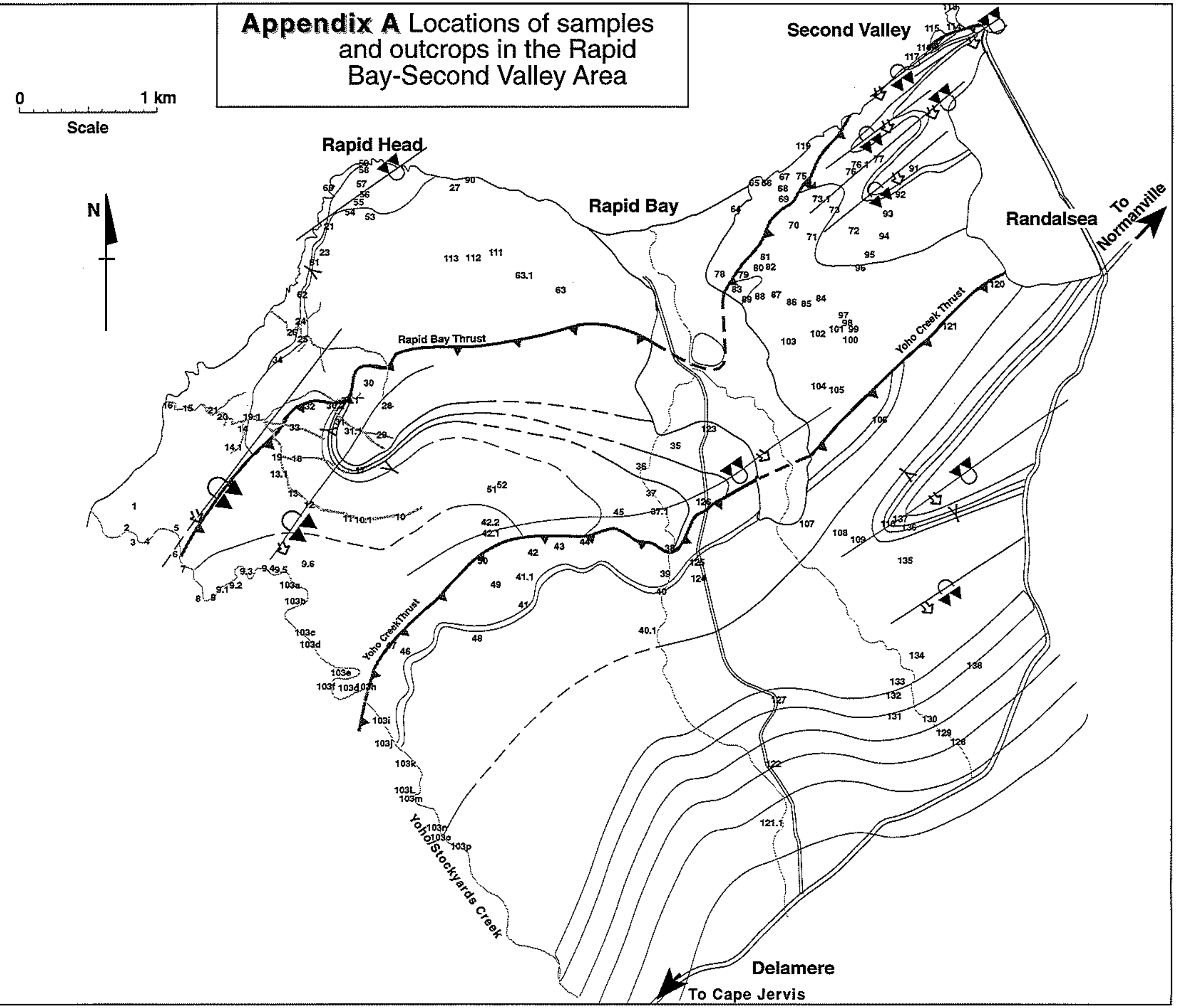
Appendix A Locations of samples and outcrops in the Rapid Bay-Second Valley Area



Appendix B

See Vulcan manual "creating a DG1 file" to get started.

Creating a three dimensional computer model

Images such as maps and cross sections which have been created by hand are first scanned into computer the computer using a standard scanner. A "ScanMaker 600ZS" connected to a Macintosh power PC 8100 was used to scan the relevant images in this example. When saving these images, the "gif" picture format should be chosen, as this format is readable by most computer types. The shareware program Fetch 2.1.2 is then used to transfer the file from the Macintosh computer to the Silicon Graphics Indigo 2 (SGI2) computer.

Once the gif image has been imported to the SGI2, it must be converted to a Pexel format which can be used by the Vulcan software. This can be done using the command gif_to_pexel {filename1.gif} {filename2.pexel} in the Unix environment . Alternatively, an option called "convert" within envisage under the "files" menu will perform the same operation.

A triangulation should then be created in the envisage environment, which closely approximates the actual shape of the image. (i.e. for an A4 map the triangulation should be rectangular. This operation is performed by firstly creating an outline of the surface by selecting the "create" option under the "design" menu. It is sufficient to create two parallel lines on any two opposing sides of the rectangle, however a rectangular polygon was constructed for the model shown in figure 1. The program will then ask for a "layer" to be allocated in which the resulting object will be placed. An appropriate name for the layer should be given at this prompt (the name "underlay" has been allocated for the Rapid Bay model).

Once the bounding object has been drawn, a triangulation surface should then be created, using the "triangulate surface" option under the "modelling" menu. The program will then ask for a name to be given to the triangulation, and give a range of other options. The user should give the triangulation a name, select a colour for the triangulation, and make sure the "triangulate in plane view" option is selected. The program will then ask the user to select by either object, group layer or feature. Making a selection by object is the easiest option, and the previously created object (the bounding polygon) should be selected. Pressing the right hand mouse button once the object has been selected will create the triangulation.

A pexel image can now be draped over the triangulated surface. Selecting the "pexel control points" option under the "design" menu will cause the computer to prompt for a pexel file. The name of the pexel file which was created earlier should be entered. The computer will then ask the user to select the lower left hand corner and the upper right hand corner to define the extent of the pexel image. If the image does not appear after the extent has been defined, make sure that both the "solid shading" and "textured surface" icons (on the left side of the screen) are turned on. The computer will now ask the user to "indicate the world coordinate", which should be done by clicking a point on the triangulation surface. The computer will then ask the user to "indicate pexel coordinate", which should be done by clicking on a point on the pexel image which the user wants mapped onto the world coordinate (previously picked) on the triangulation. This process must be repeated at least three times, however the accuracy of draping of the image onto the triangulation will be improved by a greater number of control points indicated.

The triangulation should now be removed ("remove" under menu "modelling") and reselected ("Triangulation utility", "list" under "modelling"). When prompted to select a colour for the triangulation, the option to "use texture resource" should be selected, and the name of the pexel file entered in the space provided. When the triangulation is loaded now, the image should appear "draped" over this triangulation. This draping process can be done on any triangulation, even an uneven, undulating surface such as modelled topography. An orthophoto map has been draped over the modelled topography for the Rapid Bay model.

This process can be repeated as many times as necessary, for as many maps, or cross sections as required. Lines, polygons, arcs and splines can then be constructed, using the images as a base, to represent the features of the images in three dimensions. Triangulation surfaces or solid triangulations can then be produced by linking these objects (lines, polygons etc.).