Chapter 4

Structural setting of the Taemas Vein Swarm

4.1 Introduction

The temporal, geometrical and textural characteristics of folds, faults and veins are indicative of the physical processes and sequence of events which occur during crustal deformation. In this chapter, the Silurian and Devonian age stratigraphy of the Taemas area is briefly described. The geometry and style of regional and local scale faults and folds are outlined, to provide a structural setting for the Taemas Vein Swarm (TVS; Figs. 1.1, 4.1).

The structural setting and internal fabric of bedding-concordant fault veins (hereafter called bedding-parallel veins, BPV), bedding-discordant fault veins, and extension veins are described. This information, and the background discussion of fracturing and folding previously presented in Chapter 2 is used to infer how crustal deformation and fluid flow are interrelated. This information provides a basis for interpreting the results of isotopic and trace element analyses, which are summarised in Chapter 5 and Chapter 6.

4.2 Stratigraphy

The following description of the stratigraphy in the Taemas area is summarised from Browne (1958), Cramsie et al. (1975) and Hood and Durney (2002), and is supplemented by the author’s own observations. An idealised stratigraphic column illustrating the thickness and relationships between units is shown in Figure 4.2. The Black Range Group is the lowermost stratigraphic unit exposed in the Taemas area. This includes the Mountain Creek Volcanics (MCV; forming the basement rocks for the field area), comprising rhyolite, andesite, dacite, agglomerate and tuff, which are brown-red in appearance, and crop out prominently. This is overlain by the Sugarloaf Creek Formation (SLC), formed of tuff, shale, tuffaceous siltstone, rhyolite and agglomerate (Cramsie et al., 1975).

The Black Range Group is conformably overlain by the Murrumbidgee Group. The oldest formation in this group is the Cavan Bluff Limestone (CBL), comprising
Figure 4.1: Simplified geological map of the Taemas Peninsula (modified from Cox, 2007), showing representative bedding orientations, and major outcrops documented in this thesis; Locality 1 eastern end of Shark’s Mouth Peninsula Figs. 4.9, 4.10, 4.14 (2) Kangaroo Flat, Figs. 4.4, 4.7, 4.8, 4.13, 4.16 (3) Fig. 4.11, (4) Shark’s Mouth Anticline, Fig. 4.19, (5) W of Shark’s Mouth Anticline Fig. 4.17, (6) Fig. 4.18. Map grid is Australian Geodetic Datum (1984).
thinnely bedded flaggy limestones, interbedded with shale. Near the top of the CBL, thin red sandstone beds occur as this unit becomes transitional into the Majurgong Formation (MJF). The MJF includes well-bedded brown, orange-brown and grey sandstone. Quartz-rich beds crop out prominently, while red and grey siltstones are less prominent. Interspersed limestone beds occur near both the top and bottom of the formation.

The MJF is conformably overlain by the Taemas Limestone (TLS). This comprises shaley limestones and prominently outcropping massive limestone. The basal member of the TLS is the Spirifer yassensis Limestone member (SYL), a highly fossiliferous, thinnely interbedded unit consisting of approximately 50% limestone and 50% shale. The Currajong Limestone member (CJL) is massive, grey limestone, which outcrops prominently in many locations around the Taemas Peninsula. The CJL separates the SYL from the Bloomfield Limestone member (BFL), which has a similar lithology and appearance to the SYL, comprising thinnely interbedded limestones and shaly limestones. Notably, the SYL and BFL both appear to have highly variable thickness over the Taemas Peninsula (tens of metres variation over several kilometres). Overlying the BFL is the Receptaculites Limestone member (RCP), a massive grey limestone with a similar appearance to the CJL. Fossils within the RCP are more silicified than fossils within the CJL. The Warroo Limestone member (WRL) overlies the RCP, and consists of thinnely interbedded limestone and shaly limestone, and becomes more massive towards the top of the unit. The Crinoidal Limestone member (CNL) is the uppermost unit of the Taemas Limestone. It is a massive, well-bedded limestone consisting of coarsely crystalline grey calcite, which locally is composed almost entirely of crinoid fragments (Browne 1958). The top of the TLS is capped by fine-grained tuffs.

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4.3.1 Regional and mapping scale

The field area is part of the Eastern Belt of the Lachlan Orogen (Glen 1992). The chief structure in the area is the Black Range Synclinorium, comprising a major fold triplet (Cramsie et al. 1975). The fold triplet includes the Wee Jasper Syncline, Narrangullen Anticline and Taemas Synclinorium (containing the Taemas Peninsula, Fig. [1.1]). All three folds have a predominant NNW-SSE trend and steep west-dipping axial surfaces (Cramsie et al. 1975; Hood and Durney 2002). Within the Taemas Synclinorium, many parasitic folds are developed (with wavelengths between 0.1–2 km). These structures are NNW-SSE trending. Folds within the Taemas Synclinorium sedimentary rocks (Murrumbidgee Group) are generally open to close, while the MCV are gently folded.

Both sides of the major fold triplet are downthrown against bounding faults. To the west lies the Long Plain Fault Zone, and to the east the Dingo Dell, Warroo and Deakin-Devil’s Pass Faults. Changes in thickness of some sedimentary units adjacent to these faults suggests that predecessors of these faults pre-date the Devonian sequence, and controlled the Early Devonian margins of the depositional basin (Durney 1984).
On the Taemas Peninsula (Fig. 4.1), the sedimentary sequence (Fig. 4.2) has been deformed into a series of upright, gently plunging (although a few folds locally have steep plunges), gentle to close folds (Fig. 4.3). Fold axes trend north-northwest-south-southeast and have vertical to steeply west-dipping axial surfaces (Fig. 4.3).

Figure 4.3 demonstrates that at the base of the sedimentary sequence (in the SLC formation and the underlying volcanic basement) bedding dips are low (typically < 20°), and bedding is gently folded, with fold wavelengths in the order of hundreds of metres to more than 1 km. Higher in the sequence, particularly in the CBL, SYL and BFL, close to tight folds occur, with shorter fold wavelengths (tens-to-hundreds of metres; see Figs. 4.3, 4.4). Bedding traces on steep hillsides show that folds become tighter with increasing stratigraphic height within the SYL. Surface traces of folds reveal cuspate folds within the BFL. The decrease in fold wavelength in the interbedded limestone-shale units (Spirifer yassensis Limestone and Bloomfield Limestones) compared to underlying and overlying units (Majurgong Formation and Receptaculites Limestone) indicates that localised bedding-decoupling is required to accommodate folding of the interbedded limestone-shale units (CBL, SYL and BFL).

Within the CJL, field measurements and aerial photos show that folds are usually broad, particularly when the CJL is relatively flat-lying. Higher in the sequence,
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in the RCP, the fold style is similar to the CJL, with broad, gentle to open, long wavelength folds developed.

Cleavage is strongly developed in the MJF, and shaley beds in the SYL and BFL. Within sandstone beds in the MJF, cleavage fans strongly around outcrop-scale folds, and is approximately orthogonal to bedding in these outcrops. This implies that layer-parallel shortening occurred early during fold growth, with subsequent buckling of bedding. In general, shale beds develop a strong penetrative slaty cleavage, while limestone beds have a weaker pressure-solution cleavage. Total strain, calculated by dividing lengths of bedding surfaces over a particular distance in cross section, is in the range of 20–50%. Given geological strain rates in the order of $10^{-14}$ s$^{-1}$ to $10^{-15}$ s$^{-1}$ (Pfiffner and Ramsay, 1982; Mueller et al., 2000), this would imply that folding occurred over a period of 0.5 Ma to 15 Ma.

Cliffs provide clean, well-exposed outcrop of quartz and calcite veins, particularly in the Cavan Bluff, Spirifer Yassensis, Currajong and Bloomfield Limestones. These outcrops are found in several locations (marked on Fig. 4.1). However, vein calcite is abundant as float over much of the Taemas peninsula, implying that veins are not limited to these cliff outcrops.

### 4.3.2 Outcrop scale

Calcite, quartz and (rare) fluorite are hosted in:

1. **Fault veins** - veins which cut across, and displace bedding along shear fractures.

2. **Bedding-parallel veins** - veins which are concordant to bedding and have evidence for shear such as laminations and slickenfibres.

3. **Extension veins** - veins which have no evidence for shear motion.

All three vein types are found in most outcrops, and are interrelated in various ways. The texture, orientation and timing relationships of veins with other rock structures allow the mechanism and cause(s) of vein formation to be inferred. In the following section, fault veins, bedding-parallel veins and extension veins are described, and examples of these veins are shown in a series of outcrop photographs and sketches.

The observations outlined below demonstrate that folding, faulting and vein formation are intimately related. Critically, dilation of various types during folding (e.g. saddle reefs, fracturing, decoupling between beds) creates space, allowing fluid infiltration and mineral precipitation. Figure 4.5 shows relationships between folds, faults and veins which are common in the Taemas Vein Swarm.

#### Fault veins

Fault veins crosscut and displace bedding, and are found in several outcrops. Fault veins are dominantly calcite, with minor quartz and rare fluorite. Massive and laminated textures are common, and are often found in the same fault (Fig. 4.6).

Fault veins may be broadly classified as:
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Figure 4.3: Cross sections constructed from field mapping, aerial photographs and pre-dawn infrared images, showing fold style in the Black Range and Murrumbidgee Groups. Note that fold wavelengths are longer (∼ km scale) in the Black Range Group, and rapidly decrease to wavelengths of 100 m or less in the Spirifer Yassensis and Bloomfield members of the Taemas Limestone. Equal area stereonet shows poles to bedding (circles) and cleavage (red squares) throughout the Taemas Peninsula. Poles to fold axes, indicated by red spots, show a NNW–SSE trend that is consistent throughout the peninsula, with a very gentle south plunge (green square is pole to best fit great circle).
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1. Bedding-discordant faults directly connected to bedding-parallel slip veins. These are found in a variety of settings, but are invariably closely linked to fold structures (Fig. 4.7).

2. Bedding-discordant faults which cut bedding, and are not obviously linked to bedding-parallel veins. Bedding-discordant fault veins cut through cleavage. Extension veins are common next to these faults.

3. Sub-vertical (apparently late) faults, with evidence for strike-slip movement.

Fault veins are commonly linked to bedding-parallel slip veins. Displaced marker beds and the size of dilational jogs indicates that the majority of fault veins have net slips in the order of centimetres (Figs. 4.8, 4.9). However, other faults have indeterminate displacements, which may be in the order of tens-of-metres (Fig. 4.10, Locality 1). Fault veins are variously connected to extension veins. Laminated textures are common within fault veins, and contain variably coloured calcite. Calcite mineralisation is thicker in dilational jogs, and on some faults is almost entirely localised in jogs. Slickenlines occur on the surface of laminations, and suggest almost pure dip-slip on some faults. Rare subvertical faults cut earlier formed veins. These subvertical faults have subhorizontal striations, which, in places, overprint earlier dip-slip striations. These strike-slip faults occur late in the deformation history.

A laminated bedding-discordant vein (~1–5 cm thick) is shown in Figure 4.7 (Locality 2, Fig. 4.1). The eastern terminus of this vein is significantly thickened (c. 30 cm) and has a triangular shape. The end of this zone is brecciated, and clasts are cemented by vein calcite. This zone of calcite mineralisation is associated with the development of a small (metre wavelength) recumbent fold in the immediately

![Figure 4.4: Folded Spirifer Yassensis and Currajong Limestone beds at Kangaroo Flat (Locality 2 on Fig 4.1). Note decoupling which must occur between and within SYL and CJL limestones to allow observed fold shapes geometries. Red rectangles (from left to right) mark the locations of (left) Figures 4.7 and 5.15 (centre) Figure 5.16 and (right) Figure 4.16.](image-url)
adjacent sedimentary beds. Fault slip has caused strain around the fault tip, leading to folding and the development of wing cracks (e.g. Kim et al., 2004).

Commonly, bedding-parallel slip veins become discordant to bedding and thus form fault veins. Several notable examples of this occur, with one of the most spectacular sites of calcite mineralisation in the TVS occurring near the bottom of the Cavan Bluff Formation at Tates Straight (Fig. 4.1, Locality 3). Here, a laminated bedding-parallel vein occurs, which, as it is traced further south, becomes a discordant fault as bedding becomes folded. The fault displaces two anticlines against one another. Where bedding begins to change orientation, the BPV becomes discordant to bedding, and thick zones (∼1 m wide) of laminated and massive calcite occur in the dilatant regions (Fig. 4.11). Such dilatant sites probably acted as high permeability zones allowing significant fluid flow. In another example, a bedding-parallel vein becomes discordant in the subvertical limb of an asymmetric anticline-syncline pair. In the bedding-discordant area, the thickest zone of calcite mineralisation occurs (Fig. 4.7, Locality 2 in Fig. 4.1).

Bedding-parallel veins

Bedding-parallel veins are faults in their own right. However, in this thesis, bedding-parallel veins (BPV) are differentiated from fault veins because they do not cut across bedding. Commonly, BPV and fault veins are closely linked (see sketch in

Figure 4.5: Schematic diagram showing relationships between different fracture types which may be produced during the folding of a multilayer sequence, based on observations at Taemas. Varying material properties and deformation mechanisms during folding produce complex overprinting relationships between folds, faults and veins. Modified after Cox (2007).
Figure 4.6: Laminated vein cut perpendicular to laminations, with the long axis of slickenlines parallel to the cut surface (top, with 8 cm scale bar) and (bottom) laminations amongst massive calcite in a bedding-parallel vein (15 cm long pencil for scale) at Locality 3 in Fig. 4.1.
Figure 4.7: Photo panorama and interpretative sketch showing a bedding-parallel vein and other faults at Kangaroo Flat on the eastern side of Taemas Peninsula (Locality 3 on Fig. 4.1). Outcrop is approximately 40 m wide. Bedding traces are dashed lines, and regions of calcite mineralisation are thicker zones of solid black. Note decoupled bedding and associated wing crack (bottom of sketch).
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Figure 4.8: Dilational jog on small fault vein in the Spirifer yassensis Limestone near the centre of an anticline at Kangaroo Flat (anticline in central red rectangle in Fig. 4.4). Size of jog suggests around 8 cm of reverse displacement. Pencil (15 cm long) for scale, photo oriented SW (left) NE (right).

Figs. 4.5 [4.12]. Bedding-parallel veins range from less than a centimetre thick, to about 30 cm thick. Calcite is the dominant vein-filling mineral, and quartz is generally absent or minor in BPV. Individual BPV have been traced up to 50 metres along strike within an individual outcrop. In addition, the consistent stratigraphic position of some BPV suggests that individual veins may extend over hundreds of metres. Bedding-parallel veins usually contain tens to hundreds of macroscopic grey-brown laminations, which lie subparallel to the vein margins. Individual laminations may be traced for several metres within a vein. Laminations may be traced from the footwall to the hanging wall of some veins, and are typically inclined at an angle of $< 5^\circ$ to bedding. Within some veins, laminations are folded (Fig. 4.13). Laminations are usually striated, and generally subperpendicular to the strike of the BPV, particularly on veins dipping at more than 40°. The dip of BPV around folds is quite variable, between 20° and $\sim 80^\circ$. Most veins have dips ranging between 40° and 60°. At ‘Shark’s Mouth’ (Locality 4 in Fig. 4.1), in an anticline within the SYL, a BPV dips at $\sim 20^\circ$ SW. The trend of striations on this vein varies by over 55° on different laminae (although this degree of variation is unusual compared to other BPV).
Two BPV with discontinuous calcite mineralisation, and only a few laminations (\(< 10\)), are observed at two different locations. Individual patches of calcite mineralisation are typically \(\sim 10\) cm long, and 2–3 cm thick. The patches are linked to one another by thin, planar shale-like layers. Calcite mineralisation is localised to regions where space has been created along the bedding plane by slip (Fig. 4.14). These are interpreted as bedding-parallel laminated veins at an early stage of growth.

Figure 4.7 illustrates a syncline-anticline pair at ‘Kangaroo Flat’ on the eastern side of Taemas Peninsula (Locality 2 in Fig. 4.1). Here, bedding within the SYL has been folded into two open, asymmetric, folds. This vein contains ‘m’ symmetrical folds at the synclinal hinge. On the east limb of the anticline, ‘s’ asymmetric folds are observed. An orange-brown dolomitic marker bed allows displacement and deformation of the rocks in this fold to be traced. A bedding-parallel vein is continuous through both the syncline and anticline. A orange-brown marker bed indicates that the bedding-parallel vein becomes bedding-discordant through the antclinal hinge, and suggests a reverse sense of displacement on this vein. At this site, two bedding-discordant faults splay off the hanging wall of the main vein (Labeled \(\alpha\) on Fig. 4.7). Buckling of bedding around the anticlinal hinge is associated with a dilatant site of calcite mineralisation.

Bedding-parallel veins are found between many beds in the Currajong Limestone.
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Figure 4.10: Top: Bedding-discordant fault in Spirifer yassensis Limestone, NE end of Shark’s Mouth Peninsula (photo approx. 5 m across). Bottom Left: View up same fault plane, note jogs along fault plane. Bottom right: Laminations within this fault have slickenfibres on their surfaces, which are consistent with reverse motion. (pencil tip, bottom right, 2 cm long for scale).
Figure 4.11: Sketch map (top) and photograph (bottom, looking northwest) with interpretative sketch showing folds, faults (dashed lines on photo) and bedding orientations at Tates Straight, in the Cavan Bluff Limestone. Cross section is constructed from this map and unpublished data of Cox. Bedding trends and orientations do not match on map because bedding cuts across the steeply sloping hillside. Bedding and fault traces are shown in white, strongly fanned cleavage is highlighted in yellow, and calcite vein fill is red. Grid references are UTM, Australian Geodetic Datum 1984.
Many of these veins are heavily weathered, and are generally poorly preserved. Most BPV contained within the Currajong Limestone lack laminations, particularly where they are developed between the most massive limestone beds. In the CJL, laminated BPV are more common immediately below the Bloomfield Limestone. These are probably shear fractures, as striated laminae are found within some fractures, although formation of some bedding-parallel veins by pure dilation cannot be discounted.

The laminated, bedding-parallel veins are analogous to those described by Gaviglio (1986); Tanner (1989); Jessell et al. (1994) and Fowler (1996, and references therein). Slickenfibres and slickenlines found on laminations in the bedding-parallel veins record the slip vector. Ramsay (1974) put forward the first integrated model for flexural-slip, and described space problems which arise in the hinge zones of flexural-slip folds. Subsequent workers have assumed that slip takes place between competent and incompetent beds (or each bed), and followed this model (e.g., Ramsay and Huber, 1987; Tanner, 1989; Fowler and Winsor, 1997).

The gentle dip of some BPV (c. 20°) suggests that flexural slip begins at an early stage of folding. The presence of BPV in fold hinge zones, and parasitically folded laminations also imply that bedding-parallel slip occurred early during fold growth. The variable orientation of slickenfibres on a low-angle vein at Shark’s Mouth Peninsula implies that a variety of slip vectors occurred on BPV. Bedding-parallel veins with higher dip angles have slickenfibres with a more consistent orientation (usually raking ∼ 90° in the fault plane, and perpendicular to fold hinges). It is inferred that as folds begin to amplify, slip occurs between bedding planes in a nonconsistent manner. As folds begin to tighten, and fold hinges become well defined, slip vectors become more consistent.

Some BPV may be traced directly around folds. Asymmetrically folded laminations within some of these veins suggests that ongoing fold growth postdated initial

Figure 4.12: Sketch showing relationship between bedding-concordant and bedding-discordant faults in a fold pair.
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Figure 4.13: (a) Photo of bedding-parallel vein near top of BFL. Black square indicates location of (c). (b) Sketch of (a). Hammer (30 cm long) for scale. Grey area indicates region of calcite mineralisation. Note splitting of vein into two discrete segments. Dashed lines represent bedding traces. (c) Vein with asymmetric folding of laminations (implying reverse shear on fault). Part of hammer (5 cm long) for scale. (d) Sketch of (c) showing trace of laminations, and region of brecciation between laminated areas (hatched zone). Note obvious folding of laminae. (e) Enlargement from (c). Pencil tip (3 cm) for scale.
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Figure 4.14: (a) Laminated, bedding-parallel vein at an early stage of development within the SYL (next to the fault zone shown in Figure 4.10). Note that vein is at a low angle to bedding. Pencil (15 cm long) for scale. (b) Interpretative sketch of (a). $S_0$ is bedding, $S_1$ is a penetrative slaty cleavage developed within shale beds. (c) Laminated vein at an early stage of development within the CJL. Notebook (15 cm long) for scale. (d) Interpretative sketch of (c). Dilational jogs and associated extension veins imply a top-to-the-north sense of shear.

flexural slip. It seems likely that during the initial stages of folding, significant strain is accommodated via slip between bedding layers. However, as bedding dips increase during folding, frictional lockup will occur [Ramsay 1974]. At this point slip on BPV may cease, and new faults may form which cut across bedding. Saddle reefs indicate that dilation occurs at some fold hinges during fold amplification.

The two veins with discontinuous calcite mineralisation illustrated in Fig. 4.14 are believed to be BPV preserved in their initial stages of development. Inclusion bands within veins are oriented parallel to bedding and are inferred to have formed via the mechanism outlined in Koehn and Passchier [2000] also see §4.4. It is suggested that the veins are actually oriented at a very slight angle to bedding, and that the slip vector is parallel to bedding. This inference is supported by several bedding-parallel veins which crosscut bedding at low angles (Fig. 4.14). This means that as slip occurs along bedding planes, calcite mineralisation will appear continuously along the fault plane, and a connected vein will form parallel to bedding (Fig. 4.15).
Figure 4.15: Schematic diagram showing the growth mechanism and resulting microstructures during the formation of inclusion and crack-seal bands during bedding-parallel slip. Crack-seal bands and layers are produced in dilational jogs, while inclusion bands are produced on the bedding planes along which slip is occurring. After Koehn and Passchier (2000).
Extension veins

Extension veins are present in many different structural settings, and are associated with a variety of larger structures (both faults and folds). Two main types of extension fractures are identified from the Taemas region. These are:

1. Small, (usually less than 10 cm long and < 1 cm thick), randomly oriented veins are found in the massive Currajong and Receptaculites limestones. These veins have highly variable orientations.

2. Larger (usually > 20 cm long and more than 1 cm thick), approximately planar extension veins. These veins occur within all the major sedimentary units. High vein densities are usually associated with high strain zones, when fold growth is accommodated by buckled bedding (Fig. 4.7), or occur on steeply inclined fold limbs (Fig. 4.16). Closely spaced veins often have similar orientations, and also occur in en echelon extension vein arrays (Fig. 4.17). Extension veins also occur around bedding-discordant fault veins.

Small, randomly aligned extension veins are found extensively within the CJL and RCP. These veins cannot be linked with larger fault structures, folds, lithology variations or other structural features. Timing relationships between these veins are rare, and they are not considered further here.

Larger extension veins are found in four dominant types:

1. Veins found in en echelon arrays, which may or may not coalesce to form fault veins.

2. Veins oriented approximately orthogonally to bedding within massive limestone beds.

3. Veins connected to, and/or associated with, fault zones.

4. Veins formed during flexural flow folding.

En echelon extension vein arrays occur at several locations, and are commonly associated with fault-fill veins. The change in connectivity of veins within fracture sets implies that as strain increases, veins become increasingly developed, and eventually connect to form a throughgoing fault zone (Fig. 4.17, Locality 5 in Fig. 4.1). This has been previously suggested by Brace and Bombolakis (1963) and subsequent workers. Most extension veins have angles of 20°–30° between the long axis of extension veins and the dip of vein arrays (Fig. 4.17).

Bedding orthogonal extension veins in the CJL are illustrated in Figure 4.16. These veins are common in the steeply dipping (> 50°) beds of massive limestone in the SYL and CJL. The absence of these veins in gently dipping (~ 35°) massive CJL beds on the north side of Shark’s Mouth peninsula implies that bedding orientation was a dominant control on the formation of these extension veins. Fold limbs rotated into steep orientations have undergone limb-parallel stretching, resulting in incipient bedding boudinage and associated subhorizontal extension veins. Extension veining of this type is most prevalent in the CJL. This is likely due to the high competence
Figure 4.16: (a) Photograph of Currajong Limestone with extension veins in sub-vertical bedding at ‘Kangaroo Flat’ on the eastern side of Taemas Peninsula. (b) Interpretative sketch of (a). Bedding is dashed black, calcite veins are red. Representative fault and bedding orientations are shown. Equal area stereonet shows the average orientation of bedding (great circle) and poles to veins (note higher density of veins at approximately 90° to bedding). Outcrop is ~ 10 m wide. (c) Photograph of calcite extension veins from limestone on right hand side of photograph (a). Pencil tip (10 cm) for scale. (d) Interpretative sketch of (c). Note that vein sets ($v_n$ and $v_{n+1}$) with similar orientations show mutually overprinting relations. Stylolites are approximately parallel to bedding. Some veins crosscut stylolites, while other veins are truncated against stylolites. (e) Boudinaged limestone beds and extension veins on upper transition of CJL to BFL. Note pencil (15 cm) for scale.
Figure 4.17: Photograph and interpretative sketch of en echelon extension vein arrays within a massive limestone bed of the Spirifer yassensis Limestone on the southern side of Shark’s Mouth Peninsula (Locality 4 in Fig. 4.1). Hammer (30 cm long) for scale. Note lower vein array is increasingly connected along strike to ESE. Stereonet shows orientations of bedding (great circle), poles to low angle vein arrays, poles to veins within that array, and poles to veins contained within the moderately dipping vein array.
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Figure 4.18: (a) Photograph (looking south) of transitional upper Majurgong Formation (Locality 6 on Fig. 4.1). Photo shows extension veins associated with flexural flow in limestone and shales. (b) Interpretative sketch of (a). Bedding is dashed black, cleavage is dotted blue and extension veins are coloured red. Hammer (30 cm long) for scale. (c) Stereonet showing representative orientations of bedding (great circle) and poles to cleavage (blue dot) and veins (red dots) (d) Photograph and interpretative sketch of extension veins within anticline W of beds featured in (a). Bedding is black, cleavage is dotted yellow and veins are red. The bedding-parallel vein (left hand side of photo, and bottom left photo insert) is crosscut by more gently dipping extension veins, probably associated with flexural flow folding. Outcrop is approximately 15 metres wide. Stereonet showing representative orientations of bedding (great circle) and poles to cleavage (C) and veins (V).
Figure 4.19: Relationships between stylolites and veins in the (a) CJL at Shark’s Mouth Peninsula (Locality 4 in Fig. 4.1; pencil tip 5 cm long) and (b) CBL (Locality 3 in Fig. 4.1; notebook 15 cm long). Note that veins both crosscut stylolites, and are overprinted by stylolites.
of the CJL relative to the surrounding interbedded limestone-shale of the SYL and BFL.

On the east side of Taemas Peninsula (Locality 6 in Fig. 4.1), extension veins are exposed in two anticlines (Fig. 4.18). Bedding is steeply dipping on both limbs (50°–60°). Cleavage is strongly developed within shaley beds, and is at a high angle to bedding (≈60°–70°). Calcite extension veins are present and cut cleavage at a high angle on the limbs of both anticlines. A bedding-parallel vein is present between the two anticlines (orientation 354/66W). This vein has slickenfibres which rake 90° on the fault surface. The bedding-parallel vein is cut by extension veins, which dip east (342/37E). The bedding-parallel vein is interpreted to be the result of flexural slip during folding. The high angle of calcite extension veins to cleavage within folds is consistent with veins formed during flexural flow folding (Ramsay and Huber 1987). Extension veins crosscutting the bedding-parallel vein imply that strain may be accommodated via flexural flow folding after bedding-parallel slip ceases, due to frictional lock up of beds (Ramsay 1974). It is noted that en echelon arrays of flexural flow related veins form only in semi-competent and incompetent beds, and do not form within more competent massive limestone beds.

Extension veins show mutually overprinting relationship to cleavage (in shale rich beds) and stylolites (in more massive limestones). This implies that vein formation and folding were contemporaneous (Fig. 4.19). Furthermore, mutually overprinting relationships of similarly oriented extension veins (such as those illustrated in Fig. 4.16c,d) imply that stress fields were dynamically varying over time.

Extension veins sometimes show mutually overprinting relationships to one another (Figs. 4.16c,e, 4.19a). Variation in the orientation of extension veins imply that the orientation of \( \sigma_3 \) (at least locally) has changed over time. Furthermore, the mutually overprinting relationships of similarly oriented extension veins (such as those illustrated in Fig. 4.16c,d) implies that stress fields were dynamically varying with time.

### 4.4 Vein textures

#### 4.4.1 Introduction

The stress and fluid pressure conditions required for the three major fracture types (extension, extensional-shear and shear fractures) are defined in §2.2. Here, textures for material filling these fractures are discussed, and proposed growth mechanisms for veins are outlined. It is noted that the majority of epithermal vein textures are not considered here (see Dong et al. 1995, for a review). The following vein texture descriptions are based on the reviews of Bons (2000) and Oliver and Bons (2001), with additional information from Ramsay (1980), Ramsay and Huber (1983), Ramsay and Huber (1987), Passchier and Trouw (1996), Foxford et al. (2000) and Koehn and Passchier (2000).

The microscopic morphology described here relates to the shape and arrangement of crystals inside a vein. The vein microstructures described are:

1. Fibrous veins
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2. Elongate blocky veins (including crack seal veins)
3. Stretched crystal veins
4. Veins with euhedral crystals
5. Blocky textured veins

Fibrous veins

When fully developed, fibrous veins have crystals with high length to width ratios (e.g. 10:1 to 100:1), and all grains have approximately the same shape. The shape of fibres is determined by the growth history of the vein, and any subsequent deformation (Durney and Ramsay 1973). Growth competition between adjacent crystals is thought to be restricted by a very narrow (or absent) aperture (Hilgers and Urai 2002). Fibrous textures only develop if no additional crystal nucleation occurs once crystal growth has begun.

Elongate blocky textured veins (and crack seal veins)

Elongate blocky veins contain crystals with moderate length/width ratios. This texture forms when nucleation of new grains does not occur during vein growth, and all growth is crystallographically continuous on existing grains. Growth occurs at existing crystal tips. These ‘seed’ grains may be pre-existing in the wallrock, or formed during an initial nucleation phase. Elongate blocky veins show distinct signs for growth competition (as opposed to fibrous veins). Vein-parallel bands of wallrock inclusions, accessory vein minerals and fluid inclusions are common. Each inclusion band is believed to represent one cycle of fracture opening and sealing (e.g. the crack-seal mechanism; see Ramsay 1980). This cyclicity has been related to hydraulic fracturing due to repeated fluid-pressure fluctuations (Cox 1987; Boullier and Robert 1992).

As growth progresses, increasing numbers of crystals are outgrown by their neighbours (when the crystal fast growth direction is at a high angle to the fracture wall). Hence, the average grain width increases in the growth direction. Growth competition between crystals may occur when crystals grow into a fluid-filled crack (Fisher and Brantley 1992; Bons 2000; Oliver and Bons 2001).

Stretched crystal veins

Stretched crystal veins have crystals that span the entire vein width (Durney and Ramsay 1973). They are formed by repeated cracking and subsequent sealing of existing grains. These veins are a type of crack-seal vein. However, they differ from the elongate-blocky vein type described above as the cracking and sealing increments are distributed irregularly throughout the stretching grains. No growth direction can be determined, and crystal widths are approximately constant across the vein (Durney and Ramsay 1973).
Veins with euhedral crystals

Veins with euhedral crystals show evidence for growth competition between grains (Bons 2000). Typical euhedral textures include crustification, and vuggy crystals. Grains are usually elongate at high angles to the vein walls. Euhedral textured veins form if the host fracture was held open sufficiently long to enable crystals to grow continuously into a fluid-filled cavity (rather than crack-seal veins, which grow episodically during multiple opening and sealing events). Such vein textures are common in the shallow crust, where hydrostatic fluid pressures generally exist, and fractures remain open for longer periods of time. Some authors have described euhedral veins from amphibolite and eclogite facies rocks, with mineral assemblages in these veins consistent with growth at high temperature and pressure (Oliver and Bons 2001 and references therein).

Crustiform textures (or crustification banding; Adams 1920) are successive, narrow (up to several cm), subparallel bands. These bands may be distinguished by colour, texture or mineral proportions. Banding is commonly developed symmetrically from both walls of a fissure (Adams 1920; Dong et al. 1995). Any process which causes a change in fluid conditions may lead to the formation of crustiform bands. These could include cooling, fluid mixing, fluid-rock reaction and boiling. Crustification banding has been noted in geothermal production wells (Simmons and Browne 2000). The production of complex crustiform bands, with repetitive changes in mineral composition or texture requires a recurring process. It has been suggested that episodic pressure changes may drive the formation of crustification banding (Dong et al. 1995, and references therein). A change in the total confining pressure may cause fluid boiling, driving gas release, cooling, pH rises and subsequent mineral precipitation. Dilation (caused be extension fracturing or fault rupture) is one mechanism by which pressure release may occur (Dong et al. 1995).

Blocky veins

The vein textures described above are characterised by no crystal nucleation after initial nucleation at the beginning of vein growth. If ongoing nucleation occurs, then blocky, equidimensional, non-idiomorphic grains form. Very high supersaturation of vein-forming minerals is a cause for continuing nucleation (Oliver and Bons 2001). Such high supersaturations would be anticipated in fault veins, in which large, near-instantaneous fluid pressure drops during fault rupture result in rapid supersaturation of a mineral phase. However, blocky textures may also be produced by dynamic recrystallisation. Other causes for massive, blocky textures include repeated, chaotic fracturing of a vein, which will prevent the formation of regular, elongate crystals.

4.4.2 Vein growth

Vein growth can occur in three different ways (see Fig. 4.20):

1. **Syntaxial growth** - occurs when material nucleates on existing minerals on the fracture walls, and progresses inwards (i.e. oldest material at wall rock-vein interface, youngest material at centre of vein).
4.4. Vein textures

2. *Antitaxial growth* - occurs when material deposits at the contact between wall rock and vein material, and continues at the wall rock-vein interface (i.e. oldest material at vein centre, youngest material at wall rock-vein interface).

3. *Composite* (Ramsay and Huber 1983) and *ataxial* growth (Passchier and Trouw 1996) are marked by more complex growth mechanisms, whereby fracturing and growth may occur at multiple locations in the vein, producing no distinct growth history in the vein.

*Syntaxial growth* occurs in veins where the vein-filling mineral is common in the host rock (e.g. calcite vein in a limestone). Within these veins, material nucleates on existing minerals on the fracture walls (i.e. epitaxial growth; Durney and Ramsay 1973). For syntaxial veins, growth occurs on a single median surface. On this surface (commonly a thin fracture) material is added by overgrowth on vein crystals on both sides of the growth plane. Thus, the oldest material is found at the outside of the vein, with the most recently precipitated crystals found at the median plane (often marked by a discontinuity in the vein fabric; Durney and Ramsay 1973).

For *antitaxial growth*, the vein-filling mineral is commonly not abundant in the wall rock (Durney and Ramsay 1973). In antitaxial vein growth, mineral formation occurs at the contact of vein-filling minerals and the wall rock. A median line may be present, defined by small grains of the fibrous mineral, or fragments of wall rock. The median plane indicates the initial nucleation site of the vein.

*Composite veins* form when antitaxial fibres develop along the median plane of syntaxial fibres (the vein thus contains 3 growth surfaces). *Ataxial* (Bons 2000) or *stretched crystal* veins (Durney and Ramsay 1973) have a non-localised growth surface, with fracturing and vein growth occurring at varying sites in the vein.

Fibrous vein textures may be produced by antitaxial, syntaxial or stretched crystal growth mechanisms. Antitaxial and syntaxial growth mechanisms can usually be distinguished by systematic changes in mineral size (particularly in fibrous or elongate-blocky veins), or the presence of a median line (for antitaxial growth veins). Massive texture veins likewise may grow via syntaxial or antitaxial growth mechanisms, but recognising growth directions in blocky veins is complicated.

4.4.3 Textures of veins in the TVS

Veins with a variety of textures occur throughout the Murrumbidgee Group. Veins dominantly have massive, laminated and fibrous textures, with elongate-blocky and crustiform textures also occurring. In this section, I describe and illustrate vein textures observed in the Taemas Vein Swarm. Understanding growth directions in veins is critical for the interpretation of microchemical analyses presented in Chapter 6.

Bedding-parallel and fault veins dominantly have massive and laminated textures, with fibrous textures preserved in some parts of fault and bedding-parallel veins. Conversely, extension veins dominantly have massive, elongate-blocky or fibrous textures (laminated textures are absent in extension veins).

Figure 4.21 shows extension and fault veins in the Currajong and Cavan Bluff Limestones. It is emphasised here the particular textures are not isolated to specific
host lithologies, and different textures are found both within the same outcrop, and within the same vein. Notably, veins may contain both fibrous and massive calcite (Fig. 4.21). Some extension veins contain both grey and white calcite. Fibrous quartz-calcite veins are particularly common in the Cavan Bluff Limestone (e.g. Fig. 4.21b,f), and some of these veins show mutually overprinting relationships with both fibrous veins, and massive calcite veins. Displaced markers (e.g. fossils, other veins) indicate that most extension veins opened by nearly pure extension.

Several veins have fibrous textures (usually immediately adjacent to the vein-wallrock boundary), with the vein texture changing to elongate-blocky and/or massive away from the vein walls. Within the Currajong Limestone, rare veins contain fluorite. In one vein, fluorite occurs as larger crystals in the interior of a vein, whereas calcite has a fibrous habit immediately adjacent to the vein wall (Fig. 4.22). Figure
Figure 4.21: Photos showing co-existing vein textures (pencil $\sim 0.5$ cm wide for scale). (a) fibrous and massive vein in CJL. (b) fibrous quartz-calcite vein cross-cutting, and being overprinted by other massive and fibrous calcite veins in CBL. (c) Fibrous quartz-calcite vein alongside massive calcite vein in CJL. (d) Vein with crystal size increasing as a function of vein aperture in CJL. (e) Vein with two generations of different coloured calcite, with quartz being restricted to the inner (creamier) calcite zone. (f) Fibrous quartz-calcite vein in CBL. Calcite has been dissolved by weathering, revealing the fibrous quartz texture.
4.23 shows the tip of a fault vein and associated extension veins. The extension veins and end of the fault vein contain quartz and calcite fibres. Away from the fault tip, the fibrous texture changes to massive calcite. Such textures, with fibres at vein-wall rock boundaries and massive to elongate-blocky textures in vein interiors suggest that these veins grew via a syntaxial growth mechanism.

The majority of extension veins in the TVS preserve massive textures, making growth histories difficult to distinguish. Textural changes from fibrous habit at wall rock-vein interfaces to elongate-blocky and massive textures in vein interiors suggest that the majority of extension veins in massive limestone host rocks grew via a syntaxial growth mechanism. The lack of median line, or variation in fibre width in many fibrous veins suggests that these veins form via a stretched crystal mechanism (e.g. Figs. 4.22a, 4.23).

Laminated textures are most common in bedding-parallel slip veins, and are also found in some fault veins. Bedding-discordant fault veins generally are massive, but locally have coarse laminations. The term ‘laminated’ refers to a vein with layers of calcite or quartz separated by thin (< 1 mm), subparallel bands of dark, fine-grained minerals, and slivers of wall-rock (Fig. 4.6). Fault veins usually contain fewer laminations, and these laminations are spaced at larger intervals than laminations in BPV (Fig. 4.24). Laminated veins usually contain only calcite between laminations, with laminations themselves composed of various minerals, including phyllosilicates (probable illite), with minor calcite and accessory rutile, albite and quartz (identified using light microscope and scanning electron microscopy). Laminations in many veins are crosscut by calcite and (less commonly) quartz extension veins. Pieces of wallrock are commonly incorporated between, or as part of, calcite laminae. The surface of calcite laminations commonly have slickenlines, which usually rake at 70–90° in the plane of laminations. The orientation of laminae to bedding, and (rarely preserved) stepping fine-structure on slickenfibre surfaces suggest that the majority of laminated faults have reverse motion, with minor strike-slip components.

In bedding-parallel veins, laminated textures have been classified by Koehn and Passchier (2000). Inclusion bands are thin, dark bands which are parallel to the vein margins. Crack-seal bands are thin, dark bands found between parallel inclusion bands, and typically form at angles of 20° – 35° to inclusion bands (Fig. 4.15). Crack-seal bands are typically separated by distances of 100 µm to 2–3 mm, and hundreds of crack-seal bands may occur in an interval of around 10 cm along one calcite lamina. Inclusion bands are ubiquitous in all laminated veins. However, crack-seal bands are less common, and generally isolated to small areas (i.e. 10 cm or less) between a few discrete inclusion bands. Here, an inclusion layer is defined as the material lying between two subparallel inclusion bands. A crack-seal layer is the calcite lying between two crack-seal bands. Crack-seal layers are inferred to have formed along dilational sites during slip along laminations on the BPV. It is suggested that each crack-seal band formed during one episode of slip, likely during individual microseismic slip events (Fig. 4.15 Koehn and Passchier 2000).
Figure 4.22: Various textures preserved within extension veins from different stratigraphic units, with inferred vein growth mechanism. (a) Fibrous vein calcite (B) crosscutting earlier fibrous vein (A) in the CBL (sample SM-80). Note slight component of oblique opening on vein (A), with fibres apparently tracking the vein opening direction (stretched crystal mechanism). (b) Fibrous calcite vein with a cataclastic shear zone cutting through the vein centre (probable stretched crystal growth mechanism; sample CJ-206B). (c) Calcite-fluorite vein from the CJL. Note fibrous calcite texture next to vein wall, with more massive fluorite syntaxially overgrowing of calcite fibrous fringe in vein interior (sample RFF-2). (d) Calcite vein from the CJL with fibrous texture at the vein-wall rock interface and massive calcite on the vein interior (syntaxial growth mechanism; Sample CJ-20A). (e) Vein from the CJL with mixed fibrous, elongate-blocky and massive textures (stretched crystal growth mechanism; sample SM-1A).
4. Structural setting of the Taemas Vein Swarm

4.5 Implications for fold growth and fluid migration

The Taemas Vein Swarm is hosted in upright, open to close folds. These folds grew via a variety of fold mechanisms. Flexural slip folding led to the development of bedding-parallel veins and saddle reefs at fold hinges, while flexural flow in semicompetent and incompetent beds led to the development of en echelon extension vein arrays. Fold lock-up was accompanied by the development of bedding-discordant faults (and extension veins related to bedding-discordant faults), and limb-parallel stretching on subvertical fold limbs (associated with the development of subhorizontal extension veins). Several previous field and experimental studies have demonstrated the links between folding, fault formation and fracturing (e.g. Ramsay [1974], Chester et al. [1991], Cox et al. [1991]).

Field observations made in this study suggest that veins formed throughout fold growth, with episodic vein opening and calcite (± quartz and fluorite) deposition. Evidence includes; (1) bedding-parallel slip veins occurring along low angle bedding planes, early in fold growth, (2) presence of folded and unfolded laminations in the same bedding-parallel veins, (3) mutually overprinting relations between veins and stylolites (in limestone beds), (4) extension veins cut cleavage in marly and pelitic layers and (5) bedding-parallel slip veins crosscut by extension veins (likely related to flexural flow folding). Variations in fold geometry from the basal sedimentary units upwards into the Spirifer yassensis, Currajong and Bloomfield Limestones imply that significant strain (perhaps up to 50%) was accommodated in these stratigraphic
Figure 4.24: Thin sections showing textures in bedding-parallel laminated veins with inclusion bands (dominant bands lying subparallel to edge of photomicrographs) and crack-seal bands (small, lying between and obliquely to inclusion bands). Samples (from top to bottom) are CB-100, SM1C-2, SM-1C.
units. In comparison, the underlying Mountain Creek Volcanics and overlying Receptaculites Limestone have more open folds, and apparently underwent less intense deformation (Fig. 4.3).

Fold-controlled veining has been previously described from the Bendigo-Ballarat area by Cox et al. (1991). In that region, folding created space for quartz (± gold) mineralisation via flexural slip on bedding and associated dilatancy at fold hinges (forming saddle reefs). More recently, Lefticariu et al. (2005) carried out geochemical analyses on calcite veins formed within a detachment fold complex. They found that late stage fold tightening was accompanied by significant fracturing and associated permeability development, and that during this stage of folding, significant fluid migration occurred. Field observations in this study suggest that where bedding orientations change significantly (particularly where fault and fold hinges interact), significant dilation and associated permeability enhancement and hydrothermal mineralisation occurs (Figs. 4.7, 4.11).

The protracted history of vein formation indicates that veins formed spasmodically, over a period of time. Veins in some outcrops show mutually overprinting relationships. Vein textures suggest that many veins grew incrementally, with multiple episodes of mineral deposition required to form some veins. Furthermore, varying crystal size and shape within the same vein (e.g. fibrous to massive) suggest that vein opening rates and/or precipitation rates varied during the formation of a single vein. Incremental growth textures imply that episodic permeability enhancement and destruction occurred at local scales.

4.5.1 Folding, seismicity and fluid pathways

In active fold-and-thrust belts, strain is accommodated in sedimentary rocks by a combination of folding and thrust faulting (e.g. Shaw and Suppe, 1994). Seismic reflection profiles and surface mapping suggest that actively growing folds are intimately related to seismically active faults. It is inferred that fold growth in many sedimentary sequences involves flexural slip folding, particularly in early fold growth, prior to lockup of fold limbs (Ramsay, 1974). Crack-seal textures in bedding-parallel veins indicate that bedding-parallel slip was episodic, suggesting that fold growth occurred episodically. Episodic fold growth and associated fracturing is likely related to the generation of significant fracture permeability in actively deforming fold-thrust belts (Finkbeiner et al., 1997, Cox, 2005).

In reservoir related seismicity from the Nurek Reservoir, Vakhsh valley, Tadjikistan, a series of small earthquakes (magnitudes −0.5 to +2) occurred above a major thrust sheet, in folded sediments overlying a larger thrust fault. The focal mechanisms for these earthquakes showed maximum compression perpendicular to fold axes mapped at the surface (Keith and Simpson, 1982, Leith and Simpson, 1986). However, none of these earthquakes could be correlated with larger faults mapped at the surface. This implies that the microseismicity might have been restricted to small faults (e.g. fault lengths of less than 5 km), which were produced during active folding.

It is suggested that crack-seal bands in bedding-parallel laminated veins formed in millimetre to centimetre-scale dilational jogs, during repeated microseismic slip
events (as per the mechanism of Koehn and Passchier [2000] Fig. 4.15). The separation of crack-seal bands within these BPV may be used to infer some characteristics of the earthquake slip events which formed the bands. If a dilational jog opens perpendicular to the finite slip vector on a fault plane, then the width of the resulting dilational jog (parallel to the finite slip vector) is equal to the displacement along the fault plane. Crack-seal bands in laminated BPV typically have separations of 0.1 mm to 2 mm. The typical ratio of average displacement ($\bar{u}$) to fault rupture length ($L$) for an earthquake lies between ([Wells and Coppersmith 1994]):

$$10^{-5} < \frac{\bar{u}}{L} < 10^{-4}$$

(4.1)

If this scaling relationship holds for the seismic events which produced the crack-seal bands in these laminated veins, then fault displacements of 0.1–2 mm imply fault rupture lengths of 1 metre to 200 metres, and rupture areas (assuming that rupture area is $\approx L^2$) of $\sim 1 m^2$ to 40,000 m$^2$ ([Sibson 2001]). These would be equivalent to earthquake moment magnitudes of around 0 to +2 ([Sibson 2001]), or possibly magnitudes as high as +4 ([Wells and Coppersmith 1994]). This calculation gives a rough estimate of the length of fluid flow pathways generated along bedding-parallel veins during seismic slip. This assumes that permeability was significantly enhanced following earthquake slip (see review of [Sibson 2001]). Larger earthquake ruptures along bedding-parallel veins may have occurred, but no information on the dimensions of these ruptures is texturally preserved in the resulting veins.

Fault and bedding-parallel veins occur over a range of scales. Mutually cross-cutting veins, and incrementally developed vein textures suggest that permeability is dynamically created by fracturing during earthquake slip, and then destroyed via hydrothermal mineral precipitation. The framework of bedding-parallel veins, fault veins and extension veins would create a myriad of pathways along which fluid could migrate. Larger fractures (with wider apertures) would have the highest fluxes (equation 2.15), provided they are connected to a fluid reservoir. Dilatant areas such as low-displacement faults and veins are spatially associated with fold hinges, and often have significant hydrothermal mineralisation (see also [Cox 1995]).

According to the conditions for tensile failure outlined in §2.2.1, fluid pressure must exceed the least compressive stress and the tensile strength of the rock to cause extension fractures to form. In a contractional (i.e. reverse) faulting regime, gently dipping extension veins imply that (a) the least compressive stress was vertical and (b) that the fluid pressure (at least transiently) exceeded the lithostatic pressure (i.e. $\lambda_\sigma > 1.0$). Additional evidence for transiently high fluid pressures is provided by steeply dipping bedding-parallel slip veins (i.e. where $\theta_\epsilon$ approaches or exceeds $2\theta^*_r$). The presence of folded and unfolded laminations in some of these veins suggests that slip continued on these veins throughout fold growth, with some vein dip angles exceeding 70°. For slip to continue at these angles requires a negative $\sigma'_1/\sigma'_3$ ratio (i.e. $\sigma'_3 < 0$), and thus $P_f$ to be supralithostatic ([Sibson 1985]).

Differential stress levels must have varied significantly during deformation (at least on a local scale). Parts of the stratigraphy must have had low differential stress levels at the time of vein formation to form extension fractures (as required by equation 2.7). Mutually overprinting relationships between shear and extension fractures indicate that differential stress values oscillated between $(\sigma'_1 - \sigma'_3) < 4T$
4. Structural setting of the Taemas Vein Swarm

and \((\sigma'_1 - \sigma'_3) > 5.66T\) (equation 2.10). Such differential stress variations could be related to stress loading and release during repeated seismic slip events (Sibson, 1989), during progressive fold growth and crustal shortening.

4.6 Conclusions

In summary, structural and textural relationships preserved in hydrothermal veins on Taemas indicate that:

1. Vein formation was intimately related to space created during folding.
2. Vein growth and associated fluid flow occurred throughout the history of folding.
3. Mutually crosscutting relationships between veins indicate that vein growth was intermittent, and that veins formed as localised stress fields underwent significant changes in both orientation and magnitude.
4. Fluid pressures intermittently exceeded lithostatic levels, over (at least) local regions of the deforming crust.
5. Individual veins grew incrementally, and preserve a variety of textures (fibrous, massive and laminated), and indicate that vein opening and mineral deposition rates varied significantly.
6. Incrementally developed vein textures suggest that permeability was episodically created and destroyed. Permeability creation is likely related to earthquake rupture along fault zones.
7. Mutually crosscutting veins, and incrementally developed vein textures imply that high-permeability fluid flow pathways varied dynamically through time and space.

The evidence presented in this chapter demonstrates that different vein types developed incrementally, with some veins preserving evidence for hundreds to thousands of individual vein opening and mineral precipitation events. Flexural slip was a major mechanism for strain accommodation, and was accompanied by flexural flow, limb stretching and faulting to accommodate crustal shortening. Permeability was structurally controlled, and was episodically created by fault slip and fracture opening, and destroyed by hydrothermal mineral precipitation. The structural observations and inferences drawn here form the framework for examining variations in vein chemistry throughout the Taemas Vein Swarm in Chapter 5.