

Sequence and kinematics of multiple deformation around Taemas Bridge, Eastern Lachlan Fold Belt, New South Wales

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The area around Taemas Bridge in the Gilgandra–Cowra–Yass Zone, southwest of Yass, contains Devonian limestone, silicic volcanics and terrestrial sedimentary rocks that are folded by four deformations of inferred Carboniferous age. Interference between folds is well developed, mainly as Type 1 and Type 2 interference patterns. The two most prominent fold trends can be found more widely throughout the Lachlan Fold Belt as northwest/north-northwest and north/north-northeast regional trends. Early folds may be more localised. The fold axes associated with consecutive generations display an anticlockwise directional sequence, suggesting that incremental strain axes rotated anticlockwise during the Carboniferous deformation. North-northwest-trending faults in the area are inferred to have moved by both sinistral strike-slip and reverse mode at different times. Small-scale structures, such as veins, vein arrays and tectonic stylolites, are well developed in the Lower Devonian limestones. These structures can be correlated with, and indicate the 3-D incremental strain directions and kinematics of, the fold events. Early folding shows a predominantly wrench style of deformation and appears to be related to wrench motion on the bounding faults. North-northeast-trending F_2 folds are 30° clockwise to faults and, together with associated small-scale wrench indicators, suggest sinistral shear on these faults. Northwest-trending F_3 folds are associated mainly with reverse faulting, indicating a change in kinematic style. These are in turn overprinted by wrench motion associated with ?minor north/north-northwest compression. The results of this study suggest a multiphase contraction and wrench history that is more complex than previously proposed for this part of the Eastern Lachlan Fold Belt.

KEY WORDS: deformation (structural geology), Kanimblan, Lachlan Fold Belt, New South Wales, reverse faults, strike-slip faults, stylolites, Tabberabberan, Taemas Bridge, veins.

INTRODUCTION

Various large-scale tectonic models have been proposed for the later stages of structural development of the Lachlan Fold Belt. These include sublatitudinal contraction (folding, thrusting, subduction) or dextral or sinistral transpression, developed either episodically ('deformations' and 'orogenies') or as a single final event, or progressively over a protracted period (Powell 1984a, 1984b; Packham 1987; Fergusson & Coney 1992; Glen 1992; Scheibner & Basden 1998; Foster *et al.* 1999; Scheibner & Veevers 2000; Willman *et al.* 2000). Such models should be compatible with detailed structural histories observed in local areas: in particular, the orientations, kinematics (thrust, wrench, extension or oblique), sequence and timing with respect to stratigraphy of the local structures. Relatively few attempts have been made to decipher multiple deformations affecting the younger (Upper Silurian to Lower Carboniferous) rock series of the Lachlan Fold Belt in New South Wales (Powell *et al.* 1985; de Roo 1989; Fowler 1989; Glen & Watkins 1994, 1999; Lennox *et al.* 1998). Part of the problem is the existence of a single or dominant penetrative cleavage throughout much of the stratigraphical succession of the fold belt (Rickard 1978), which reinforces the often-expressed view that the structures, whether formed episodically,

continuously, or by a single major event, are 'submeridional'. However, structural grain, both fold-belt wide and locally (Figures 1a, 7), can show considerable variation between northwest and northeast trends.

To determine the cause of this variation and its possible tectonic implications, detailed field studies of fold and fault systems are required in local areas. In this paper we report on multiple convergent deformations in Lower to Upper Devonian strata of the Black Range Synclinorium between Yass and Wee Jasper in the central part of the Eastern Lachlan Fold Belt of New South Wales. Particular attention is directed to structures in the Lower Devonian limestones near Taemas Bridge, where superposed folding is especially well developed. Importantly, these rocks also contain small-scale discontinuous structures (tectonic stylolites, veins and shears) that indicate the type or kinematics of deformation associated with the folds: shortening with subvertical extension (contraction or thrust-type) or shortening with

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subhorizontal extension (wrench-type). This information is not normally available from inspection of folds and cleavages on their own. Together with the fold sequence, it constrains possible movement senses on adjoining faults and the characterisation of the late-stage tectonic evolution of this part of the Fold Belt.

Setting

LOCATION AND REGIONAL STRUCTURE

Taemas Bridge is located on the Wee Jasper – Yass road crossing of the Murrumbidgee River at 556685E 61248N [AMG references: 1:100 000 topographic sheets Brindabella

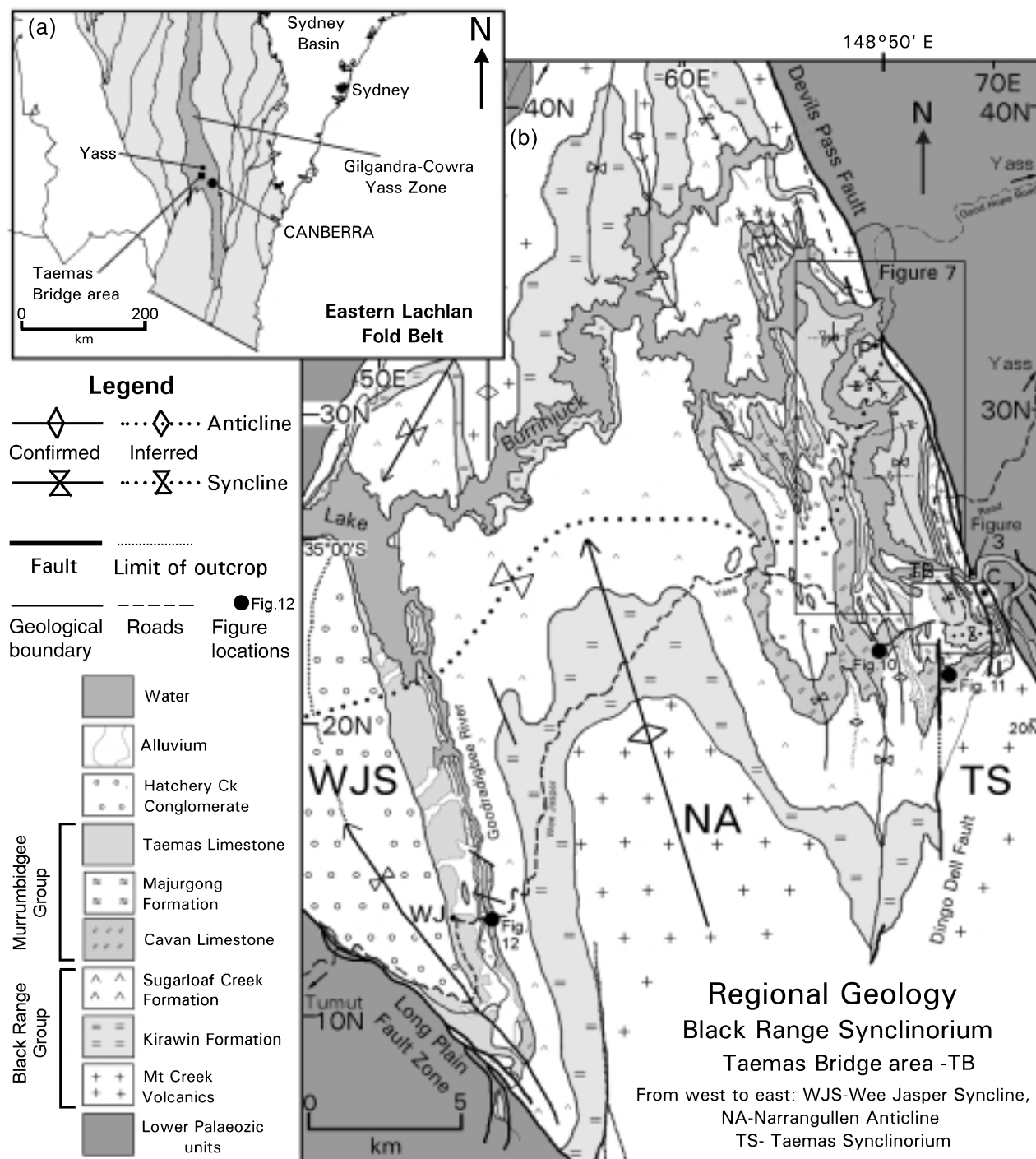


Figure 1 (a) Location of Taemas Bridge area in the Eastern Lachlan Fold Belt (shaded) in New South Wales (modified after Scheibner & Basden 1996). (b) Regional structure of the Black Range Synclinorium showing the main fold trends, F_1 NE–SW (heavy dotted line), F_2 NE–SW and F_3 NW–SE (solid lines), F_4 WSW–ENE (fine dotted line), and significant faults (thicker solid lines). Major structural elements are: WJS, Wee Jasper Syncline; NA, Narrangullen Anticline; TS, Taemas Synclinorium. The locations of Figures 3 and 7 are indicated by rectangles; other figure localities are shown as black dots labelled Fig. 10–12. Localities identified as letters are: C, 'Cavan'; P, 'Patmores'; WJ, Wee Jasper. Modified from Hood (1996); geology based on Cramsie *et al.* (1975) and Owen and Wyborn (1979).

(8627) and Yass (8628)], approximately 25 km southwest of Yass, New South Wales (Figure 1a, b). Detailed work was focused on an area of superposed folding immediately south of the bridge on 'Cavan' property (Hood 1996; Hood & Durney 2000a) and is supported by additional observations to the north ('Patmores') and southwest ('Mountain Creek' and Wee Jasper).

The Taemas Bridge area and adjoining sites belong to the southern part of the Gilgandra–Cowra–Yass Zone of Scheibner and Basden (1996) in the Eastern Belt of the Lachlan Orogen (Glen 1992) or Eastern Lachlan Fold Belt (Gray 1997) (Figure 1a). The chief structure here is the Black Range Synclinorium (Cramsie *et al.* 1975; Owen & Wyborn 1979), which includes a major fold triplet some 25 km wide and 180 km long, comprising the Wee Jasper Syncline, Narrangullen Anticline and Taemas Synclinorium (Figure 1b). Within the study area, all three of the major folds are doubly plunging, open to close structures with a predominant north-northwest–south-southeast trend and steep west-dipping axial surfaces. The Taemas Bridge local area contains smaller wavelength parasitic folds on the eastern margin of the easternmost major fold, the Taemas Synclinorium. The fold triplet contains a succession of Lower Devonian volcanics and volcanoclastics (Black Range Group) and overlying Lower Devonian limestones (Murrumbidgee Group) in the two major synclines.

Both sides of the main triplet structure are downthrown against bounding faults: the Long Plain Fault Zone to the west and Dingo Dell Fault, Warroo Fault and Deakin–Devils Pass Fault to the east (Browne 1959; Owen & Wyborn 1979). The antecedents of these faults probably pre-date the Devonian sequence and controlled the original Early Devonian margins of the depositional basin (Durney 1984). On the western side there are Silurian metasedimentary and mafic to silicic intrusive and extrusive rocks (e.g. Micalong Swamp Complex, Goobarragandra Volcanics) and to the east, Silurian volcanic and sedimentary rocks including the Yass Basin sequence to the northeast.

We presume that the basement rocks for the synclinorium are Ordovician flysch (Nungar beds) and Upper Silurian igneous rocks and pelite–carbonate sequences (Paddys River Volcanics), which occur beneath the Mountain Creek Volcanics to the south (Cramsie *et al.* 1978; Owen & Wyborn 1979; Durney 1984).

STRATIGRAPHY

The Black Range Synclinorium contains terrestrial units including extrusive rhyolites, volcanogenic sediments, redbeds and marine limestones (Cramsie *et al.* 1975, 1978; Owen & Wyborn 1979) (Figure 1b). The Lower Devonian (Lochkovian to Emsian) succession commences with the Black Range Group, which comprises the basal Mountain Creek Volcanics, overlain by the Kirawin Formation (which wedges or is faulted out in the eastern Taemas Synclinorium) and the Sugarloaf Creek Formation. These units are predominantly exposed around the edges of the Black Range Synclinorium and in the core of the Narrangullen Anticline.

The conformably overlying Murrumbidgee Group forms the core of the Taemas Synclinorium and most of

the Wee Jasper Syncline, and comprises three formations. The oldest is the Cavan Limestone ranging from well bedded to massive and nodular limestone. It grades into the Majurgong Formation, which comprises fine-grained, cross-bedded sandstone, shale, and minor quartzite and provides a useful marker unit. The Majurgong Formation grades into the overlying Taemas Limestone (Browne 1959). The Taemas Limestone is a mixture of alternating prominent (massive) and recessive (shaly) limestone units that are folded into complex patterns due to their differences in competency. The first five members of the Taemas Limestone at 'Cavan' are, from the base upwards: recessive *Spinella yassensis* Limestone, prominent Currajong Limestone, recessive Bloomfield Limestone, prominent Receptaculites Limestone and recessive Warroo Limestone. The youngest member, the Crinoidal Limestone Member, occurs only in a large F_3 basin at 'Patmores'. The Crinoidal Limestone Member is a very distinctive prominent calcarenite to calcirudite, composed almost entirely of well-sorted and frequently cross-bedded, crinoid ossicles. The stratigraphy at 'Cavan' youngs in a north to northwest direction from the basin edge.

The youngest unit present in the Black Range Synclinorium is the Middle Devonian (Eifelian) terrestrial Hatchery Creek Conglomerate, which forms the core of the Wee Jasper Syncline (Figure 1b) (Pedder *et al.* 1970 figure 1). Owen and Wyborn (1979) and Powell (1984a) suggested that the contact with the underlying Taemas Limestone is paraconformable to disconformable. However, our observations support previous mapping by Pedder *et al.* (1970), which showed this contact relationship to be completely concordant. Pedder *et al.* (1970) and Scheibner and Basden (1998) correlated the Hatchery Creek Conglomerate with the Middle to Upper Devonian Hervey Group, the latter authors regarding it as part of the molassic overlap sequences of the Lambian Transitional Province. Powell (1984c) included the Middle to Upper Devonian, Lambie Group, Merimbula Group, Hervey Group, Cocoparra Group and the Hatchery Creek Conglomerate as correlatives under the general name 'Lambie Facies'. Powell (1984b) indicated that the base of the 'Lambie Facies' is diachronous, and Scheibner and Basden (1998) expand on this by noting that the onset of deposition progressed west to east across the Lambian Transitional Province. Young and Gorter (1981) used fossil fish evidence to suggest that the base of the Hatchery Creek Conglomerate is Eifelian, which means that there is very little time break with the Emsian Taemas Limestone. There is, however, evidence of a very gentle angular relationship regionally at about this level as Upper Devonian Hervey Group rocks rest on Illunie Rhyolite (a correlative of the Mountain Creek Volcanics?) in an extension of the Taemas Synclinorium approximately 90 km to the north (Brunker & Offenberg 1970; D. J. Pogson pers. comm. 2000). This structural relationship between the Taemas Limestone and Hatchery Creek Conglomerate is important when considering the age of the deformations in this area. The different lithologies at this level seem to more markedly reflect a depositional change, rather than a structural discordance.

Previous work (Black Range Synclinorium)

Several aspects of the geology are described in the 1:100 000 scale geological sheets and explanatory notes for Yass (Cramsie *et al.* 1975, 1978) and Brindabella (Owen & Wyborn 1979). Browne (1959) mapped the basic structure of the Taemas Synclinorium as part of a combined palaeontological, stratigraphical and structural study. Williams (1974) and Khaiami (1977) examined deformation features in limestone at 'Cavan' and 'Mountain Creek' and Durney (1984) presented initial data for multiple deformations and suggested a multiphase northeast/northwest-trending F_1 and a later west-southwest/southwest-trending F_2 .

OBSERVATIONS AND RESULTS

Methods

The primary evidence for multiple deformation episodes in the area, symbolised as D_n (where n is a sequential episode number), is interference patterns between folds (F_n) of different attitude. The folds of the Black Range Synclinorium are predominantly gently plunging and steeply inclined structures of differing trends. They show Types 0, 1 and 2 interference patterns (Ramsay & Huber 1987), which are typical of sequential subhorizontal shortening in different directions (see experimental models in Ghosh 1993 section 15.5).

Type 0 or re-tightened folds are hybrid structures where an early fold is tightened, and possibly rotated, by later deformation without developing separate folds. This process can explain instances where a single compromise fold direction occurs instead of separate directions. We designate composite folds F_n/F_m where merging of fold generations F_n (earlier) and F_m (later) is observed, and F_n if the fold interferences could not be resolved. Relative timing cannot be determined from this pattern. Type 1, or dome-basin interference, produces alternating or crossing fold trends that help to separate the fold groups in the area. However, ambiguity about whether a given fold direction is inherited from an earlier structure or is superposed later means that relative timing on the basis of the fold directions alone is uncertain. Type 2 interference patterns show curvature of the axial surface of an earlier fold across a later one, which we consider diagnostic of relative age. These patterns may develop either by hinge replacement (Ghosh 1993: i.e. side-to-side rolling of early fold hinges) or by bending of tight early folds (Ghosh 1993 pp. 341–345; Grujic 1993).

At Taemas, Type 2 geometry is used for assessing relative timing without regard to the particular mechanism involved. Type 2 is often called crescent-mushroom interference, based mainly on outcrop patterns formed by moderately to gently dipping early folds (Ramsay & Huber 1987). This type of early fold and outcrop pattern is not well represented in this area. The term 'megakinking' (Powell *et al.* 1985) has been used where the early folds are more upright, as at Taemas Bridge. However, 'megakinks' can also be subhorizontal folds without Type 2 interference (Rixon *et al.* 1983). Also, the large Type 2 folds in the area are more often rounded than kink-like. Therefore, no term

in the literature adequately describes the particular variety of Type 2 refolds in our area. So we suggest the term 'banana' for generally rounded, near-upright, Type 2 refolds, by analogy with a longitudinally cut half of a banana resting on a horizontal surface.

Penetrative cleavages in the area are expressed in outcrop by a distinctive 'Field 2' or 'transverse blade' type of fissility (Durney & Kisch 1994). This previously unrecognised structure is marked by a single plane of splitting with a pronounced, steeply pitching, linear direction and often weakly defined strike. The cleavages may transect nearby folds (Durney 1984). Field 2 fissilities have been attributed to tectonic contraction in more than one direction (Durney & Kisch 1994; Durney 2000a). Together with the observation that the penetrative cleavage/bedding intersection (in mudstone) closely parallels the Y-axis of total tectonic strain shown by deformed mudcrack polygons (Shearsby Anticline, 5 km southwest of Taemas Bridge: Durney & Hood 2000 figure 2.13), this indicates that the cleavage represents the sum of tectonic deformations undergone by the rock, as found by Lüneburg and Lebit (1998). Thus, the penetrative cleavage here is associated with all of the folds. It is not temporally correlatable with any one group of folds and so is not useful for differentiating stages of deformation.

In contrast, wavy to stylolitic spaced cleavages (Durney & Kisch 1994) frequently appear as multiple sets in limestones in the area and can be correlated with particular fold groups. These structures are pressure-solution surfaces that cut across bedding and can contribute a significant proportion of the strain associated with folding (Groshong 1975). They have been used widely in European limestone terrains for determination of regional strain directions (Choukron 1969; Plessman 1972; Alvaro 1975; Tremolieres 1981; Letouzey 1986). The stylolitic cleavages of the Taemas Bridge area have mostly angular to rounded teeth, indicating a local shortening approximately normal to the stylolitic surfaces (Fletcher & Pollard 1981). The cleavage surfaces are designated S_n according to similarity in attitude of their bedding intersections (I_n) with nearby fold axes (F_n). Bedding/cleavage intersections are here designated I_n to simplify the terminology of these structures [cf. the alternative L_n^o in the Bell and Duncan (1978) scheme]. We call the axes of teeth related to the stylolite surfaces T_n .

Vein-stylolite pairs, vein-arrays and minor shears are used as indicators of 3-D kinematic axes or principal incremental strain axes: X (principal extension), Y (intermediate axis) and Z (principal shortening) as shown in Figure 2. Two or more of these structures with mutually compatible timing and kinematic axes are called a system. Systems are designated thrust, wrench or extensional according to whether the X, Y or Z axis, respectively, lies at a high angle to bedding. One or more of such systems commonly relate to a local stylolitic cleavage or fold axis, allowing it to be correlated with a particular fold episode F_n . Cross-cutting and superposition relations between elements of these systems may provide additional evidence for timing relations between the incremental deformations and between fold episodes. Veins can occur in several sets and are, therefore, labelled V_a , V_b , etc. according to their inferred relative time sequence at each site, without

implying a correlation between sites or with fold episodes. Not all veins and stylolites form ideal orthorhombic groups as indicated in Figure 2. The procedure in such cases has been to assign priority to the mean vein-tip attitude as an indicator of the incremental YZ plane. For example,

the error in this method, if the veins occur in a single cross-parallel array (Figure 2d) (Smith 1996), is probably no greater than approximately 20°. Minor shears are comparatively rare and were found to closely follow ideal orthorhombic symmetry.

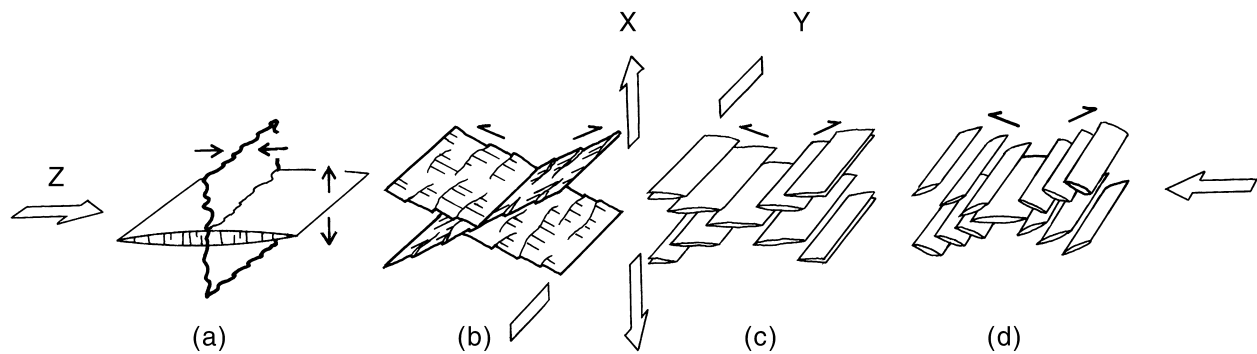


Figure 2 Models for 3-D kinematic axes associated with four types of small-scale discontinuous-structure systems (adapted from Mattauer 1976; Hancock 1985; Smith 1996). (a) Orthogonal stylolitic cleavage and extension veins. (b) Conjugate minor shears with stepped slip-fibres. (c) Conjugate arrays of bisector-parallel *en échelon* veins. (d) Conjugate arrays of cross-parallel *en échelon* veins.

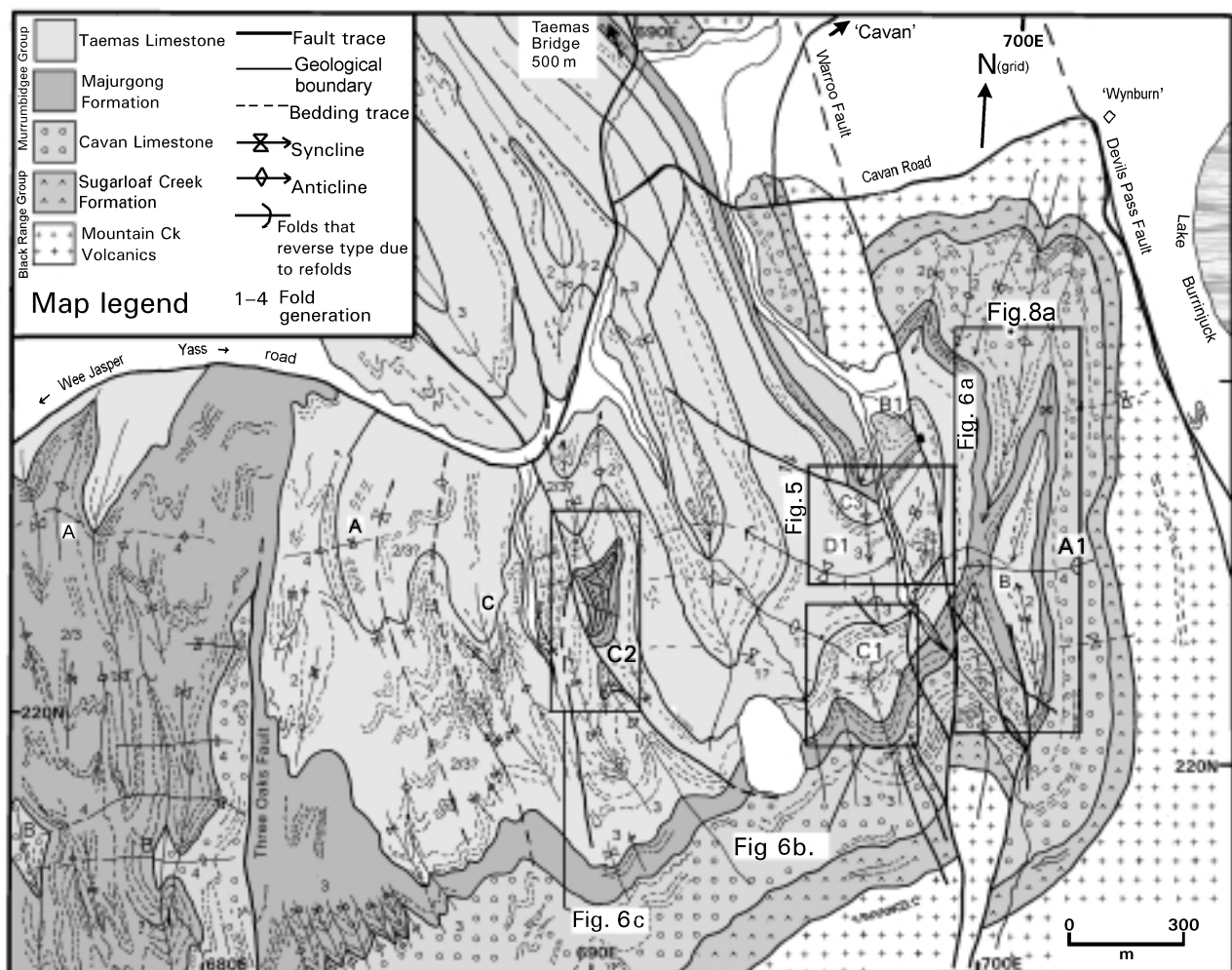


Figure 3 Geological map of Taemas Bridge area, 'Cavan' property, F_1 to F_4 fold traces (numbered by generation) and their interference patterns. See Figure 1 for location. Notable marked features include Type 2 banana bending of submeridional F_2 - F_3 folds by F_4 (A), plunge reversals due to early F_1 folds (B), crescent-mushroom Type 2 patterns towards the centre of the map (C) and banana Type 2 bending of F_1 by F_2/F_3 in a T-shaped structure (D). Specific examples mentioned in the text are given numerals (A1, B1, C1-C3, D1). Locations for Figures 5 and 6a-c are shown as rectangles and Figure 8a as a black dot. After Hood (1996).

All azimuths are referred to local grid north. Linear attitudes are given in inclination/plunge-azimuth format, and planar structures in strike-azimuth/dip/dip-sector format. Approximate structural directions are given in abbreviated form (e.g. N for north). Bedding-plane sketches and rose diagrams are viewed north or south, with respect to strike of bedding. All stereographic plots use the lower hemisphere equal-area Schimdt projection. Calculated bedding/cleavage intersections were determined from bedding/stylolite plane pairs in single outcrops by vector methods on a Microsoft Excel worksheet (Hood 1996). Calculated fold axes were derived from multiple bedding-plane attitudes in small domains by

the eigenvector method [using Georient version 4.1 (R. J. Holcombe) and SpheriStat version 2 (Pangaea Software) software].

Fold groups (Taemas Bridge)

The presence of multiple fold generations, with wavelengths ranging from metres to kilometres, observed in conspicuous to subdued outcrop, means that several characteristics are required to differentiate and group them. The fold groups are defined using data from the Taemas Bridge area, 1 km south of Taemas Bridge in the eastern half of Figure 3. Figure 3 shows the fold relationships and

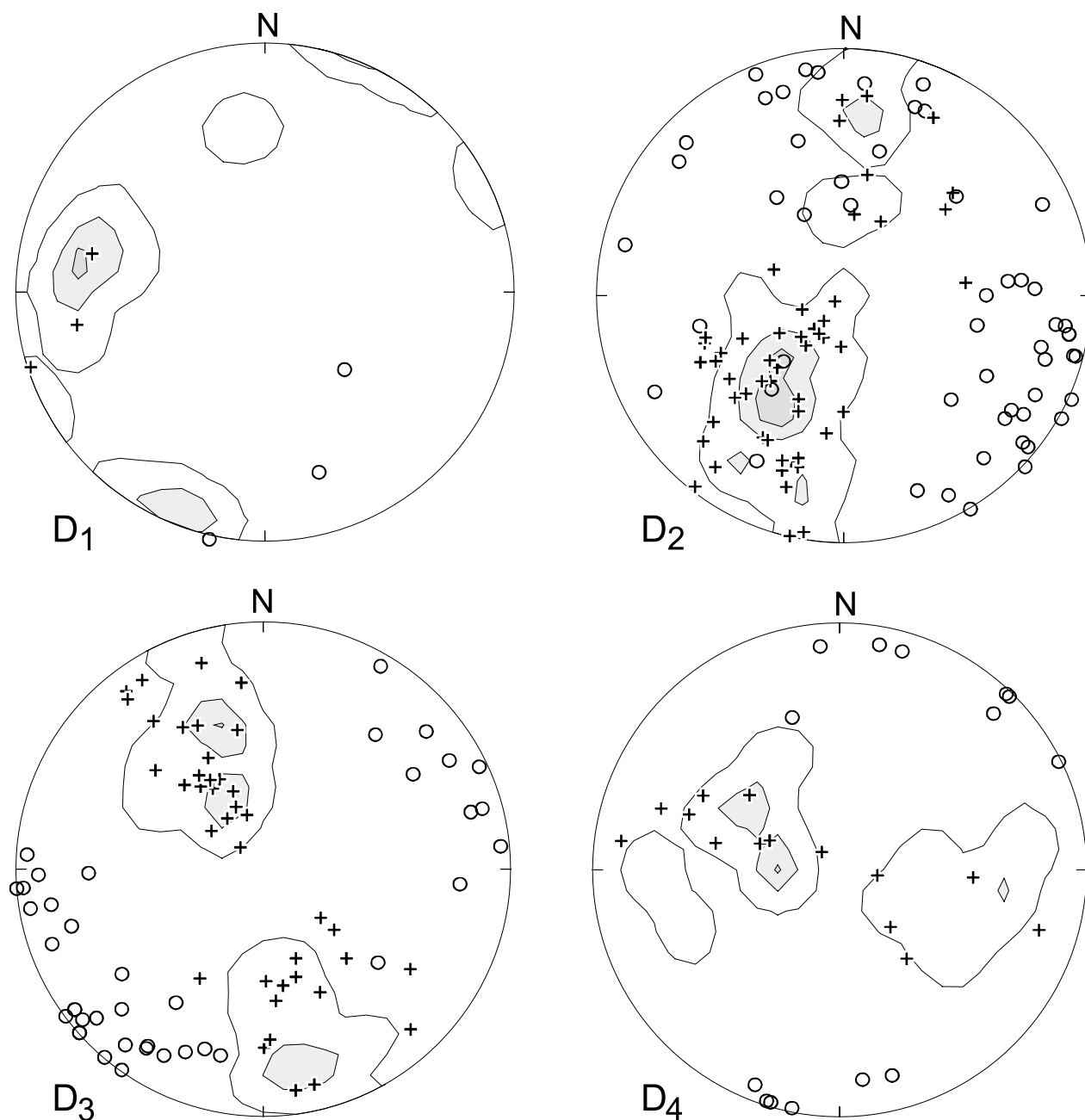


Figure 4 Synoptic equal-area stereographic projections for D₁ to D₄ structures from the Taemas Bridge area. See text for discussion. Density contours (0%, 4%, 8% area) for domain- and site-based fold axes; O, poles to site-based stylolitic cleavage planes; +, site-based stylolitic-cleavage/bedding intersection lineations. D₁ structures from fold D1, Figures 3 and 5 (14 F₁, 3 S₁ and I₁). D₂ structures (40 F₂, 48 S₂ and I₂) from the whole area. D₃ structures (25 F₃, 39 S₃ and I₃). D₄ structures (18 F₄, 18 S₄ and I₄).

interference patterns in this area and in the adjoining areas to the west.

Attitude and style were the main criteria used for separating the different fold groups. Calculated and measured fold axes from 97 domains or individual sites fall into four broad orientation groups (Table 1; Figure 4). These cluster around west/west-southwest (F_1), north/north-northeast (F_2), north-northwest (F_3) and west-northwest (F_4). The submeridional F_2 and F_3 are the dominant fold groups and were generally readily differentiated on the basis of fold trend. The sublatitudinal F_1 and F_4 groups are mostly weaker and were less easily differentiated. Data of uncertain affinity have also been measured (Hood 1996), but are not included in Figure 4.

In addition to attitude and style, superposition relations have been used to separate the fold groups (discussed in the following section). Interference with earlier or later folds indeed accounts for much of the scatter in Figure 4. Fold-axis azimuth varies most in the two earliest fold groups, F_1 and F_2 , due to Type 2 refolding by F_3 , and to a lesser extent by F_4 . All fold groups show plunge reversals due to Type 2, and especially Type 1, interference (see Table 1 for fold cluster centres, determined by cluster analysis using SpheriStat). Some additional subsets were identified by Hood (1996), but we discuss only the broad clusters here. The plunge reversal effect is especially marked for F_4 , which transects close F_2 and F_3 folds at a high angle, but is also evident for F_2 and F_3 due to local interference between these

Figure 5 Detailed map of critical outcrop area south of ‘Cavan’ homestead showing the four fold sets where they interact in the centre of a T-shape structure (fold D1, Figure 3). The locally overturned F_1 changes approximately 90° in azimuth, and slightly in inclination, due to folding by NNW–SSE-trending F_3 . F_3 changes from anticlinal to (inverted) synclinal across F_1 , characteristic of Type 2 refolding. On the eastern side of the map, small W–WNW- and E–ESE-plunging F_4 folds overprint the limbs of a N-plunging, Z-asymmetrical F_2 anticline-syncline pair that trends oblique to the hinge and the southeastern limb of the F_1 fold.

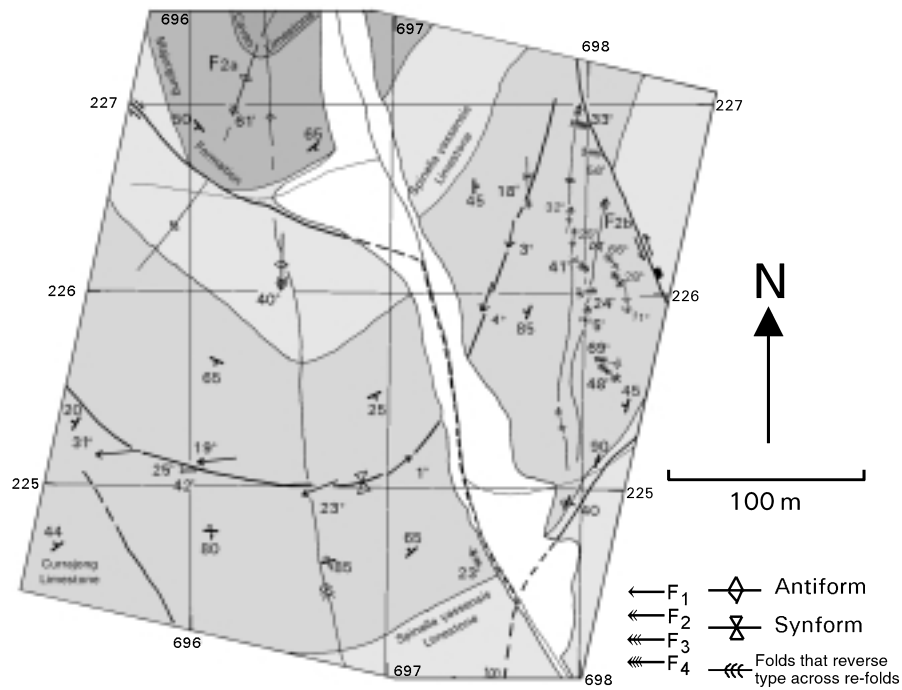
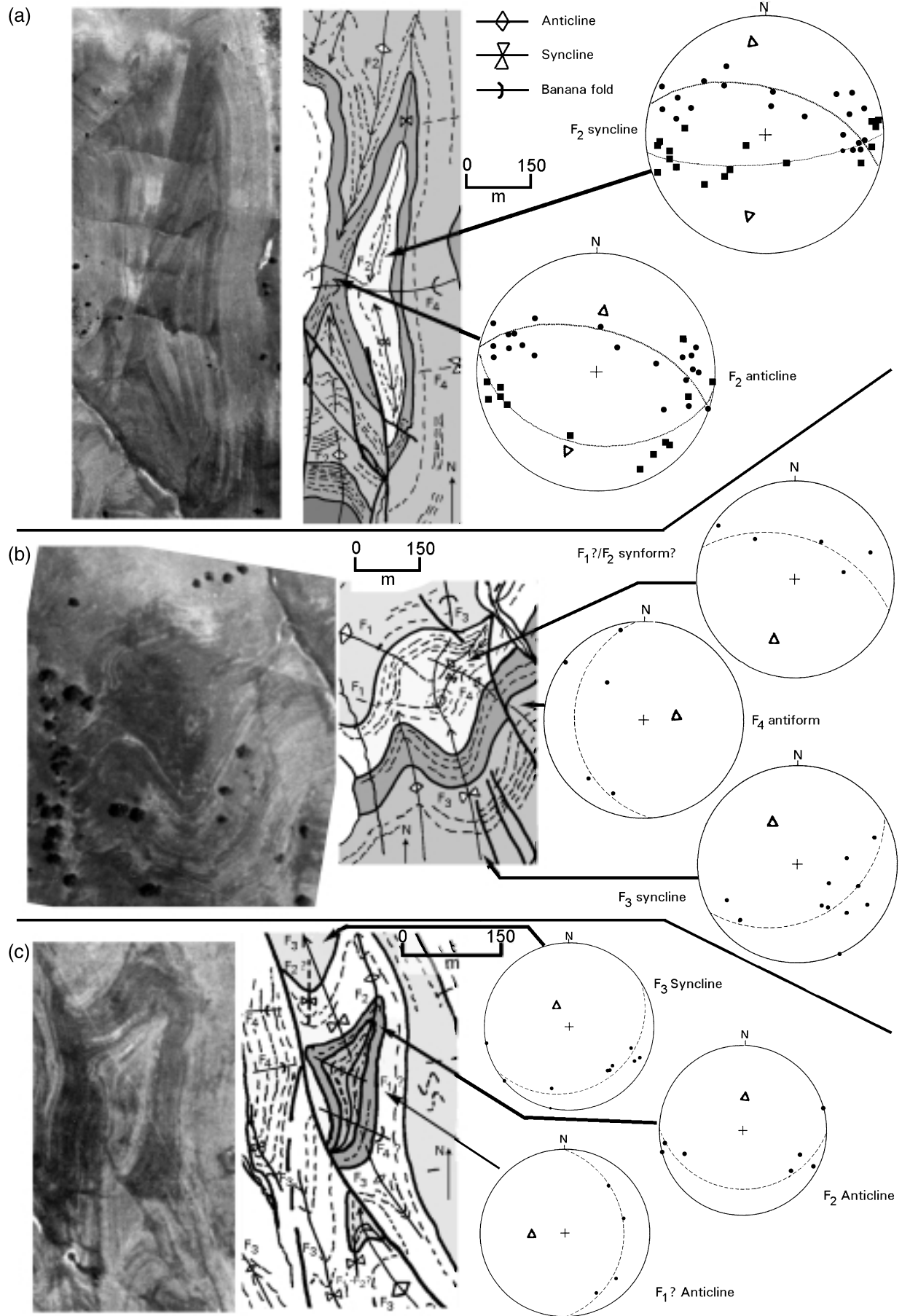


Table 1 Fold-groups and associated cleavage, Taemas Bridge area.

	D ₁	D ₂	D ₃	D ₄
Fold groups	F ₁	F ₂	F ₃	F ₄
Distinctness	Only locally distinct (fold D1)	Distinct in east	Distinct in centre, north and south	Poorly to moderately distinct
Distribution	1 definite major fold (D1) and 3 inferred/possible folds (B, C1)	Throughout	Centre and west	Throughout
Wavelength	Mainly > 4000 m	20–400 m	20–1000 m	5–1000 m
Fold-axis clusters	0°/199°, 26°/274°	33°/005°, 47°/210°	49°/333°, 26°/168°	56°/289°, 47°/103°
Axial-plane dip	Upright–steep S	Steep W and steep E	Upright–steep E	Upright
Interlimb angle	Gentle–tight	Open–nearly isoclinal, small majority close	Open–close	Mainly gentle, some folds may be tight
Shape	?Sinusoidal	Mainly chevron	Sinusoidal–chevron	Mainly sinusoidal, some chevron
Cleavages	S ₁	S ₂	S ₃	S ₄
Stylolitic cleavage limestone	Little–none	Common axial- planar to F ₂	Common to well-developed axial-planar to F ₃	Sporadic, none in in F ₄ hinges

Deformation episodes (D_n) are based on the fold groups (F_n) and related cleavages in limestones (S_n). Observations and locations in this table refer to the area in Figure 3.



groups (Figure 3) and interference between them and a broad F_1 syncline (fold D1: Figure 3).

Data for stylolitic cleavages are also included in Figure 4 and Table 1. The cleavage planes tend to be variable, mainly on account of refraction through beds of different attitude. Bedding/cleavage intersections are nevertheless broadly consistent with the fold axis distributions (Figure 4), which was our basis for correlating them with the folds.

Fold groups (Black Range Synclinorium)

Fold groups F_1 to F_3 are also recognised more widely across the Black Range Synclinorium. The dominant group is F_3 , which accounts for the north-northwest–south-southeast trend of the major fold triplet: the Wee Jasper Syncline, Narrangullen Anticline and Taemas Synclinorium (Figure 1b). The Wee Jasper Syncline is a close-tight fold with a steep west-dipping axial plane in all sedimentary units, similar to F_3 at Taemas Bridge. Thus, D_3 deformation occurred with similar direction and intensity throughout this fold and across the Black Range Synclinorium. The many parasitic F_3 folds at Taemas share these characteristics (Table 1) and so belong to the same episodes as the larger structures, an effect known as polyharmony (Ramsay & Huber 1987).

The more north–south fold trends in the north and southeast of Figure 1b may be attributed to F_2 , and the trace of the depression in the major fold triplet (dotted line in Figure 1b) to F_1 .

Fold interference patterns and timing relationships

The time relationships will be discussed mainly for the Taemas Bridge area (Figure 3), the ‘Patmores’ area farther

north, and the Black Range Synclinorium as a whole. Folds in Figure 3 are marked with numerals showing their designated groups, while letters (A, B, C, D) denote types of interference patterns: late bananas, basins, crescents and early bananas, respectively. Initial assessments for tens of metres to kilometre-size folds were made from fold interference patterns seen on aerial photographs. Axial traces determined from aerial photographs in most cases closely approach the actual trends, as the axial planes are generally steep (Figures 3, 7). Type 1, or dome-and-basin,

Figure 6 Examples of Type 1 and Type 2 refolds on ‘Cavan’ property, shown on digitally enhanced aerial photography, interpretative maps and stereographic plots (dots: bedding poles, triangles; fold axes). (a) Tight NE–SW-trending F_2 syncline-anticline pair overprints an early gentle–open ~E–W F_1 syncline resulting in a Type 1 basin and saddle (plunge reversals on plots). Later F_4 folding has produced gentle Type 2 banana bending of these structures (change of trend on plot). ■, southern domains; ●, northern domains (fold A1, Figure 3). (b) A complex structure loosely resembling an ‘ace of spades’, involving dome–basin and Type 2 refolding of a small, F_1/F_2 Z-fold pair by NNW-trending F_3 . In addition, a NW-trending F_4 fold pair (visible in the eastern half of the area) locally bends both the F_1/F_2 and F_3 axial traces in a gentle Type 2 manner (fold C1, Figure 3). (c) An enigmatic multiple-plunging and slightly double-curved dome structure (top) and a clearly defined half-crescent Type 2 refold truncated on the east by a fault (bottom). We interpret the dome as combined Type 1 and 2 refolding of a NNE-trending F_2 anticline by NNW-trending F_3 . Type 2 geometry is shown by the switch in F_3 from syncline to anticline across the dome, best seen at a distance from the dome centre. The F_2 anticline merges with F_3 to the north (see Figure 3). The W-plunging antinormal prong is probably an F_1 intersection of F_2 , in view of its tightness. The half-crescent involves NNW F_3 refolding of a N-trending F_1/F_2 syncline (fold C2, Figure 3). Maps and stereograms modified after Hood (1996), aerial photography Macquarie University 1979.

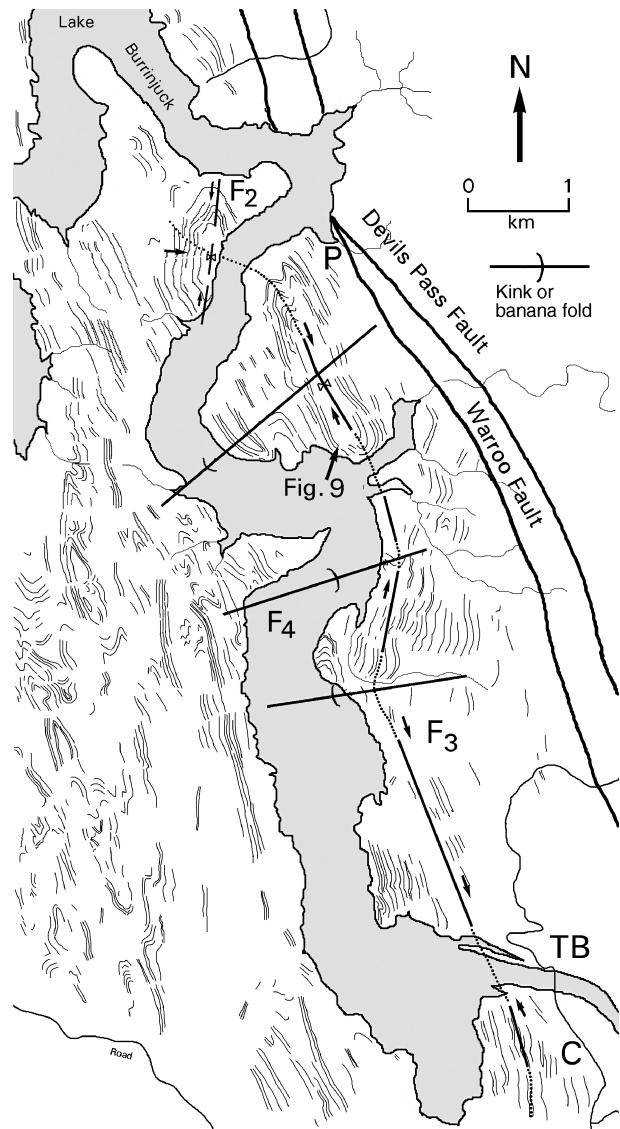


Figure 7 Aerial photographic interpretation of bedding trends showing F_4 banana folding of F_3 in the Taemas Synclinorium predominantly along the eastern shore of Lake Burrinjuck. See Figure 1 for location. The F_3 fold represents the deepest part of the Taemas Synclinorium containing the youngest members of the Taemas Limestone. The N–S F_3 basin at ‘Patmores’ (P) also displays a plunge reversal probably due to the major Black Range Synclinorium NE–SW F_1 syncline (Figure 1b). Type 1 interference with F_2 is apparent across the lake where a small N–S-trending basin occupies the northern continuation of the ‘Patmores’ fold. TB, Taemas Bridge; C, Cavan; solid arrows, plunge directions. After Hood (1996), Cramsie *et al.* (1975) and Browne (1959).

refolding is responsible for the large interference structures present in the study area. In a number of cases, these structures merge into hybrid Type 0 folds. Type 2 or banana interference is used for determining time relations. This type occurs at both small and large scales of observation and is developed between all of the four fold groups.

F_2 - F_1 INTERACTIONS

While later fold sets are generally well differentiated on the basis of trend, fold style and overprinting, a critical question concerns the separation and relative timing of F_1 and F_2 , which locally both trend in the same direction (north-northeast in the eastern part of Figure 3). Evidence for these relationships is as follows.

(1) The southeast limb of the main F_1 syncline (Figure 5) shows small north-south folds that are discordant in both trend and plunge to the local F_1 hinge. These are, consequently, a separate set with an oblique Type 1 alternating relationship to F_1 .

(2) The main F_1 syncline fold (D1 in Figure 3) is responsible for a major north-south plunge reversal of later folds across this point. To the east, this is expressed by reversed plunges in a north/north-northeast-trending elongate Type 1 saddle-and-basin pair (Figure 3 fold A1, Figure 6a). The plunge reversal here is unlikely to be caused by the east-west F_4 folding (also present) as the north-south folds are close to tight and should, thus, respond by lateral bending (banana folding) rather than by dome-and-basin folding under the weak north-south D_4 compression (cf. Grujic 1993). Therefore, the plunge reversal is attributed to F_1 , which must, albeit cryptically, turn through this point east-west and orthogonal to the north-south folds. The more variable trend of this fold supports the conclusion that it is earlier than F_2 .

(3) From north to south, F_2 folds continue with regular trend across the plunge reversal, whereas the visible F_1 folding (Figures 3, 5) swings sharply away to the west, again indicating a separate and earlier system. To the north, F_1 shares the same direction as F_2 and therefore generates a Type 0 interference pattern.

(4) At the scale of the basin syncline, the regional plunge reversal weaves about in an overall northeast direction (Figure 1b, heavy dotted line). This feature is likewise oblique to the regional north to north-northeast F_2 folds and is thus F_1 .

(5) Major north-trending F_2 or hybrid F_2/F_3 folds at the southern and northern ends of the Taemas Synclinorium (Figure 1b) are oblique to the northeast-trending regional fold-envelope traces at the northern and southern ends of the Black Range Synclinorium, further supporting a separate northeast-trending F_1 .

F_3 - F_1 INTERACTIONS

F_1 is related to a major banana (Type 2) fold in the Taemas Bridge area (Figure 5). The banana fold is designated F_3 as it is shown to be distinct from an F_2 fold north of this refold (Figure 5) (Hood & Durney 2000b). There may nevertheless be some influence of F_2 in the banana fold, which could thus also be considered a hybrid F_2/F_3 fold. Another prominent

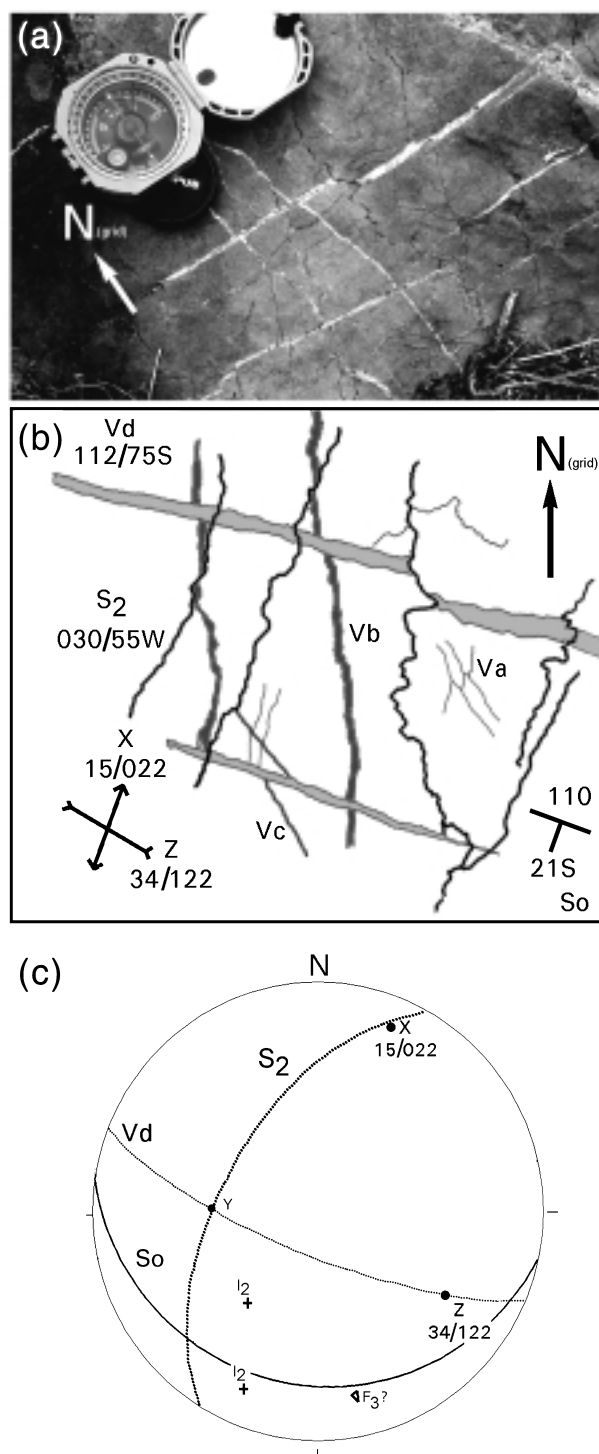


Figure 8 Vein-stylolite pairs showing wrench-kinematic deformation associated with F_2 and ? F_3 folding. (a) Bedding-plane view of stylolites and four vein sets near the hinge of a gently S-plunging F_2 anticline ($23^\circ/194^\circ$) with local superimposed F_3 ($22^\circ/168^\circ$) (Hood 1996; Site 568, Cavan Limestone, 5566997E 612313N). (b) Sketch of (a) showing S_2 stylolites (I_2 intersections $44^\circ/225^\circ$, $20^\circ/204^\circ$) contemporaneously related to youngest veins (V_a), representing wrench-style deformation during D_2 . Thin, straight *en échelon* veinlets (V_c), show similar, but more clockwise trend and are probably also related to D_2 . These structures cross cut pre- D_2 extensional veins (V_b). (c) Stereoplot for this site and immediately adjacent outcrops: Δ , fold axis; +, bedding-stylolite intersection lineation.

Type 2 example (Figure 3 fold C1) is shown in detail in Figure 6b.

Type 1 and 2 interference between the northeast-trending F_1 megasyncline and major north-northwest-trending F_3 folds (Figure 1b) is the pattern mainly responsible for the structure of the Black Range Synclinorium as a whole.

F_3 – F_2 INTERACTIONS

F_2 and F_3 are generally readily distinguished on the basis of different trends, and are often expressed as large-scale oblique Type 1 interference (Figure 3). Major merged F_2 / F_3 folds are also common: for example, the Shearsby Anticline and the syncline immediately to the west (a distinctive elliptically outcropping structure at 662E 218N), which are north- to north-northwest trending folds that are transected anticlockwise by the northwest-trending penetrative cleavage (Durney 1984).

A case of Type 2 F_3 – F_2 interference is shown in Figure 6c (Figure 3 fold C2). The pattern here is that of two crescent structures, one anticlinal the other synclinal, separated by a fault. The curved north-northeast fold traces (F_2) clearly pre-date the north-northwest bending

traces (F_3). However, these directions merge to the north (Figure 3).

F_4 – F_3 / F_2 INTERACTIONS

Gentle latitudinal bending of F_2 and F_3 folds and fold limbs occurs at a range of scales. The steeply plunging kinks and bananas on the limbs of tight host folds are Type 2 interference structures and are likely to be F_4 folds. They are best developed at the margins of the Taemas Synclinorium. Figure 5 shows examples of steep mesoscopic kinks on an F_2 / F_1 fold limb. Figure 7 shows map-scale kinking of a major synclinal fold trace further north along the Taemas Synclinorium.

Kinematics (Taemas Bridge and 'Patmores')

Three-dimensional kinematic axes associated with particular fold groups were determined using compatible systems of tectonic stylolites, veins, vein arrays and minor shears. These structures indicate mainly wrench kinematics, with three separate systems identified. Many limestone outcrops at 'Cavan' contain examples of vein arrays with wrench kinematic attitudes. A smaller number of outcrops also contain low-angle thrust veins that have been cut by wrench veins of D_2 or later generations. Earlier systems are also present and may be D_1 .

PRE- D_2 KINEMATICS

At least three sets of veins pre-date D_2 -related veins and their kinematics appear to be both wrench and probably thrust. Examples of these systems are shown in Figure 8a and b. The earlier systems occur with easily recognisable (although occasionally ambiguous) cross-cutting relationships between each other, and with D_2 .

D_2 KINEMATICS

The first known wrench system is associated with D_2 , where vein-stylolite and vein-array sets are present in or near the closures of F_2 folds. Figure 8a–c shows examples of wrench vein-stylolite sets that are related to D_2 . Principal shortening was east-southeast/southeast to west-northwest/northwest, which corresponds to the direction expected for north-northeast-trending F_2 folds. The vein-stylolite-bedding geometry indicates that the F_2 folds were stretched parallel to the fold axis during their formation (Durney 2000a).

D_3 KINEMATICS

At 'Patmores', there are clear geometric and timing relationships between mesoscale thrust faults and a north-northwest/northwest-trending F_3 fold. Southwest-dipping thrust faults (Figure 9a) occur in a complex anticlinal hinge structure that is parallel to the major $12^\circ/324^\circ$ -plunging F_3 syncline 100 m to the east (Figure 7). The intimate relationship between folding and faulting in the fold and the consistency of compression directions for the two structures suggest that they are closely related in time. Stepped slip-fibres on the fault planes and low-angle

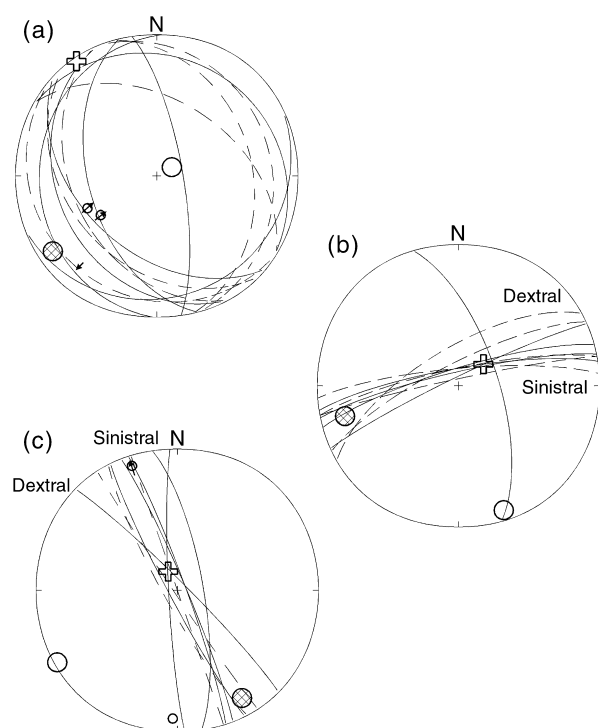


Figure 9 Minor faults and vein arrays in Crinoidal Limestone Member at 'Patmores'. See Figure 7 for location. Solid great circles: fault and array planes; broken great circles: feather and *en échelon* veins; small open circles: striae; large circles: mean kinematic axes, shaded Z and open X; open cross: mean kinematic axis Y. Sinistral and dextral labels indicate respective movement senses of conjugate shear planes. (a) Syn- D_3 minor thrust-faults, striae and feather veins, bedding attitude $252^\circ/15^\circ\text{W}$ (site 565, Hood 1996; 556662E 61303N). (b) Late D_3 cross-parallel vein arrays, bedding attitude $168^\circ/75^\circ\text{E}$ (site 559, Hood 1996; 556662E 61305N). (c) Post F_3 (D_4) minor wrench faults, striae and feather veins cross-cutting D_3 minor thrusts (site 565).

feather-veins associated with the faults show hangingwall movement to the northeast. Conjugate arrays of low-angle *en échelon* veins are also intimately associated with the faults. Kinematic axes for this system (D_{3a}) were determined from eigenvectors of the combined mean conjugate shear- (fault- and array-) planes and the corresponding two

mean veins planes (cf. Figure 2b and d). The directions are X: $80^\circ/060^\circ$, Y: $1^\circ/325^\circ$ and Z: $10^\circ/234^\circ$ (Figure 8a). The shortening axis (Z) is orthogonal to F_3 and is, thus, in the direction expected for F_3 folding at this site.

The second wrench system (D_{3b}) is interpreted to post-date D_{3a} . Steep east-west- and east-northeast-west-

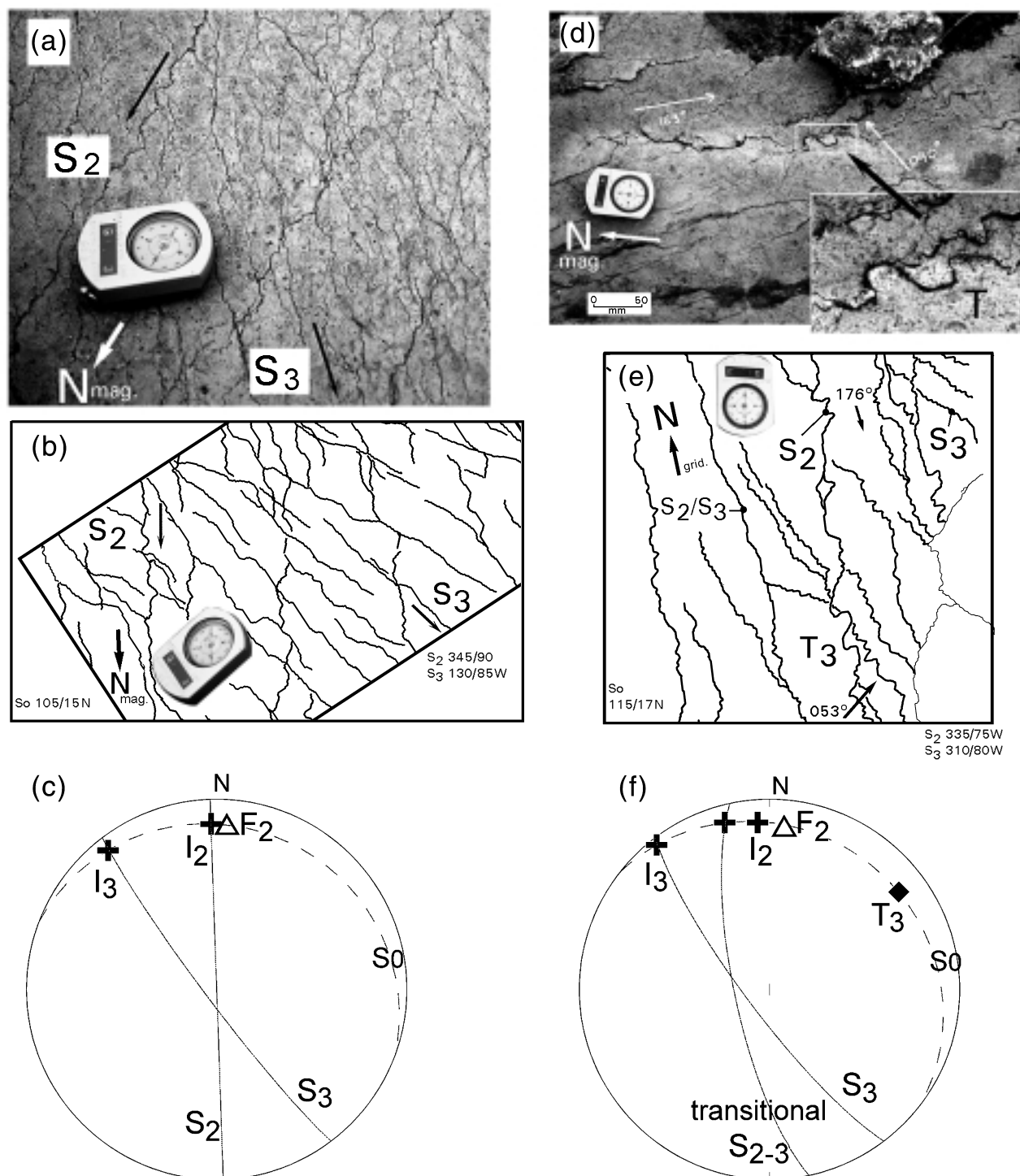


Figure 10 Stylolite traces on bedding (a) and (d) from the west limb of a N-plunging F_2 syncline, Cavan Limestone (556662E 61218N). Example (a) and its interpretation (b) show two intersecting stylolite sets, with the N-trending set (S_2) being more widely spaced and continuous. Example (d) and (e) shows S_3 dissolution reactivating the earlier S_2 stylolite to produce teeth (T_3) oblique to S_2 . (c) and (f) are the corresponding stereographic plots. Location shown in Figure 1. Stereoplot key: F_n , fold axes; I_n , intersection lineations; S_n , stylolitic cleavage planes; S_0 , bedding.

southwest-trending, wrench-style, cross-parallel (Smith 1996), *en échelon* veins in the steep western limb of the major F_3 syncline on 'Patmores' show a mean principal shortening Z : $18^\circ/255^\circ$ (Figure 9b). This is approximately consistent with F_3 folding and the D_3 thrusts (Z : $10^\circ/234^\circ$). However, the extension direction (X : $7^\circ/160^\circ$) is nearly parallel to F_3 , analogous to the D_2 wrench veins at Taemas Bridge. The wrench veins at 'Patmores' both cut, and are cut by, well-developed bedding-parallel stylolites. The stylolites are interpreted to have been original compaction structures that were reactivated by east-northeast–west-southwest shortening late in the F_3 folding (they are best developed on steep fold limbs). We, therefore, assign this system to late D_3 .

It is reasonable to conclude, then, that D_3 contains elements of both thrusting and wrenching, either sequentially or alternating, depending on slight variations in the strain field. Of the two D_3 deformation styles, thrusting appears to be more widespread, as indicated by common occurrences of low-angle (? D_3) veins in roadside exposures of the Taemas Bridge area.

D_4 KINEMATICS

The thrust faults at 'Patmores' are overprinted by minor wrench faults with subhorizontal slip-fibres. Veins associated with the wrench faults cut thrust-fault-related veins. Dextral faults trend northwest–southeast and sinistral faults trend north–south (Figure 9c). The mean shortening direction, determined from the mean fault and vein planes (Z : $12^\circ/149^\circ$) is consistent with east-northeast–west-southwest D_4 folding in the area (Figure 7).

Stylolite–stylolite relations (west of Taemas Bridge)

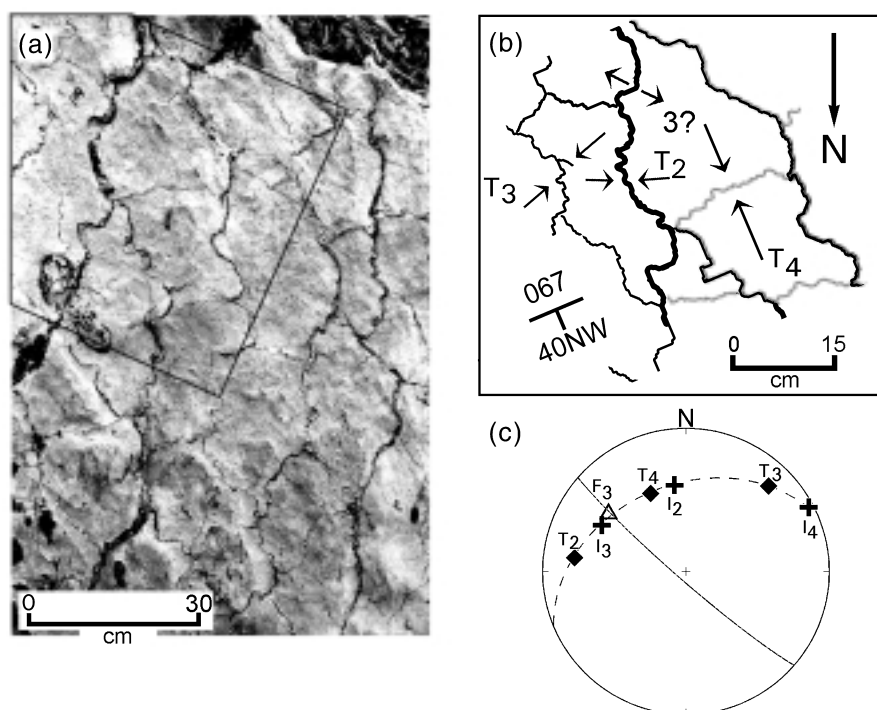
Some limestone beds, notably in the Cavan Limestone, contain two or more stylolitic cleavages (transverse to

bedding), which provide further evidence of multiple contractional deformation in the region. Different sets can be recognised according to preferred orientations of their intersections (I_n) with bedding and/or their column or teeth axes (T_n), which lie in the plane of bedding.

Figure 10, from a distinctive syncline approximately 5 km southwest of Taemas Bridge (Figure 1b), shows two examples with north–south and northwest–southeast stylolites. Each of the two directions appears to have developed by the process of 'anticrack' propagation (Fletcher & Pollard 1981) normal to its respective maximum principal compressive stress (principal incremental shortening strain) direction. The north-trending set is the more continuous of the two (Figure 10a, b). We explain this by interrupted propagation: propagation of the northwest set is interrupted by the prior existence of the north set. Thus, the northwest set is more discontinuous and inferred to be younger. The stylolite teeth (T_3) of the northwest-trending stylolites are superimposed on the north-trending stylolites (Figure 10d, e). The teeth of a pre-existing stylolite, when subjected to an oblique shortening, may be reactivated and grow in the new shortening direction and may, thus, appear oblique to the stylolite trend. This also places the northwest set after the north set in time. As these sets correlate geometrically with D_3 and D_2 , respectively, their time relation corroborates evidence from fold superposition that F_3 (D_3) structures post-date F_2 (D_2).

As shown in Figure 11, desiccation cracks may control the local stylolite-trace directions in some beds and become strongly indented by the stylolitisation process. Three sets are recognised from stylolite teeth directions. The thick north–south set has been reactivated by oblique compression, opened and filled with vein calcite in places, subsequent to its dissolution stage. As the opening best correlates with D_3 , this reinforces the inferred sequence that the northwest–southeast stylolite set (S_3) post-dates the north–south

Figure 11 Example of multiple stylolite interactions in Cavan Limestone, near the hinge of a small F_3 syncline adjacent to Mountain Creek Road, 556678E 61203N (location on Figure 1). Bedding-plane image (a) and its interpretation (b) show S_2 , S_3 and S_4 stylolites (I_2 , I_3 and I_4) preferentially formed on the sides of pre-existing mudcrack polygons. Polygon elongation shows the total strain in bedding, which lies intermediate between I_2 and I_3 (Durney & Hood 2000). S_3 has reactivated S_2 , which opened and filled with calcite. (c) Stereoplot: +, stylolite/bedding intersections; ♦, stylolite teeth trend; △, fold axis; solid line, axial plane. Modified after Durney and Hood (2000).



set (S_2). A further compression direction is shown here by the east-northeast stylolite set, which is presumed to be S_4 (D_4) as the stylolite teeth appear to be undisturbed.

Up to four stylolite-trace directions and teeth directions are present in the Wee Jasper Syncline (Figure 12). Although relative timing is less clear in this example, the three main sets (labelled I_2 to I_4) show orientations roughly similar to F_2 to F_4 folds and S_2 to S_4 stylolitic cleavages in the Taemas Synclinorium (Figures 4, 11). This strongly suggests that deformation associated with the D_2 to D_4 events also exists in the Wee Jasper Syncline and, thus, throughout the Black Range Synclinorium.

Faults

There are two major faults in the Taemas Bridge area, which extend approximately north-northwest-south-

southeast for kilometres. The easternmost is the Deakin-Devils Pass Fault, which separates the Lower Devonian basin sequence from the Silurian Yass Basin rocks to the east (Figure 1b). The Warroo Fault, approximately 500 m to the west, shows sinistral strike-slip displacement of the major F_1 fold with a component of east-side-down dip-slip (Figure 3). Approximately 2 km further west again, a steeply west-dipping reverse fault that we call the Three Oaks Fault, displaces and attenuates the east limb of a north-south F_2/F_3 anticline (Figure 3). In our interpretation this fault, rather than the Warroo Fault, may join the Dingo Dell Fault to the south (Figure 1b).

Faulting post-dates the Murrumbidgee Group and truncates the F_1 and F_2 fold generations and, at 'Patmores', F_3 . No F_4 fold traces were found displaced by faults. The Devils Pass and Warroo Faults are slightly sinuous and concordant with F_3 , indicating that they both could have

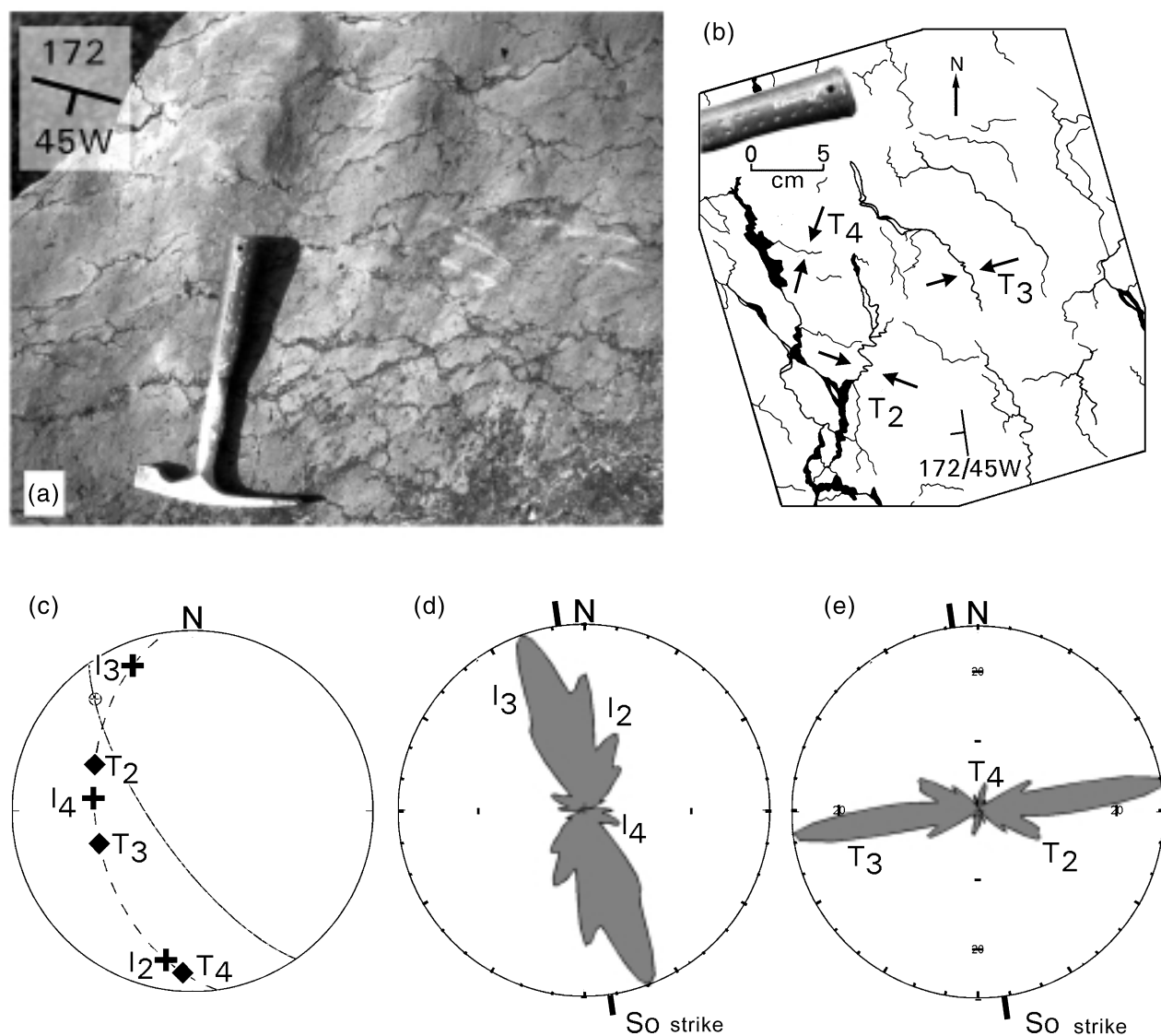


Figure 12 Intersecting tectonic stylolitic cleavages in massive Cavan Limestone, east limb of Wee Jasper Syncline on Wee Jasper Road, 556533E 61135N (location in Figure 1). (a) Bedding plane viewed east (photo courtesy of R. Higgs 1996). (b) Interpretation of (a) showing three principal sets of stylolite teeth (T_2 to T_4 , assuming a correlation with Taemas Bridge and Mountain Creek areas). S_2 disrupted by S_3 , and S_4 branch from S_3 . (c) Stereoplot: +, stylolite intersections; ♦, mean stylolite teeth, both on bedding; fold axis (○) and axial plane (solid line), both of Wee Jasper Syncline. (d) Rose diagram of stylolite-bedding intersections, linear frequency scale ($n = 107$). Note minor subgroup of I_3 stylolites. (e) Rose diagram of stylolite teeth in bedding, linear frequency scale ($n = 107$).

been folded by F_4 . Certainly, the Three Oaks Fault is gently folded by outcrop scale F_4 . Although the downthrow on the Devils Pass Fault is stratigraphically to the west, the presence of F_2 folds with predominant wrench deformation approximately 30° clockwise from this fault (Figure 3) is geometrically and kinematically compatible with possible sinistral movement on the fault (Hood & Durney 2000b). The Three Oaks Fault probably also began to form at about this time, although its orientation is north-south and its movement is reverse rather than wrench.

The minor faults trend predominantly northwest-southeast and northeast-southwest and some of these link up to the major faults, suggesting that they may be splay faults, particularly near the major fault terminations (Ramsay & Huber 1987; Bürgmann & Pollard 1994).

DISCUSSION

Superposed folding: Black Range Synclinorium

This study suggests that the deformation history of Devonian rocks in the Black Range Synclinorium is more complex than previously envisaged. As noted by Browne (1959) in earlier 1:44 000 mapping, 'domes and basins' and folds with a 'sinuous course' are fairly common in the Taemas Synclinorium. These patterns can also be found in strata of similar age in other parts of the Eastern Lachlan Fold Belt, such as the northern part of the Hill End Trough (Colquhoun *et al.* 1997), although a single 'submeridional' fold direction usually dominates. In the

Black Range Synclinorium, the dominant fold direction is north-northwest, but is ornamented by patterns of the kind referred to by Browne (1959). In the more complex southeastern margin of the Black Range Synclinorium at Taemas Bridge, detailed 1:10 000 to 1:280 scale mapping and domain analysis (Hood 1996) has shown four distinct fold trends and associated stylolitic cleavages, which, as discussed here, can be established in a time sequence using critical Type 2 fold-interference relations. Elsewhere, the first three of these generations could be recognised across the entire Black Range Synclinorium from Type 1 (dome and basin) and Type 0 (hybrid, north-south, F_2/F_3) patterns and from stylolitic cleavage and stylolite teeth directions in certain limestone units (multiple stylolite generations in Figures 10–12). Only F_4 seems to be restricted to the Taemas Synclinorium, although minor stylolites of this possible age are present in the western (Wee Jasper) region as well (Figure 12). These observations show that the successive D_1 to D_4 convergent ductile deformations, which range widely in direction, are not restricted to the Taemas Bridge area, but exist regionally throughout the Black Range Synclinorium.

The only other detailed structural sequence to our knowledge was reported in brief excursion notes (Durney 1984) for an area around 'Mountain Creek', 3 km southwest of Taemas Bridge. This area is representative of the more common situation where Type 2 interference is absent to weakly developed. The main overall folding and penetrative cleavage were referred to as F_1 and S_1 , respectively, with four subsets of F_1 being recognised on the basis of restricted domains of differing fold trend and fold tightness

Directions	Browne (1959)		Durney (1984)			This paper			
	Sp	F	Sp	F	Ss	Sp	F	Ss	K
WSW		Cross-warping	2						
W							4	4	
WNW				1d	1d				Minor wrench
NW			1	1c	1c	1–4	3	3	
NNW	Cleavage	Folding		1b	1b				b) Minor wrench a) Thrust
N				1a			2/3	2	
NNE							2		Wrench
NE							1	1	Minor thrust

Figure 13 Development of ideas on structural orientation groups in the Taemas Synclinorium. Sp, penetrative cleavage; F, folds; Ss, stylolitic cleavage; K, kinematics. Numbers and letters represent time episodes and stages, respectively.

in Type 1 alternating relations, called a, b, c and d. It was suggested that successive initiation of fold subsets during a progressive anticlockwise rotation of incremental shortening during F_1 resulted in decreasing tightness of the subsets, from north (F_{1a}) through to west-northwest (F_{1d}). This was supported by an F_{1a} – F_{1c} banana relation at 'Mountain Creek', anticlockwise transection of the main north-northwest F_{1b} folds by northwest S_1 and transection of early west-northwest bedding-plane slip striae (F_{1a} episode) by northwest S_1 and small-scale F_{1c} . S_2 was a postulated second cleavage thought to account for steeply plunging pencil structure in S_1 , a feature now explained by non-coaxial deformation during the S_1 (Durney 1984) cleavage event (Durney 2000a). Ideas on the kinematics and structural systems for the Taemas Synclinorium presented by various workers are shown in Figure 13.

Superposed folding: correlated in other Eastern Lachlan Fold Belt localities

Farther afield, Powell *et al.* (1985) have recognised west-northwest and east-northeast 'megakink' zones (Type 2 refolds) in Silurian to Upper Devonian units around the Hill End Trough, implying an episode of north–south shortening imposed on earlier 'submeridional' structures, both deformations being of Carboniferous age. Lennox *et al.* (1998), using new and existing radiometric data from granites in the Molong Zone, also recognised Carboniferous north–south compression, but interpreted submeridional foliation in granite as Middle Devonian. In contrast, Glen and Watkins (1999) suggested a period of Middle Devonian north–south shortening prior to the submeridional folding from observations on the eastern margin of the Hill End Trough. Our observation of D_4 north–south shortening late in the history of the Black Range Synclinorium is theoretically compatible with the sequence of Powell *et al.* (1985), and has the correct kinematics for kink or banana style refolding (wrench-kinematic, consistent with flexural slip about a steeply plunging axis). But the D_4 structures here are relatively weak and localised and do not appear to generate folds of megasynclinorium scale. We suggest that much of the sinuosity in the Black Range Synclinorium can be attributed instead to oblique Type 1 superposition of F_2 and F_3 folds, as evidenced by frequent bifurcation, domainal alternation, plunge reversals and non-concordance of the structures.

Recent work has shown that multiple fold systems also exist farther north in the Gilgandra–Cowra–Yass Zone, in Upper Devonian Hervey Group strata between Manildra and Grenfell (Gribbin 1996; Fountain 1997; Warner 1998; Durney 2000b) summarised in Durney (2000a). Domainal and locally interfering, major north-northeast and north/north-northwest folds occur in this region, consistent with F_2 and F_3 , respectively, in the present area. Late west/west-northwest folds are also postulated, although their relationships are less certain.

Fold timing

Browne (1959) suggested that the folding in the Taemas Synclinorium 'probably' occurred in the Tabberabberan event (approximately Middle Devonian), a view that

does not appear to have been much questioned in later writings about this region [apart from a reference to possible Kanimblan effects by Owen and Wyborn (1979)]. Scheibner and Basden (1998) further suggested that Middle to Upper Devonian Lambie–Hervey-type facies sedimentary sequences were deposited in 'foreland basins' that formed in response to coeval thrusting and thrust-loading. We have been unable to find evidence for any Middle Devonian convergent or fold-forming deformation event in the Black Range Synclinorium. Our earliest recognised convergent event, D_1 , post-dates Middle Devonian Hervey-facies beds of the Hatchery Creek Conglomerate in the Wee Jasper Syncline. The outcrop pattern of the Hatchery Creek Conglomerate appears to be controlled by a combination of an F_1 syncline, and a pronounced hybrid F_3/F_2 syncline to produce a basin structure. The eastern half of the Taemas Synclinorium itself can be traced to the north along the north-northwest F_3 trend into the Koorawatha Syncline (Brunker & Offenberg 1970), a structure that folds the Upper Devonian Hervey Group on alternating north-northwest and north/north-northeast trends similar to F_3 and F_2 at Taemas Bridge (Durney 2000a).

Critical to this question is the nature of the Hatchery Creek Conglomerate and its contact with the underlying Taemas Limestone in the Wee Jasper Syncline. As noted earlier, no angular discordance has been observed in this area, the two units being completely concordant with one another both at map scale (Figure 1b and, in more detail, Pedder *et al.* 1970 figure 1) and where we have seen the contact in the field (on both limbs of the syncline). In addition, it would appear that, on current palaeontological evidence, no definite time gap can be inferred to separate the two formations. If thrusting occurred during deposition of the Hatchery Creek Conglomerate, from the time of D_1 onwards, immature detritus of the Silurian Goobragandra Volcanics and associated intrusive complexes would have been expected to be shed into the Hatchery Creek Conglomerate from the upthrown block situated immediately to the west. No clasts of these rock types have been reported, or observed by us. The Hatchery Creek Conglomerate is composed principally of mature quartz-rich sediment, including quartzite and vein quartz, suggesting derivation from a distant source. A recent palaeontological review by Mawson and Talent (2000) places the Hatchery Creek Conglomerate in the latest Emsian to middle Eifelian, which theoretically allows Tabberabberan folding and thrusting *after* deposition of the Hatchery Creek Conglomerate and before the Upper Devonian Hervey Group (Owen & Wyborn 1979). However, this would have produced significant discordance between, or possibly within either of, the Middle and Upper Devonian successions. No such discordances have been reported from the northern Eastern Lachlan Fold Belt, nor any internal discordances or fold-related thickness variations within these groups of the kind that would be expected if deposition occurred during thrusting and folding (Ford *et al.* 1997).

The conclusion we draw from these observations is that all four of our convergent folding events, D_1 to D_4 , together with associated or later faulting, post-date the Middle to Upper Devonian sequences. That is, the deformation occurred during the Carboniferous Kanimblan event. This

accords with the major Kanimblan deformation suggested by Powell *et al.* (1976) for the Hill End Trough, except that they noted some gentle Middle Devonian angular discordances in that area. Only mild topographic uplift, signalled by a change from shallow marine to terrestrial environment, can be inferred for the Wee Jasper area at this time.

Episodic or continuous deformation?

Concerning episodicity versus continuity of convergent tectonic activity, our finding of a Carboniferous age for the folding would indicate that the Devonian succession experienced only a terminal, and therefore single, convergent tectonic event. However, as shown by the multiple fold systems that were formed, there was a progressive anti-clockwise rotation of the shortening direction, relative to the affected rocks, during this time in the Black Range Synclinorium. This may indicate a rotation of the external stress field, either through partitioning as suggested by Glen (1992) or fundamental changes such as changing plate motion vectors. The alternative—a clockwise rotation of the rocks in small blocks during constantly orientated strain—lacks evidence for the required blocks and their independent rotations.

Kinematics: wrenching and thrusting

The alternation of wrench and thrust kinematics further suggests that changes in applied strain occurred. Folds associated with D_2 show slight *en échelon* characteristics adjacent to the eastern bounding faults and have possible early thrust kinematics, but predominantly wrench kinematics. This indicates that D_2 involved either sinistral transpression [cf. Gray and Mortimer (1996) on folds in the Mt Wellington Fault Zone] or sinistral shear motion parallel to the north–northwest–trending boundary faults (Hood & Durney 2000a). The reverse situation is associated with D_3 structures, which show predominant northeast–southwest-directed thrust kinematics overprinted by two later wrench-deformation events. This later wrenching is both integral with D_3 and related to weak D_4 deformation. Thrust(?) faulting may be more widespread, as at Bungonia to the northeast where Glen (1992) and Fergusson (1998) noted the presence of west-dipping thrusts affecting Lower Devonian limestone and also the Upper Devonian associations.

CONCLUSIONS

Four generations of convergent deformation, called Taemas D_1 to D_4 , have been established for the Lower Devonian carbonate sediments of the Taemas Bridge area in the Eastern Lachlan Fold Belt using map-scale banana Type 2 fold superposition relations and associated stylolitic cleavages, S_1 to S_4 , and are recognised regionally across the Black Range Synclinorium: D_1 —broad, gentle, sinuous, northeast folds, responsible for regional north to south plunge-reversals of later submeridional synclinoria; D_2 —north to north-northeast map-scale folds and stylolitic cleavage in limestone; D_3 —dominant north-northwest

map-scale to regional folds and associated north-northwest to northwest stylolitic cleavage in limestone; and D_4 —mesoscale to map-scale gentle sublatitudinal warping of close F_2 and F_3 folds on the eastern margin of the Taemas Synclinorium and related weak stylolitic cleavage regionally in limestone.

Type 0 and oblique Type 1 interference between F_2 and F_3 folds are common. Mudrocks display a single north-northwest/northwest penetrative cleavage that is believed to represent the sum total of all of the deformation systems.

Kinematic indicators, comprising vein arrays, stylolite-vein pairs, minor faults and fault-vein pairs, show a minimum of five kinematic stages alternating between wrench and thrust deformation during D_1 to D_4 folding. Combined with the trend of the fold structures, the D_2 kinematics indicate a dominant sinistral wrenching or transpression on the eastern bounding faults, whereas D_3 indicates a dominant contraction normal to these faults. D_4 kinematics are consistent with subhorizontal flexural slip on steeply dipping F_2 and F_3 fold limbs. The possible role of D_1 is unclear and requires further examination.

These deformations post-date the Middle to Upper Devonian Hervey-facies sediments of the region, and are therefore ascribed to the Early Carboniferous (Kanimblan) regional folding event. No evidence is found for fold-forming deformation of Early, Middle (Tabberabberan event) or Late Devonian age in the Black Range Synclinorium and its continuation to the north.

The results suggest that simple tectonic models and two-stage histories, (east–west shortening followed by north–south shortening) for the Kanimblan event in the area need to be reviewed in light of the nature of the observed deformation history. The sequence of deformations shows a marked anticlockwise, non-coaxial progression of incremental shortening with time, accompanied by alternations between wrench- and thrust-style kinematics. The extent and cause of this pattern are presently unknown, although the results suggest that the Kanimblan deformation in the Lachlan Fold Belt could be more complex than previously envisaged.

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