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Structural evolution of the Porcupine Creek anticlinorium, Western Main Ranges, Rocky Mountains, British Columbia

W. H. LICKORISH

Department of Geology and Geophysics, University of Calgary, Calgary, Alberta, Canada T2N 1N4

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Abstract—The structure of the Western Main Ranges of the Canadian Rockies is dominated by the Porcupine Creek anticlinorium. The anticlinorium developed by internal deformation of thrust sheets formed above relatively flat décollement horizons. Deformation continued by a downward stepping of décollement horizons. Earlier décollements, formed at a high structural level, were folded and the thrust sheets above redeformed by continued deformation on deeper, later décollement horizons. The successive décollement horizons occurred not only deeper but also in a more northward location, leaving deformation in only stratigraphically higher positions in the south, but producing deeper structures to the north. This northward progression of décollement horizons requires that the Porcupine Creek anticlinorium grew diachronously from south to north with earlier structures preserved in the south and later ones developed in the north.

Motion on each décollement horizon produced an additional phase of deformation in the rocks above it. However, additional structures could only develop locally where pre-existing structures were at sufficiently high angles to the orientation of incipient structures. Elsewhere the previous anisotropy prevailed and early phase structures were tightened with no evidence of the later phase.

INTRODUCTION

THE Porcupine Creek anticlinorium, the dominant structure of the Western Main Ranges of the southern Canadian Rocky Mountains, lies between the relatively simple thrust belt of the Rocky Mountains to the east (Bally *et al.* 1966, Price & Mountjoy 1970) and the complex multiple deformations of the Columbia Mountains to the west (Simony *et al.* 1980). It is therefore likely to have evolved structurally in a manner transitional to the two styles.

The Rocky Mountain Main Ranges are composed of late Proterozoic and early Palaeozoic strata (Fig. 1) carried in few major thrust sheets. The Eastern Main Ranges (Figs. 2a&b) are composed of a series of large thrust sheets formed in a normal foreland propagating fashion (Bally *et al.* 1966). Within these sheets the Palaeozoic succession, dominated by platform limestones, forms relatively simple structures with minor thrust splays separating large folds (Fig. 2b). A decrease in the structural competence of the stratigraphy in the Western Main Ranges causes a corresponding change in structural style to smaller thrust sheets internally deformed by multiple phases of folding and the strong development of slaty cleavage (Cook 1975).

The Porcupine Creek anticlinorium dominates the structure of the Western Main Ranges for more than 250 km along strike from a region northeast of Cranbrook (Leech 1958) almost to Valemount (Klein & Mountjoy 1988) (Fig. 2a). At its southern end it is a relatively narrow structure separated from the Eastern Main Ranges by other folds of the same deformational style as the Western Main Ranges (Leech 1958, Balkwill 1972). With its slight southeast plunge, and non-cylindrical nature, the core exposes progressively deeper rocks to the northwest. The structure also widens northward with its eastern flank eventually encroaching on the carbonate facies of the Eastern Main Ranges. Towards the north, the anticlinorium becomes indistinct as it broadens towards the Yellowhead culmination and the component structures of the anticlinorium become significant in their own right.

Detailed structural studies of the Porcupine Creek anticlinorium from Golden to the Sullivan River (e.g. Balkwill 1972, Gal 1990) (Figs. 2a and 3) have shown the anticlinorium to consist of a complex association of folds and faults with considerable strike-parallel variation in structural style.

The results presented here are largely based on field work undertaken in an area of about 700 km^2 of the Western Main Ranges between the Sullivan and Wood rivers (Fig. 3). In this area, Upper Proterozoic strata start to outcrop in the core of the anticlinorium with Palaeozoic strata exposed only on the limbs. For structural analysis the area has been divided into domains of different structural styles (Fig. 4a). In the westernmost exposures a detachment zone separates the Middle Cambrian Chancellor Group from the underlying Lower Cambrian Gog Group (Meilliez 1972, Ferri 1984, Gal 1990). The rocks above the detachment (domain 1) show two phases of folding, whereas the Gog Group and the upper part of the underlying Upper Proterozoic Miette Group strata (domain 2) show only one. Miette Group strata exposed in the core of the anticlinorium (domain 3), however, also preserve polyphase structures. These become more intense at structurally deeper levels, and point to the existence of detachment on a horizon within the Miette Group. Overprinting relationships of structures indicate relative ages of deformational events, and can be used to reconstruct the evolution of the Porcupine Creek anticlinorium.

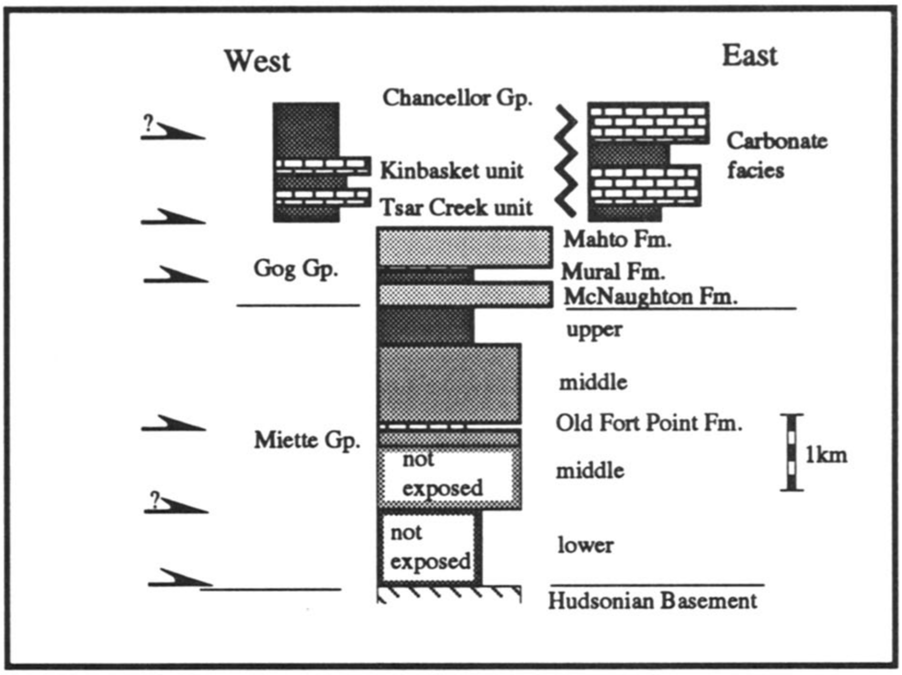

Fig. 1. Generalized stratigraphic section for the Main Ranges. The thickness of the McNaughton Formation is shown at its thinnest. Typical glide horizons are shown by the arrows on the left.

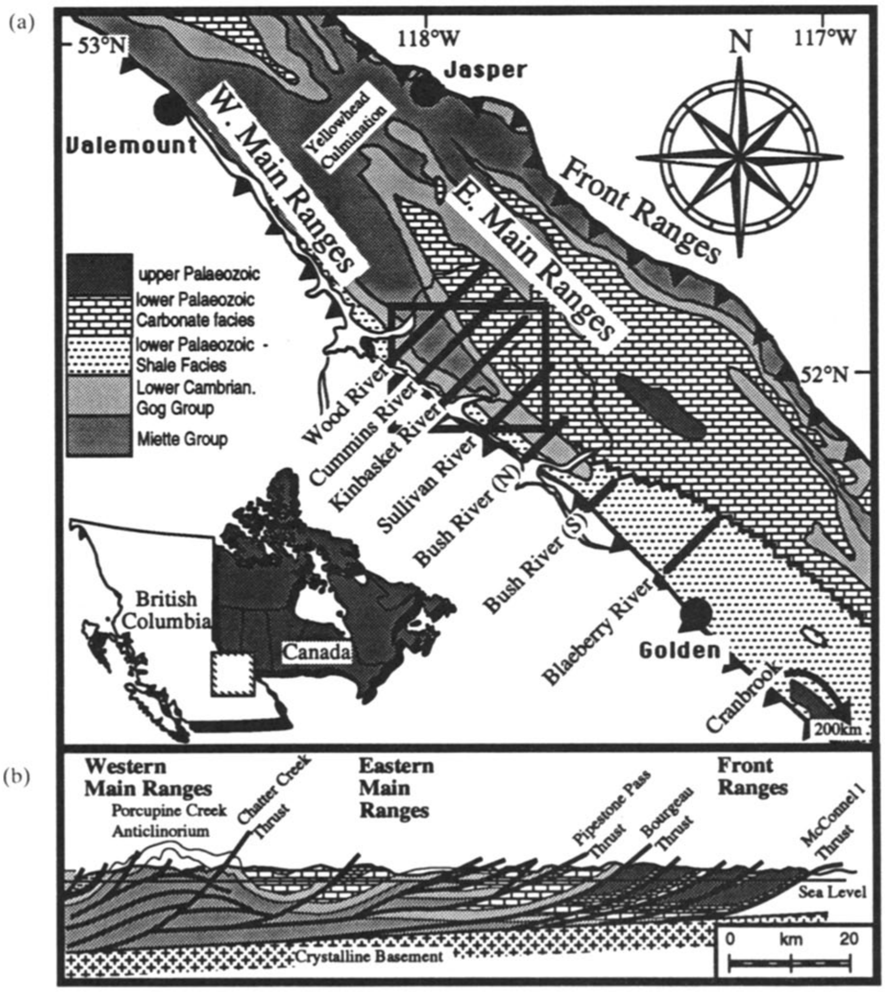

Fig. 2. (a) Geology of the Rocky Mountain Main Ranges between Golden and Valemount. Boxed area is shown in detail in Fig. 3 and cross-sections in Figs. 10 and 11. (b) The Wood river cross-section extended across the Eastern Main Ranges and Front Ranges, illustrating thin-skinned thrusting in the foreland.

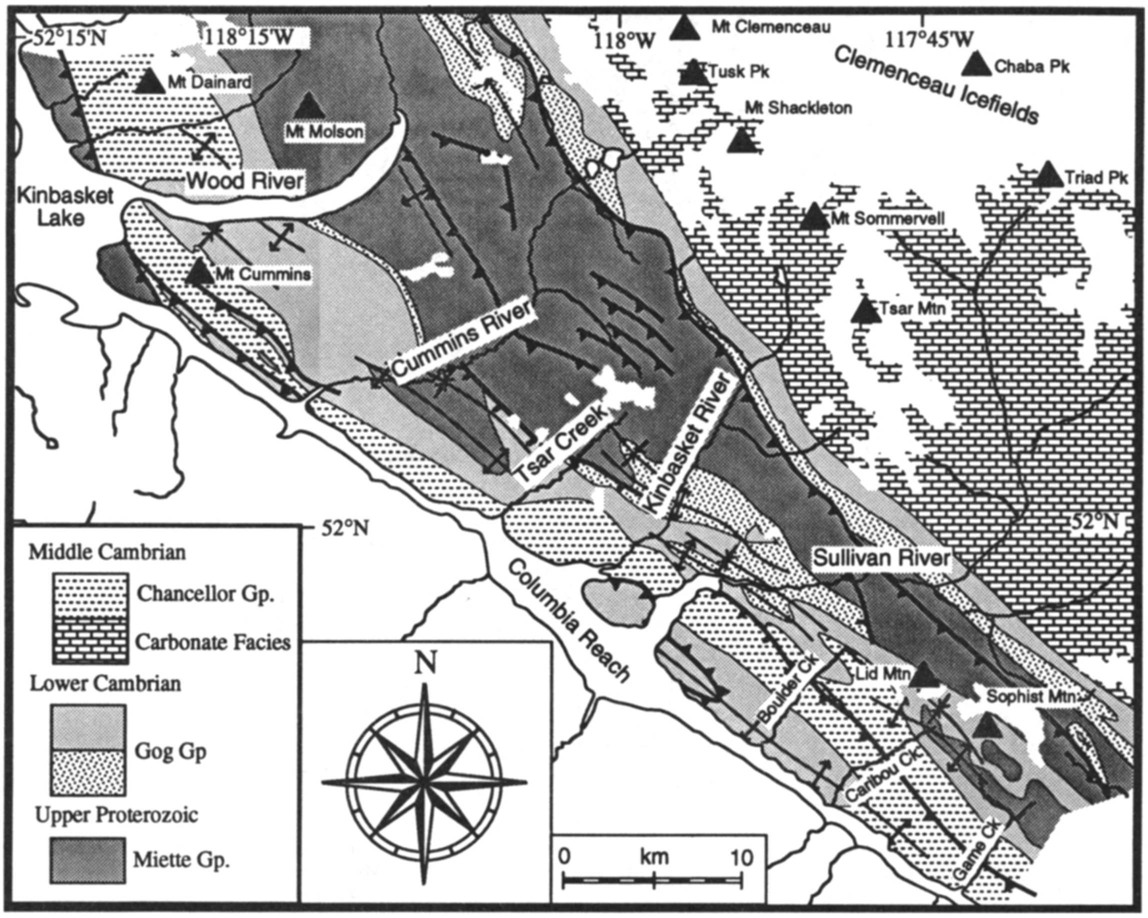

Fig. 3. Geology of the area between the Sullivan and Wood rivers. The core of the Porcupine Creek anticlinorium runs along the strip of Miette Group rocks in the centre.

STRATIGRAPHY

In the stratigraphic sequence of the Main Ranges (Fig. 1) Miette Group rocks of the Upper Proterozoic Windermere Supergroup lie directly on top of the Archaean and Proterozoic crystalline basement (McDonough & Simony 1988). The Miette Group has been divided into three units: a lower dominantly slate unit; a middle dominantly grit unit; and an upper slate unit. The lowest strata exposed in the study area belong to the 2 km thick package of the middle Miette Group. The middle Miette Group consists essentially of two lithofacies: grit, an immature quartzo-feldspathic coarse sand or granule conglomerate, and slate. The distribution of these lithofacies strongly influences the competence, and hence deformational style, of the Miette Group. Dramatic facies changes have been observed within the middle Miette Group, varying from a thick package of stacked grit beds, to a package of slates with a total absence of grits (Mountjoy & Grasby 1991). This facies variation is used to differentiate between structural styles in domains 3a and 3b (Fig. 4a).

The Lower Cambrian Gog Croup, overlying the Miette Group, consists of 1–2 km of quartzite with minor shale and limestone. Throughout the study area the Gog Group is divisible into three formations: the McNaughton Formation, a lower quartzite unit; the Mural Formation, a middle shale and limestone unit; and the Mahto Formation, an upper quartzite unit.

The overlying Palaeozoic sequence is mainly a platformal carbonate facies in the Eastern Main Ranges and a basinal shale facies in the Western Main Ranges (Cook 1970).

STRUCTURAL ELEMENTS

Between the Sullivan and Wood rivers (Fig. 3) many of the fine-grained rocks show at least one cleavage. However, the number, and origin, of deformational phases recorded in the rock varies at different localities. It is therefore best to consider different structural domains that show distinct characteristics (Fig. 4a).

Terminology of polyphase structures

It is common to use a D_1, D_2, D_3, etc., notation to refer to successive deformational events, with F_1, F_2, F_3, etc., referring to related folds and S_1, S_2, S_3, etc., referring to the associated planar fabrics. When applied at a regional scale such terminology can become confusing because: (1) some phases are not present in some

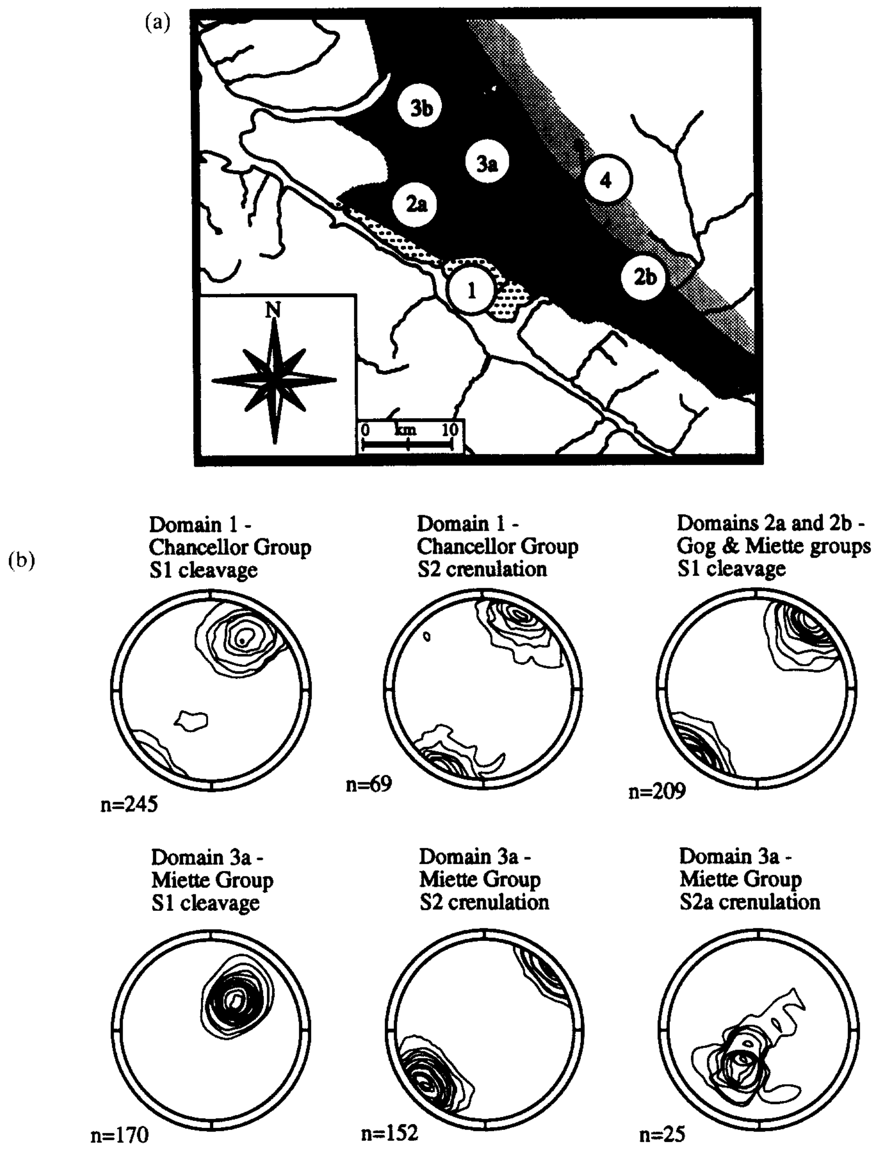

Fig. 4. (a) The area separated into structural domains: 1—Chancellor Group, western flank; 2a+b—Gog and Miette groups on the sides of the anticlinorium; 3a+b—Miette Group in the core; 4—Middle Cambrian carbonates, eastern flank. (b) Equal-area projections showing orientations of various structural elements in the area.

areas, requiring phase numbers to be omitted; or (2) continuous renumbering of phases is required when earlier or additional intermediate phases are recognized as more work is done or if a larger region is considered. In areas where deformation is dominated by detachment folding or thrusting, deformational events may correlate with motion on separate detachment horizons. If motion on these horizons is considered to be diachronous, or even simultaneous with motion on other faults, then the order of timing of D_1, D_2 and D_3 in different parts of the region may become ambiguous.

In this paper a more field-oriented system of nomenclature is employed. The deformational phases referred to are only those that are seen preserved in the rocks in small, sub-regional domains. Thus in one domain D_1 may refer to a phase that is not recorded in another domain, in which D_1 refers to a later phase. Deformational phases are correlated with motion on different thrusts, and will be referred to by the associated thrust fault which is inferred to have caused the folding.

Western flank: domain 1 *of Fig.* 4

The western flank of the Porcupine Creek anticlinorium exposes metamorphic rocks of the Chancellor Group from garnet to staurolite grade (Gal 1990). Bedding (S_0) is locally preserved where the original lithology contained sand or carbonate beds interbedded in the shales. Elsewhere the dominant fabric is a schistose foliation (S_1) defined by alignment of micas (Fig. 4b). Where observed, S_1 parallels both bedding (Fig. 5a) and the axial planes of tight F_1 folds. The F_1 fold hinges are tight to isoclinal, and generally trend approximately down dip on the limbs of the F_2 folds, suggesting some

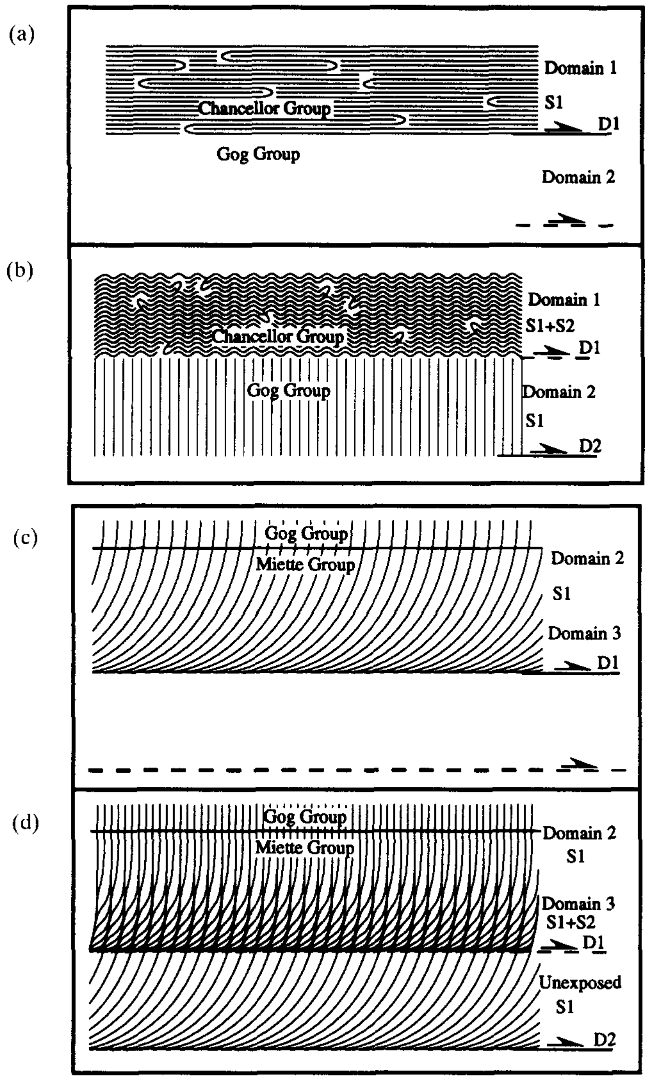

Fig. 5. (a) Formation of S_1 cleavage in the Chancellor Group (domain 1). (b) Formation of S_2 crenulation in the Chancellor Group (domain 1) and S_1 cleavage in the underlying Gog Group (domain 2a). (c) Formation of S_1 cleavage in the Miette Group of domains 2 and 3a. (d) Formation of S_2 crenulation in domain 3a and tightening of S_1 in domain 2.

degree of rotation of fold hinges towards the transport direction.

Upright, usually open, F_2 folds fold the dominant S_1 fabric (Figs. 5b and 6a). A crenulation cleavage (S_2) (Fig. 4b) parallel to the axial planes of F_2 folds formed in the fold hinges. Rarely, F_2 folds have tight closures. Most tight closures lack the S_2 crenulation and are assigned to F_1, although it is possible that in some cases the S_2 fabric may have completely overprinted the S_1 fabric rendering impossible differentiation of folding phases.

Anticlinorium limbs: domains 2a and 2b of Fig. 4

This domain consists of the Gog Group and part of the Miette Group on the limbs of the anticlinorium. It is at chlorite–chloritoid to biotite grade, a lower metamorphic grade than domain 1. The strong, competent quartzites of the Gog Group form the main structural beam in the Western Main Ranges, and generally form large folds with wavelengths of a few hundred metres between the more incompetent packages of the overlying Chancellor and underlying Miette groups. Intense deformation within the Gog Group tends to result in mesoscopic faulting. This is especially common in the core of the Porcupine Creek anticlinorium (Meilliez 1972, Gal 1990).

Many of the quartzite beds of the Gog Group and some of the grit beds in the Miette Group show no obvious cleavage, but all the fine-grained rocks of the Gog and Miette groups have at least one well developed slaty cleavage (S_1). Upright, symmetric F_1 folds fold bedding with axial planes parallel to S_1 (Fig. 4b) with wavelengths of tens of metres in the Miette Group and hundreds of metres in the Gog Group. These F_1 folds, although somewhat larger, are of the same orientation and open style as the F_2 folds in domain 1.

The Mural Formation, the shale and limestone unit separating the upper and lower Gog quartzites, acts as a zone of detachment between the underlying McNaughton and the overlying Mahto formations giving tighter, E-verging, folds in the Mahto. Locally a crenulation cleavage is developed in the green slates at the base of the Mural Formation, in which case the S_1 cleavage is at a much lower angle to horizontal than regionally in domain 2, and the S_2 crenulation is more upright. This is similar to the relationship seen in domain 3a, suggesting that a small amount of slip may have taken place at the base of the Mural Formation.

Anticlinorium core: domain 3a of Fig. 4

South of the Cummins River, in the core zone of the Porcupine Creek anticlinorium, the middle Miette Group is composed dominantly of the slate facies. The S_1 fabric in these fine-grained rocks is a well developed slaty cleavage that typically dips 30° to the west (Fig. 4b). The orientation of S_1 varies little across the domain, primarily because later folding in the slates is rare, D_2 deformation being dominated by a crenulation cleavage (S_2) (Fig. 6c). The S_2 crenulation cuts the S_1 cleavage at a high angle (Fig. 4b) with a NW-trending subhorizontal intersection lineation. A second set of kinks and crenulations (S_{2a}) also cuts S_1 in this domain. These S_{2a} crenulations are not as well developed as S_2 and they have anastomosing traces on S_1 surfaces. S_{2a} crenulations typically are NE-dipping conjugate to the SW-dipping S_2 cleavage (Fig. 4b). The angle between the two conjugate crenulations is most commonly around 40° (Fig. 7a) and is likely to be controlled by the anisotropy of the medium (Cosgrove 1976). The dominance of S_2 over S_{2a} is due to the higher angle between S_2 and the anisotropic layering (S_1) than between the conjugate S_{2a} and S_1.

F_1 folds here differ in style from those in domain 2. Instead of forming upright folds, F_1 folds are E-verging with axial planes dipping about 30°W, and are usually very asymmetric with the overturned limb almost paralleling the S_1 fabric and locally sheared out along small thrust faults (Fig. 6b). The F_1 folds also lack the high strain and tight closures associated with F_1 folds in domain 1. Conversely the F_2 folds are upright and open and very similar to the F_1 folds in domain 2.

Anticlinorium core: domain 3b of Fig. 4

In contrast to domain 3a, the middle Miette Group north of the Cummins river, in domain 3b, is dominantly composed of the grit facies, providing a more competent stratigraphic package. Because of the greater competence deformation is less evenly distributed, and structures are larger than in domain 3a. The grit package is folded above the décollement surface into a single large anticline with a relatively steep W-dipping axial plane (Lickorish & Simony 1991) (Fig. 8d).

The reduced ability of the rock to respond to a shear stress, due to the higher competence of the rock, produces a highly sheared zone that is thinner than in the corresponding area with a dominance of slate. S_2 crenulations are therefore only seen locally in some of the core structures of the anticline.

Eastern flank: domain 4

On the eastern flank of the anticlinorium are rocks of the Middle Cambrian carbonate facies. These rocks, in contrast to the Chancellor Group on the west, form a relatively competent multilayer which is folded into a single large syncline with a wavelength of more than 10 km. Small-scale structures are not common, but the Arctomys Formation exposed on both sides of the syncline shows minor folds verging away from the synclinal core.

No penetrative fabric pervades the rocks of the eastern Middle Cambrian carbonate facies, although some of the finer grained formations often show a pencil cleavage formed by intersection of bedding fissility and an incipient spaced cleavage.

CORRELATION OF DEFORMATION PHASES

Folding events are correlated between domains on the basis of fold style and geometry. In domain 1 the S_2 cleavage is of similar orientation to the S_1 fabric of the underlying domain 2a (Fig. 4b). Likewise the F_2 folds in domain 1 are of the same upright and open styles as the F_1 folds in domain 2. Thus D_2 in domain 1 and D_1 in domain 2 are presumably coeval (Gal 1990). Therefore D_1 in domain 1 pre-dates D_1 in domain 2.

The similarity between F_1 folds in domain 3a and F_1 folds in domain 2 suggests the possibility that these two fold sets are related. This model would then imply that the D_1 phase of deformation is of local extent in domain 3a, and the later deformation is a regional event. A more reasonable model proposed here has the D_1 structures in both domains coeval, and the D_2 event localized. The dip of the S_1 cleavage decreases with increasing structural depth. Localization of D_2 deformation then occurred because new D_2 structures did not initiate in domain 2 because reactivation and tightening of D_1 structures was the preferred mechanism of deformation. In contrast in domain 3a the D_1 structures were at a sufficiently high angle to the flattening plane of D_2 stresses that a new phase of structures was initiated.

In total, three phases of deformation are required to describe the observed structures. The earliest deformed only the rocks in domain 1, leaving domains 2 and 3 unaffected. The second phase deformed the whole package, developing a crenulation cleavage in domain 1. The final phase formed a crenulation cleavage only in domain 3 where pre-existing fabrics were favourable. In domains 1 and 2 deformation due to this final phase must be present, but associated structures are no different from those of the previous phase.

MODELLING OF THE DEFORMATION

The model proposed for the development of the crenulation cleavages is that of two thrust faults, or décollement horizons, lying one above the other (labelled 5 and 6 in Fig. 8d). Deformation in the thrust sheets is produced by motion on the underlying fault, thus the upper thrust sheet will be deformed and shortened by motion on either of the two faults, but the lower sheet will only be affected by motion on the lower fault. It is a simplification to presume that there will be no deformation in the footwall of the fault, but particularly in the case of the sub-Chancellor décollement it does appear to be minimal. The nature of strain, and hence the orientation of cleavage, will vary with height above the fault in the thrust sheet (Sanderson 1982, Gray & Willman 1991). In the absence of stretched overturned limbs of large nappes it is reasonable to assume that there will be internal shortening within the thrust sheet and that this will be represented by a pure shear component of strain which is likely to remain roughly constant in a vertical direction throughout the thrust sheet. There will also be a component of simple shear and this will be more intense lower in the thrust sheet closer to the fault or shear surface, but high in the thrust sheet the simple shear component may be very small. Thus, with the increased simple shear component, planar structures in the lower part of the thrust sheet will be rotated towards the shear plane, while the structures higher in the sheet will retain a more upright orientation (Fig. 9a).

A second phase of deformation on a lower fault will produce fabrics in the upper thrust sheet that are consistent with those at a high level in the lower thrust sheet and hence in an upright orientation. Initiation of a crenulation cleavage is unlikely to occur where the principal flattening plane is at less than a critical angle of 45° (Gray & Durney 1979) to a pre-existing cleavage, and in this case the D_2 deformation will merely tighten the pre-existing structures. However, at lower levels in the upper thrust sheet, where D_1 structures have been flattened and rotated by simple shear, this angle is likely

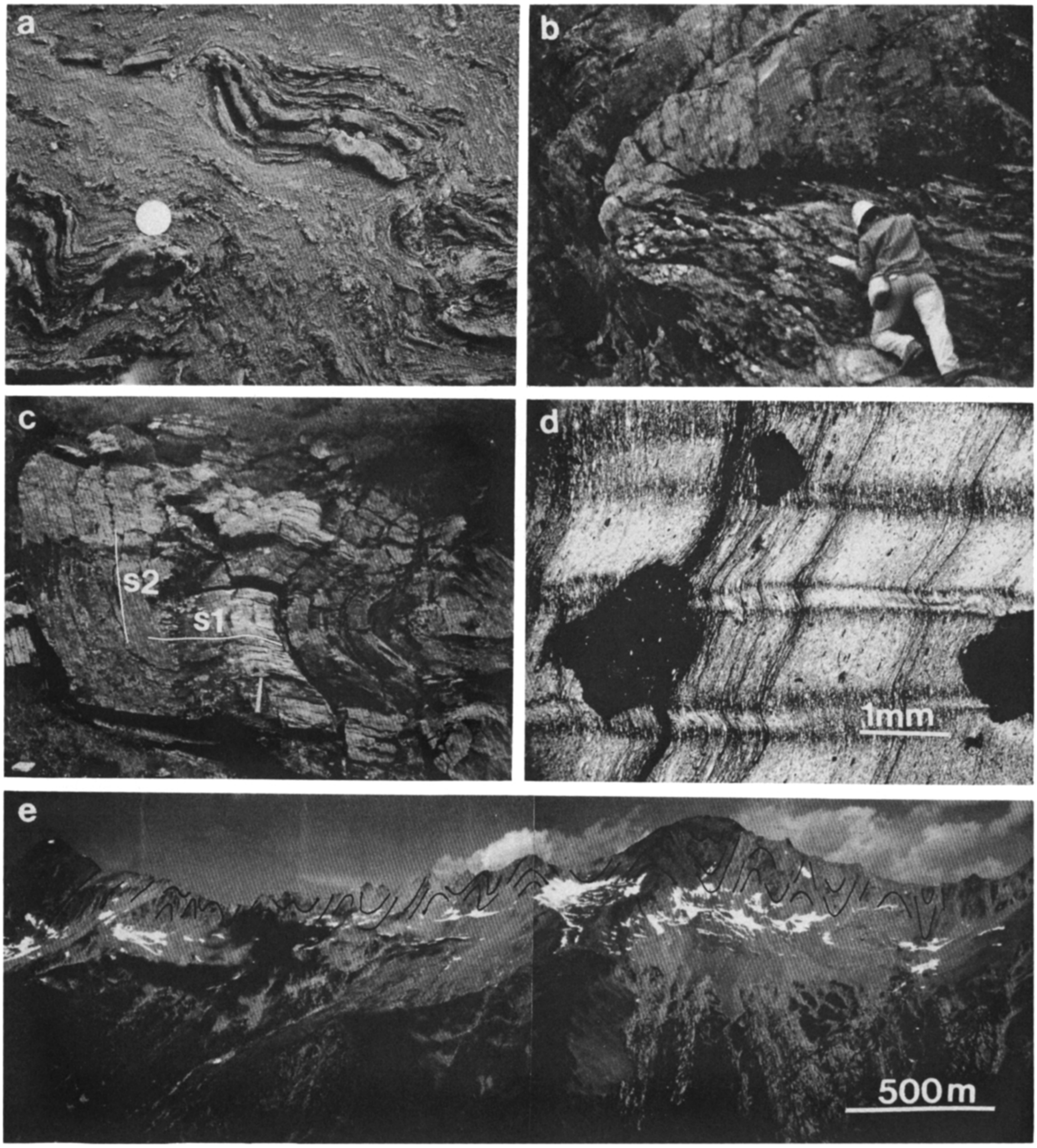

Fig. 6. (a) Refolded isocline in the Chancellor Group (domain 1). Coin for scale. (b) F_1 fold in domain 3a with lower limb sheared out along a minor thrust. (c) F_1 fold in domain 3a showing both S_1 cleavage and S_2 crenulation. Hammer for scale. (d) Photomicrograph of crenulation in domain 3a. (e) Fold train exposed along ridge in domain 2a.

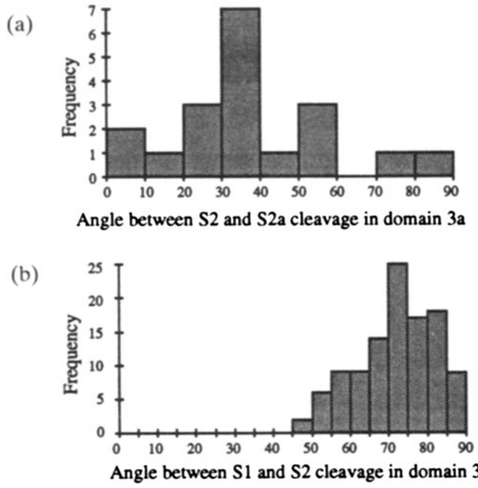

Fig. 7. (a) Frequency distribution of angle between S_2 and S_{2a} crenulations (domain 3a). (b) Frequency distribution of angle between S_1 cleavage and S_2 crenulation (domain 3a).

to be exceeded and it is only at these levels that distinct D_2 structures will initiate. It is observed that the angle between S_1 and S_2 is never less than 45° (Fig. 7b).

In a two-dimensional model (after Sanderson 1982), with the x-axis in the direction of thrusting and the z-axis vertical (Fig. 9), the deformation gradient tensor D_1 can

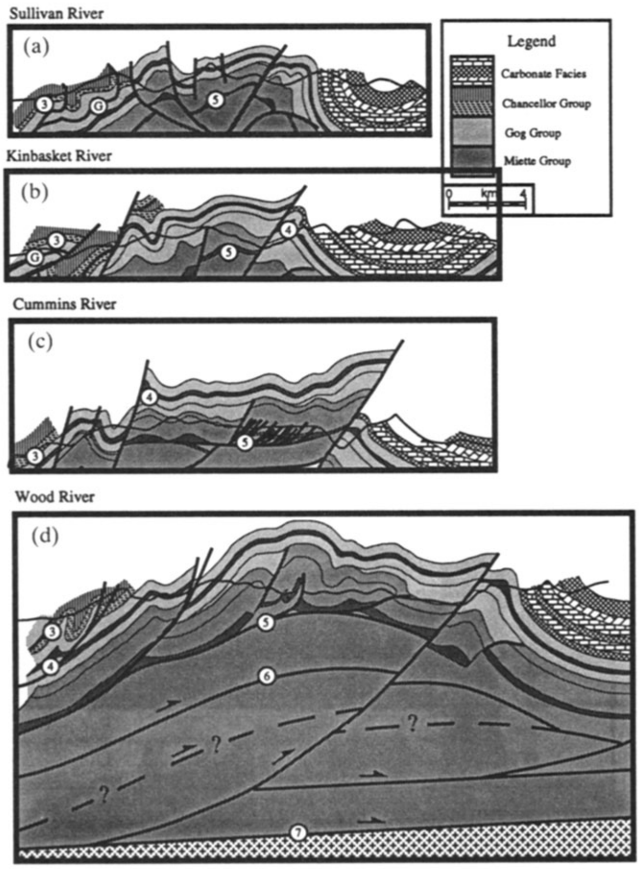

Fig. 8. Cross-sections between the Sullivan and Wood rivers. Detachment horizons (1–6) are numbered sequentially in order of decreasing age as in Fig. 11. G is the Garret Creek thrust associated with both décollements 3 and 4. (a) Sullivan river. (b) Kinbasket river. (c) Cummins river. (d) Wood river. The extension down to basement is schematic and is included to illustrate the possible structural style at depth. The dashed fault is required by balancing considerations if a brittle style is considered, but considerable ductile deformation is likely to be involved.

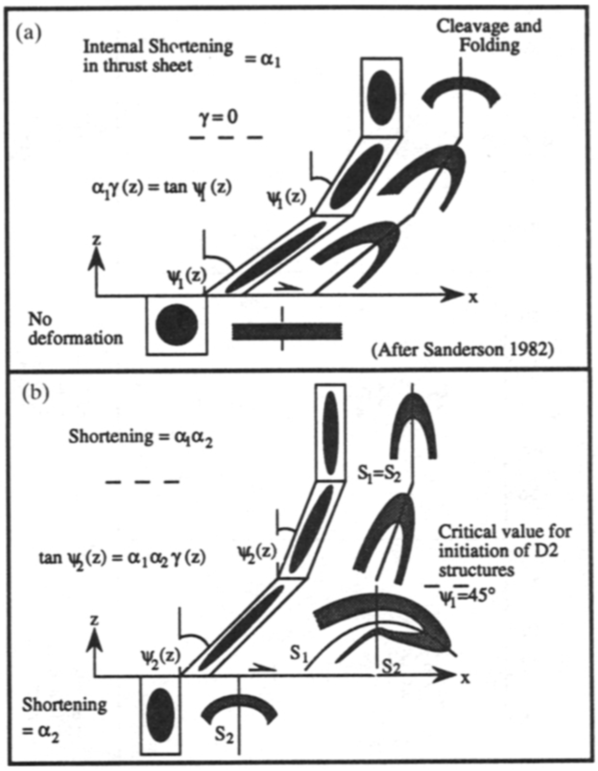

Fig. 9. Schematic illustration of strain relationships within a thrust sheet. (a) Strain after D_1 deformation. (b) Strain after D_2 deformation.

be described by pre-multiplying a pure shear component with a simple shear component.

$$\begin{bmatrix} x' \\ z' \end{bmatrix} = \mathbf{D}_1 \begin{bmatrix} x \\ z \end{bmatrix} = \begin{bmatrix} \alpha_1 & 0 \\ 0 & \alpha_1^{-1} \end{bmatrix} \begin{bmatrix} 1 & \gamma(z) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ z \end{bmatrix} = \begin{bmatrix} \alpha_1 & \gamma(z)\alpha_1 \\ 0 & \alpha_1^{-1} \end{bmatrix} \begin{bmatrix} x \\ z \end{bmatrix}, \quad (1)$$

where α is the shortening across the thrust sheet, $\gamma(z)$ is the amount of simple shear (Fig. 9a), and x' and z' are the components of the position vector in the strained slate. This model assumes the unlikely case of separate pure shear and simple shear events. For simultaneous development of pure and simple shear, strain-rate tensors must be considered and this produces a slightly modified deformation gradient tensor (Sanderson 1982). However, since only finite strains can be considered, this partitioning is adequate to find the bulk shortening α_1. Since the relative timing of the simple shear event will affect the value of $\gamma(z)$, the interpretation of the $\gamma(z)$ parameter is less clear.

For the second phase of deformation (D_2), because of the upright nature of the structures, it will be assumed that the component of simple shear at the level of the upper thrust sheet is negligible ($\gamma_2(z){=}0$), so that

$$\mathbf{D}_2 = \begin{bmatrix} \alpha_2 & 0 \\ 0 & \alpha_2^{-1} \end{bmatrix}$$

and the polyphase deformation is given by:

$$\begin{bmatrix} x'' \\ z'' \end{bmatrix} = \mathbf{D}_2\mathbf{D}_1 \begin{bmatrix} x \\ z \end{bmatrix} = \begin{bmatrix} \alpha_1\alpha_2 & \gamma(z)\alpha_1\alpha_2 \\ 0 & \alpha_1^{-1}\alpha_2^{-1} \end{bmatrix} \begin{bmatrix} x \\ z \end{bmatrix}, \quad (2)$$

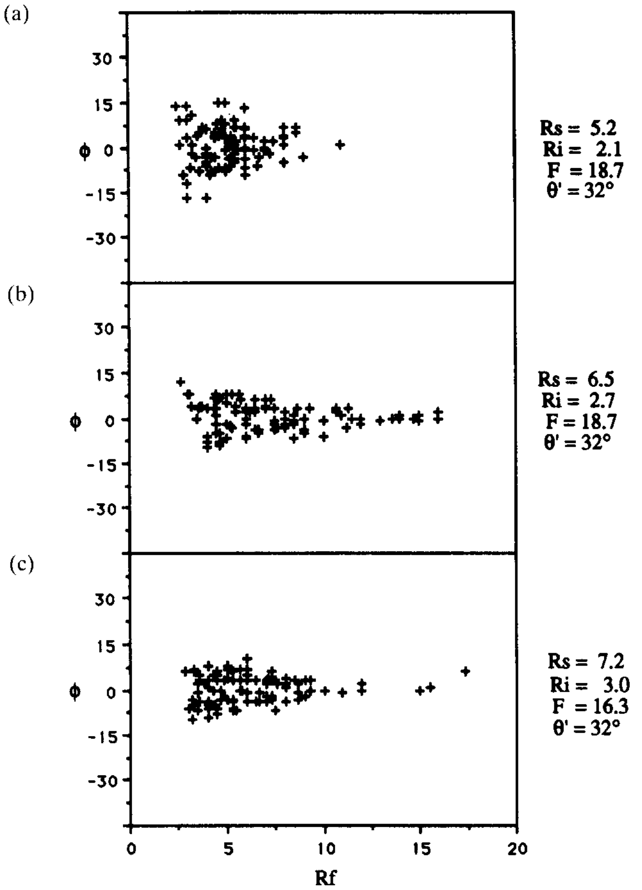

Fig. 10. R_f/ϕ plots for quartz clasts located between crenulations in three samples from domain 3a. The angle θ' is the dip of the S_1 cleavage.

where x'' and y'' are the components of the resultant position vector.

After event D_1 the angle ψ by which a material line will be rotated from the vertical is given by the arctangent of the value in the upper right corner of the deformation gradient tensor. Thus

$$\psi_1 = \tan^{-1}\{\alpha_1\gamma(z)\}. \quad (3)$$

It is this value that will determine whether D_2 structures are initiated, requiring $\alpha_1\gamma(z)>1$ for this to occur (Figs. 5d and 9b). Although this angle will be subsequently decreased by D_2 shortening it is the angle ψ_1 that is critical, not ψ_2, since once initiated D_2 structures will continue to tighten. The final angle, ψ_2, may therefore be somewhat less than 45° depending on the amount of D_2 shortening,

$$\psi_2 = \tan^{-1}\{\alpha_1\alpha_2\gamma(z)\}. \quad (4)$$

Since the lower thrust sheet is nowhere exposed, direct estimation of α_2 is impossible, and so values for α_1, α_2 and $\gamma(z)$ must be estimated from the polydeformed sequence. Phase 2 deformation in the slates is concentrated in the thin zones of the crenulations, and between these zones it is assumed that the strain in the fabric is affected by D_2 only to a small degree. It should, therefore, be possible to measure directly D_1 strain between these crenulated zones. In thin section strained quartz grains can be measured and the results plotted on R_f/ϕ diagrams to give an estimate of D_1 strain (Fig. 10). The value of R_s so obtained is the total D_1 strain, which the model predicts should vary with $\gamma(z)$ above the thrust sheet. To find a useful parameter to characterize D_1 it is necessary to then factorize this strain into the α_1 and $\gamma(z)$ components. This can be done if both R_s and θ' are known (Sanderson 1982). The angle θ' is the angle made by the cleavage with the thrust plane. This angle is difficult to measure for two reasons: the thrust plane is nowhere exposed and is hard to constrain, and the orientation of the cleavage may have been somewhat modified by F_2 folding. To find θ', samples were taken from near the core of the anticlinorium where there is greatest constraint on a horizontal orientation of the thrust plane. The θ' is taken as the dip of the S_1 cleavage. The solution to the equations factorizing α and $\gamma(z)$ (after Sanderson 1982) shows that about 30% shortening ($\alpha_1 = 0.7$) can be attributed to D_1. D_2 shortening can be estimated from shortening of S_1 by the S_2 crenulations. Although crenulated rocks of domain 3a show various degrees of crenulation from 0% (uncrenulated) to 37% shortening, a typical sample (Fig. 6d) shows about 10% shortening ($\alpha_2 = 0.9$). Additionally, combined $D_1 + D_2$ deformation can be measured in domain 2a along a ridge segment exposing a fold train over 2.5 km long (Fig. 6e). The estimated shortening on this ridge, by comparing folded and unfolded bed lengths, is about 37% ($\alpha_{1+2} = 0.63$). This value is surprisingly consistent with the more approximate values for the individual estimates of D_1 and D_2 shortening,

$$\alpha_{1+2} = \alpha_1\alpha_2, \text{ i.e. } 0.63 = 0.7 \times 0.9. \quad (5)$$

DEVELOPMENT OF THE PORCUPINE CREEK ANTICLINORIUM

Structural styles and complexity of deformation in the Porcupine Creek anticlinorium change considerably along strike. Thus, local models for development of the anticlinorium differ accordingly. Now that a large length of the Porcupine Creek anticlinorium has been mapped in detail, it is possible to construct a regional model that accounts for the strike-parallel variations. A series of eight cross-sections (Figs. 8 and 11) illustrates the structure of the Porcupine Creek anticlinorium from Cranbrook in the southeast up to the Wood river in the northwest. This sequence shows that the Porcupine Creek anticlinorium is a high level detachment fold structure in the south. Progressively deeper structures are exposed towards the north.

It is proposed that the Porcupine Creek anticlinorium developed above a stack of blind thrusts, terminating in thrust-fault flats (e.g. 5 in Fig. 8). Deeper detachment horizons are exposed at the surface in the core of the Porcupine Creek anticlinorium (Lickorish 1991) in a northward progression as stratigraphically lower units are exposed. Northwards from the Bush river the anticlinorium is then further uplifted by an increasing amount of duplexing at a deep level (Fig. 8d).

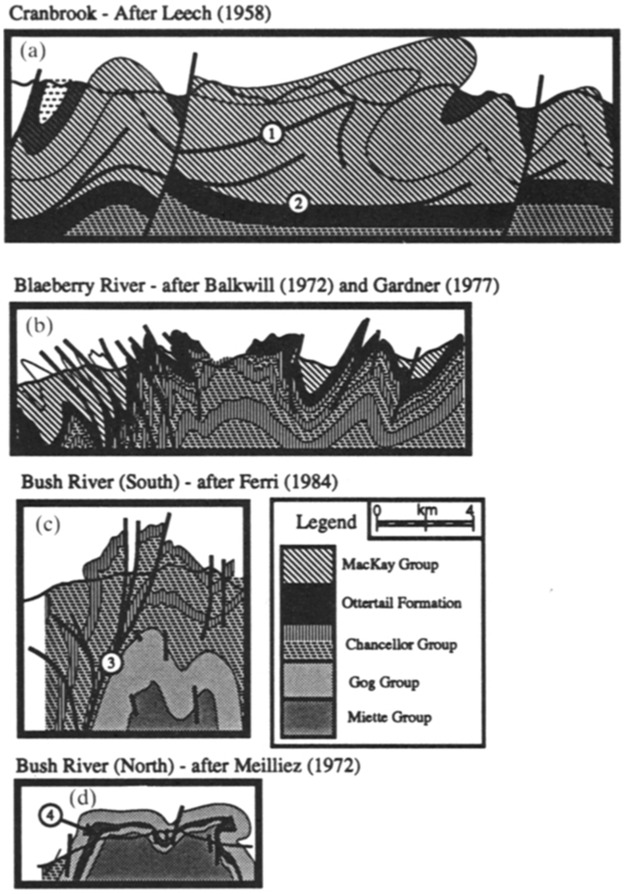

Fig. 11. Cross-sections of the southern Porcupine Creek anticlinorium. Detachment horizons are numbered sequentially with age as in Fig. 11. (a) Cranbrook (after Leech 1958); (b) Blaeberry river (after Balkwill 1972 and Gardner 1977); (c) Bush river (south) (after Ferri 1984); (d) Bush river (north) (after Meilliez 1972).

Along the length of the Porcupine Creek anticlinorium, décollement surfaces have been documented at several horizons. Motion on deeper horizons is restricted to progressively more northward locations. Lateral ramping between décollement surfaces at different levels is not observed. Instead, the décollement surfaces are seen to be folded by, and over-printed with cleavages associated with, movement on the next deeper décollement. Structures associated with deformation due to motion on more than two décollement surfaces can never be demonstrated at the same outcrop, but each décollement horizon is deformed by movement on a deeper, later one. The relative ages of the décollement horizons, youngest to oldest and lowest to highest, can therefore be inferred on a regional scale.

At the southern end of the Porcupine Creek anticlinorium, northeast of Cranbrook, Leech (1958) mapped a thrust fault within the Cambro-Ordovician Mackay Group (1 in Fig. 11a). This thrust fault is folded by a train of folds which is estimated to die out above the Ottertail Formation, implying that another décollement exists above this formation (2 in Fig. 11a).

East of Golden, cross-sections constructed by Balkwill (1972) show that the Ottertail Formation and the shales of the underlying Chancellor Group are significantly deformed. Refinement of these sections by Gardner (1977) suggests that there is very little room for any of the Gog Group in the core of the anticlinorium (Fig. 11b). This requires a décollement horizon near the base of the Chancellor Group. This décollement horizon is localized in the western shale facies, and no equivalent deformation is seen to exist in the eastern carbonate facies. Balkwill (1972) proposed that the carbonates have a buttressing effect, preventing continued propagation of the décollement.

The décollement at the base of the Chancellor Group is exposed at the latitude of the Bush river (3 in Figs. 8 and 11). Here the Chancellor Group is highly deformed above the décollement, with evidence for two deformational phases. Gog and Miette Group strata also outcrop in the core of the anticlinorium (Meilliez 1972, Ferri 1984) (Figs. 11c & d), but show evidence for only one deformational phase correlated with the later one seen in the Chancellor Group. Deformation in the Gog and Miette Group strata can be accounted for by folding above a décollement somewhere near the middle of the Miette Group.

From the Bush river north there probably is a detachment in the relatively incompetent Mural Formation in the Middle of the Gog Group (4 in Fig. 8). Tight anticlines in the overlying Mahto Formation occur above the relatively open cores of anticlines in the McNaughton Formation, a condition not balanced by the reverse situation in synclines. This situation requires additional shortening in the Mahto Formation, and so it is proposed that there was some degree of detachment within the Mural Formation. Gal (1990) interpreted the Garret Creek thrust (G in Figs. 8a & b) as a westward down-cutting of the sub-Chancellor décollement (3 in Fig. 8), but it is here reinterpreted as the Mural décollement (4 in Fig. 8) ramping up through the Mahto Formation. The ramp occurs in a more westward position than the limit of deformation above the Mural décollement and re-activated the sub-Chancellor décollement above (3 in Fig. 8), thus carrying a package of deformed Mahto over similarly deformed Mahto (Figs. 8a & b). This would explain the fact that in the footwall of the Garret Creek thrust the same deformation is seen as in the hanging wall, and that the Chancellor Group above is apparently deformed with greater intensity.

At the north end of the study area, deformation in the Miette Group constrains the location of a décollement within it. South of the Cummins river a series of small, closely spaced thrust faults in the core zone of the anticlinorium (Fig. 8c) suggests proximity to a décollement. That décollement is also required by a large, but tight, anticline in the middle Miette Group (Fig. 8d) north of the Cummins river. The Old Fort Point Formation is strongly deformed in the core of this anticline and requires the existence of the décollement horizon not far below the Old Fort Point Formation (5 in Fig. 8). This décollement in the Miette Group may correlate with the Selwyn Range thrust, mapped north of the Wood river (Mountjoy & Forest 1986).

The Selwyn Range thrust is itself folded around an anticline, and at the deepest exposed levels another zone of sheared rocks, the Ptarmigan Creek shear zone, is

Table 1. Distribution of structures formed by movement on different décollement horizons in the anticlinorium

Décollement level	Cranbrook	Blaeberry river	Bush river	Study area (west)	Study area (core)
Middle Mackay	D_1?	—	—	—	—
Basal Mackay	D_2?	—	—	—	—
Mid Chancellor?	?	D_1?	—	—	—
Basal Chancellor	~	D_2?	D_1	D_1	—
Mural	~	?	x	x	—
Middle Miette	~	~	D_2	D_2	D_1
Lower (?) Miette	~	~	?	x	D_2
Basement	x	x	x	x	x

Key: —, stratigraphic horizon not present in section due to erosion; x, décollement present, but no initiation of new structures; ~, décollement not developed at this level.

exposed (Dechesne 1990). The Ptarmigan Creek shear zone is a wide band of intense deformation, and is probably a major thrust horizon. An attempt to extend the Wood river cross-section down to basement requires that a major thrust be placed around the same level as the projection of the Ptarmigan Creek shear zone (6 in Fig. 8d). Deformation beneath this level is hard to constrain. Two end-member alternatives exist for interpretation of the structure: either the shortening is taken up by a thrust duplex in the style of the Main Ranges and Front Ranges to the east, or it is dominantly taken up by ductile folding in the style of the Selkirk Mountains to the west. More likely is a transitional style such as that already described for the upper portion of the Porcupine Creek anticlinorium.

The final detachment horizon to be considered is the main basal detachment that is present beneath the whole Rocky Mountains (7 in Fig. 8d) above the crystalline basement, above which the whole anticlinorium was carried eastwards with little surface expression, with continuing deformation in the foreland.

CONCLUSIONS

Polydeformed rocks are common throughout the Porcupine Creek anticlinorium, but structures associated with all phases of deformation are not necessarily developed at any one location. Between the Sullivan and Wood rivers, exposures showing two phases of deformation exist in a zone above a décollement located in the middle of the Miette Group; above this zone only one phase of structural development is present in the upper portion of the Miette Group and the overlying Lower Cambrian Gog Group. Early phase structures developed with varying orientation dependent on height above the thrust plane, with upright structures forming at higher levels, and W-dipping structures at lower levels. Second-phase structures developed in a similar manner above a deeper thrust. Initiation of a second phase of structures occurred only where the angle between the earlier structures and incipient second phase structures exceeded a critical value. Elsewhere the second deformational episode served only to tighten early phase folds.

A model has been established for the growth of the Porcupine Creek anticlinorium. In the core, structures are developed by internal shortening of thrust sheets above relatively flat décollement horizons. These are then redeformed by deformation above a décollement horizon mobilized at a deeper level. This progressive deepening of décollement horizons is consistent with the normal foreland-propagating thrust system of the Canadian Rockies. The décollement surfaces overlap with an en échelon pattern, with deeper horizons in a more northward position, so that exposures farther north in the anticlinorium involve stratigraphically deeper rocks. Table 1 shows the northwards deepening of décollement horizons along the length of the Porcupine Creek anticlinorium.

A consequence of this progressive northward deepening of décollement levels is that in the south the Porcupine Creek anticlinorium is a relatively shallow structure which gets deeper and opens up to the north. The shallower southern deformation also developed earlier, hence the anticlinorium grew from the south towards the north. In the same manner that the deeper décollement surfaces do not continue all the way south, the higher surfaces probably do not continue northwards over the whole length of the anticlinorium.

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