



The role of conjugate crenulation cleavage in the development of ‘millipede’ microstructures

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Abstract

Millipede microstructures are described from Archean metaturbidites surrounding the Back River volcanic complex, eastern Slave Structural Province. They are locally developed within andalusite porphyroblasts that grew in response to the intrusion of late syn-kinematic granitoids. The porphyroblasts acted as a mechanical heterogeneity and resulted in the nucleation of conjugate crenulations, which were then helicically overgrown by the porphyroblasts. This process produced the millipede morphology through a simple, consistent mechanism. The model presented here for the development of millipede microstructures represents an alternative to other models requiring complex deformation partitioning and restricted porphyroblast growth. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Millipede microstructures (Bell and Rubenach, 1980), more recently referred to as opposite concave microfolds (OCM) (Johnson and Moore, 1996), are characterized by a distinctive and complex internal foliation pattern in metamorphic porphyroblasts with inclusion trails (S_i) defining the following morphology. S_i is straight in the core of the porphyroblast and variably curved towards the porphyroblast rim with the sense of curvature varying from quadrant to quadrant. The resulting pattern has two planes of symmetry that intersect in the centre of the porphyroblast reflecting opposing senses of S_i curvature in each quadrant along the porphyroblast margin (Fig. 1).

There has been much discussion concerning the origin of millipede microstructure. Are they a product of bulk inhomogeneous shortening involving domains of coaxial and noncoaxial straining as suggested by Bell and Rubenach (1980), Bell (1981) and Bell et al. (1992, and references therein) or are they the product of a more homogeneous strain path involving plane strain as suggested by Passchier et al. (1992)? The problem of their origin is exacerbated by the lack of preservation of intermediate developmental

stages and hence a lack of information to constrain the strain path associated with their development.

Lower amphibolite facies metaturbidites overlying the Back River volcanic complex (Lambert, 1976), in the eastern Archean Slave Structural Province of the Northwest Territories, Canada, contain andalusite porphyroblasts with millipede microstructure. These structures are interpreted as having developed by the overgrowth of conjugate crenulation cleavages developed along the margins of the porphyroblasts. This mechanism may be generally applicable although it may not be the only mechanism for the development of millipede microstructures.

2. Structural setting

The millipede microstructures described in this paper were observed in andalusite porphyroblasts developed in metaturbidites comprising the Beechy Lake Group (Frith and Percival, 1978) from the eastern Slave Structural Province. Regional deformation (D_1 – D_3) has produced three generations of upright folds in the Beechy Lake Group (Lambert et al., 1992). The first two generations of folds (F_1 – F_2) are tight to isoclinal with generally shallowly-plunging and steeply-plunging axes, respectively, producing a regional dome and basin interference geometry and producing a northwest trending structural trend. Associated with F_2 folds is a ubiquitous subvertical axial plane slaty

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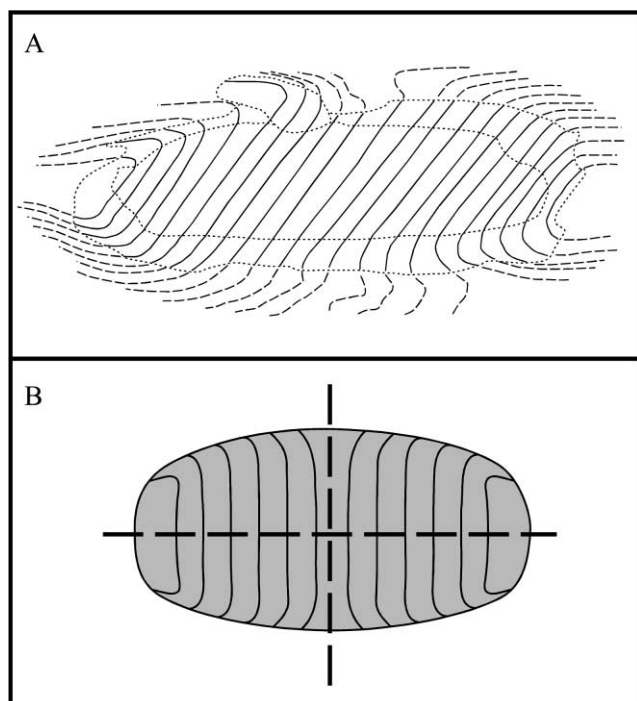


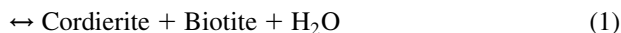
Fig. 1. (A) Line drawing of millipede microstructure (after Bell and Rubenach, 1980). (B) Idealized millipede microstructure with characteristic orthogonal symmetry planes with respect to the curvature of the internal foliation.

cleavage (S_2). S_2 is generally the oldest foliation preserved in the matrix and commonly has a weakly differentiated morphology, the result of the transposition of S_1 during tight F_2 folding. The youngest generation of folds is represented by a variety of open mesoscopic F_3 folds including box folds, kink bands and open parallel folds. F_3 folds are upright with steeply plunging axes that trend approximately east–west. The S_3 foliation is highly variable in morphology, ranging from fracture cleavage to well differentiated crenulation cleavage. In areas of amphibolite facies metamorphism and the development of coarsely porphyroblastic rocks, S_3 commonly nucleates along the margins of large porphyroblasts.

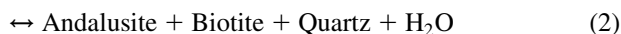
Metamorphism in the Beechy Lake Group is the product of two events (M_1 – M_2), similar to that described elsewhere in the Slave Province (Bethune and Carmichael, 1998). Regional M_1 upper greenschist to lower amphibolite facies, biotite and locally cordierite-bearing assemblages developed during D_2 . M_1 porphyroblasts commonly preserve S_1 as an internal foliation (S_i) that is discordant with the matrix S_2 foliation. M_1 assemblages are overprinted by lower amphibolite facies, low pressure–moderate-to-high temperature M_2 regional contact metamorphic assemblages in response to the intrusion of the syn-kinematic Tarantula Plutonic Suite (van Breemen et al., 1992). M_2 is characterised by the development of coarsely porphyroblastic biotite–cordierite–andalusite-bearing assemblages. Metamorphic textures suggest the following

reaction series:

Chlorite + Muscovite + Quartz



Cordierite + Muscovite



producing two generations of M_2 biotite porphyroblasts. Porphyroblast–matrix relationships are consistent with reaction (1) taking place late syn- to post- D_2 resulting in a weak M_2 biotite preferred orientation and slight S_i discordance. Reaction (2) is characterised by syn- D_3 biotite–andalusite growth. The growth of large (1–10 cm), amoeboid andalusite porphyroblasts followed the development of symmetrical open F_3 folds within the meta-sedimentary matrix. S_3 foliation development generally involved the nucleation of crenulation cleavage along the margins of the coarse-grained M_2 porphyroblasts with biotite–andalusite growth outlasting D_3 fabric development, as indicated by the inclusion of late-stage S_3 crenulation cleavage in the margins of the porphyroblasts. Andalusite porphyroblasts are strongly poikiloblastic, preserving the matrix texture as an internal foliation (S_i), defined by S_2 parallel quartz inclusions, and pseudomorphic replacement of matrix M_1 and M_2 biotite.

3. Millipede microstructures

The millipede microstructures in the Back River area are only developed in andalusite porphyroblasts. Syn-kinematic andalusite growth during F_3 folding appears to be critical for millipede development in this area, explaining why largely inter-kinematic cordierite lacks millipede microstructures. The millipedes consist of ovoid porphyroblasts elongated parallel to the F_3 axial planes and are outlined by S_i (S_2), which is tightly folded in the rim of the porphyroblast but only gently curved within the porphyroblast (Fig. 2). With the exception of the porphyroblast rim, the curvature of S_i is constant and similar in wavelength and amplitude to the open F_3 folds of the external S_2 matrix foliation (S_e). This relationship is consistent with static porphyroblastesis or, more probably, with rapid andalusite growth relative to strain rates during late-stage D_3 deformation. Following the initial period of the andalusite, growth tight F_3 microfolds and differentiated S_3 crenulation cleavage formed along the margins of andalusite porphyroblasts, commonly forming conjugate pairs. In the best developed millipede microstructures, the intersection of the conjugate crenulation cleavages is at the approximate midpoint of the long axis of the porphyroblast. The nucleation of F_3 microfolds and S_3 crenulation cleavage along the margins of large porphyroblasts is common, involving biotite and cordierite, in addition to andalusite (Fig. 3). The millipede

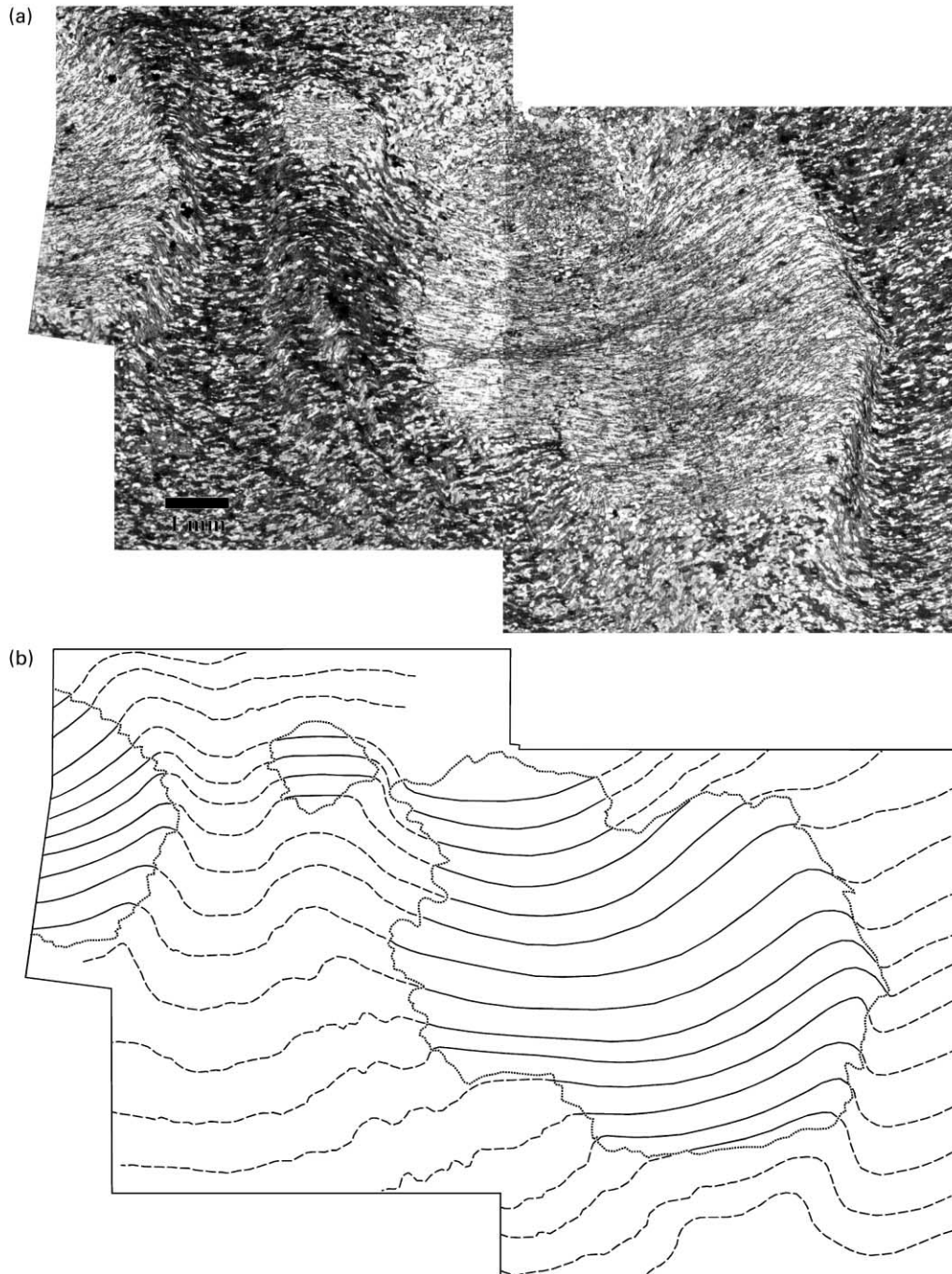


Fig. 2. (a) Photomicrograph mosaic of millipede microstructure developed in adjacent andalusite porphyroblasts. (b) Line drawing of (a) demonstrating the relationship of porphyroblasts and S_3 crenulation cleavage, highlighting the internal inclusion trail (S_1) and S_2 in the matrix (dashed).

microstructure is completed through the replacement of the muscovite–biotite-rich differentiated F_3 microfold limbs and S_3 crenulation cleavage septa and inclusion of the quartz-rich domains of the S_2 spaced cleavage comprising the matrix foliation into the rim of the andalusite porphyroblasts. Thus, producing the tightly folded porphyroblast rim and reversal in S_1 curvature characteristic of millipede microstructure (Fig. 4). The continuous S_i/S_e relationship between the quartz-rich andalusite S_i and matrix S_e (S_2)

represents a porphyroblast–matrix relationship consistent with the overgrowth of the marginal crenulation cleavage during porphyroblastesis (Zwart, 1960a,b, 1962; Spry, 1969).

The ubiquitous association of conjugate crenulation cleavage and porphyroblasts suggests that either the porphyroblasts are responsible for nucleation of the cleavage or the cleavage intersection was the preferred site for porphyroblast growth. If the latter were true the

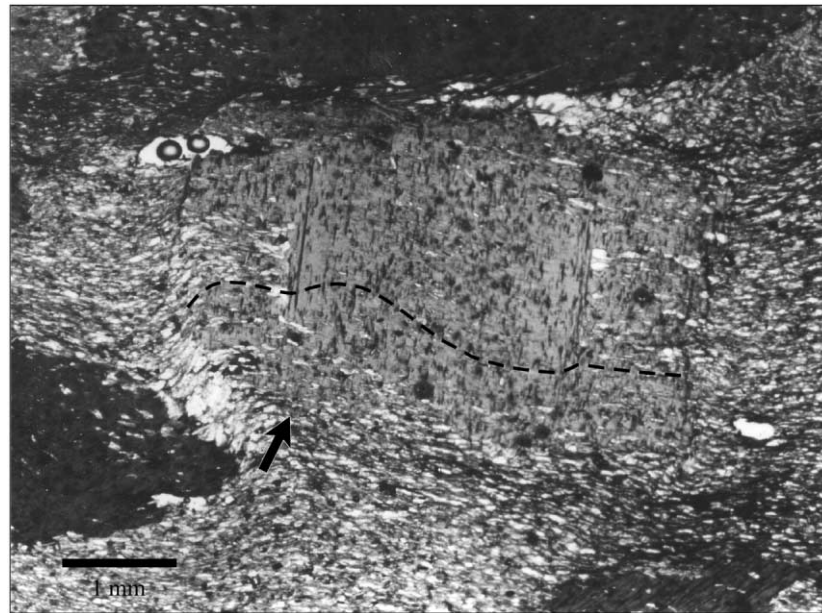


Fig. 3. Large zoned biotite porphyroblast displaying millipede characteristics. The porphyroblast core represents M_2 biotite produced during cordierite formation, mantled by a second generation of M_2 biotite produced during andalusite formation. Note the curved S_{2i} within the core, the continuous S_1/S_{2c} porphyroblast–matrix relationship on the right margin of the porphyroblast mantle, the nucleation of F_3 microfolds along the left margin and their inclusion into the rim of the porphyroblast (arrow).

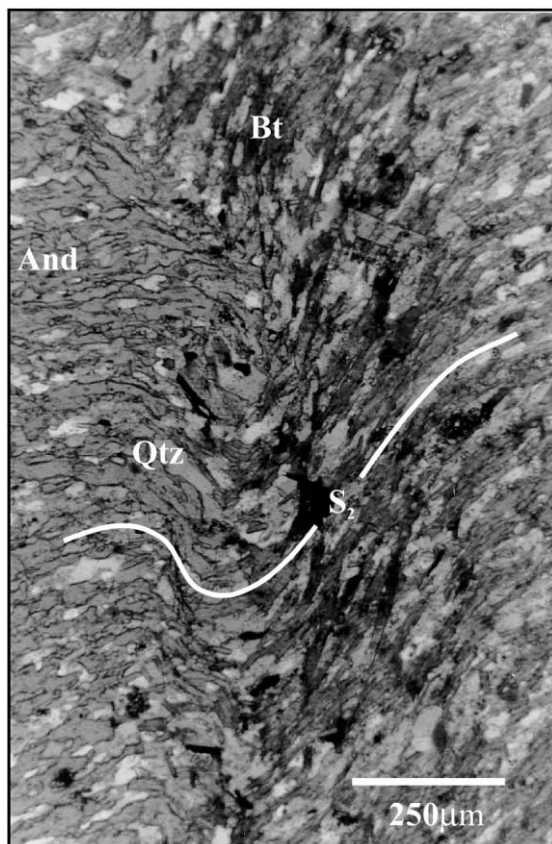


Fig. 4. Margin of andalusite porphyroblast (And) demonstrating the replacement of biotite (Bt) comprising the differentiated limbs of marginal F_3 microfolds and the incorporation of quartz (Qtz), forming the S_{2i} , into the rim of the porphyroblast.

conjugate cleavages would pass through the centre of the porphyroblast, but in fact, openly folded S_1 characterises the core and the crenulations are restricted to the margin of the porphyroblast. Thus, the conclusion is that the porphyroblasts were responsible for the nucleation of the conjugate sets. The porphyroblasts acted as strong bodies and locally perturbed what was otherwise a homogeneous deformation, as evidenced by the consistent F_3 wavelength throughout the balance of the rock (Fig. 5), and is consistent with the behaviour described by Hanmer (1979) and recent analogue modelling of Grujic and Mancktelow (1998).

The final stage of millipede development involved the incorporation of the marginal conjugate crenulation cleavage into the porphyroblast during progressive andalusite growth. This resulted in the rapid increase in the porphyroblast S_1 curvature and reversal in vergence in the porphyroblast rim characteristic of millipede microstructure. The final increment of growth most likely represents the waning stages of an exponentially decaying andalusite growth rate relative to the strain rate. It may also be the result of the accumulation of intracrystalline strain energy within the phyllosilicates (dominantly biotite) comprising the marginal S_3 septa (White, 1997) producing a second period of andalusite growth, although the inclusion of marginal S_3 septa in biotite suggests the continued development of the post-cordierite biotite–andalusite assemblage. Accordingly, the favoured mechanism involves the overgrowth of the marginal S_3 crenulation cleavage as a result of continued biotite–andalusite growth at a greatly reduced rate following very rapid initial growth. This is reflected in the consistent S_1 curvature in the core of the

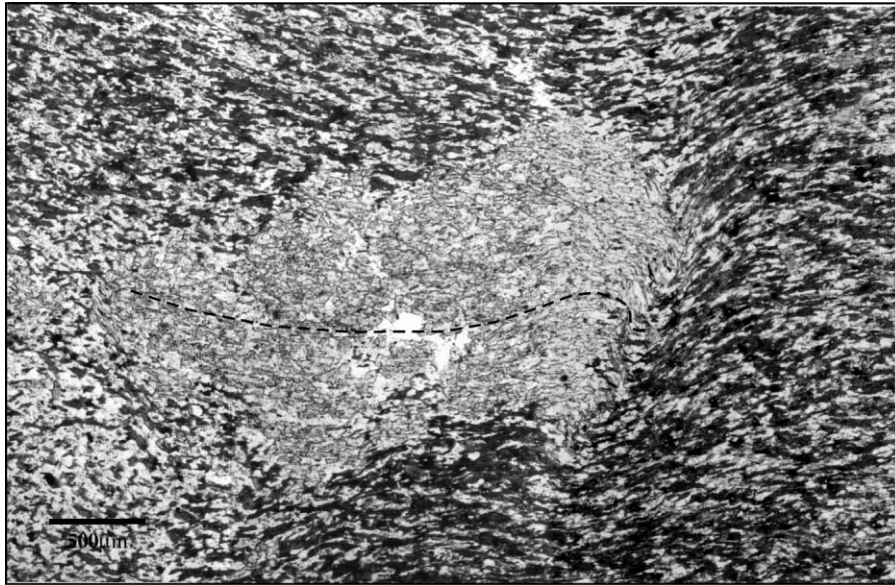


Fig. 5. Partial incorporation of tight F_3 microfold developed along the margin of an andalusite porphyroblast in an otherwise openly folded matrix.

porphyroblast, representing nearly instantaneous growth relative to the deformation rate, and the abrupt change in S_i curvature along the porphyroblast margin, representing deformation concentrated along the margin of a stable porphyroblast. The increasing change in S_i curvature characteristic of a slowly decaying growth rate, and/or fluctuating strain rate is absent. The millipede microstructure was further enhanced by the development of large pressure shadows at either end of the porphyroblast.

4. Discussion

There have been several complicated and involved models proposed to explain the development of the millipede microstructure (Bell and Rubenach, 1980; Bell,

1981; Bell et al., 1992; Johnson and Bell, 1996; Johnson and Moore, 1996) which require significant, and in this author's opinion, somewhat unrealistic strain partitioning. A simpler model (Passchier et al., 1992) involves rotation of porphyroblasts, caused by simple shear, producing small microfolds that are overgrown by a later stage of porphyroblast growth, a mechanism summarised in Fig. 3 of Passchier et al. (1992). The model presented here is simpler than any of the earlier models and does not require any special conditions other than the presence of 'rigid' porphyroblasts, growing before and during a deformation involving foliation-parallel shortening. In this model, the nucleation of conjugate crenulation cleavage along the margins of the andalusite porphyroblasts results from the presence of relatively strong bodies (porphyroblasts) in a weaker matrix (Fig. 6). The conjugate sets represent an efficient

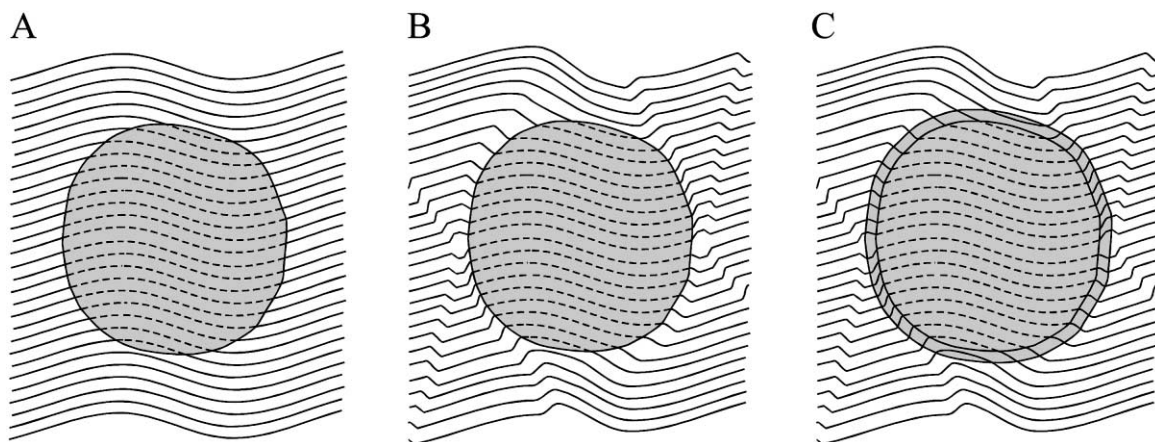


Fig. 6. Model for the development of millipede microstructures. (A) Syn-kinematic andalusite overgrows the matrix foliation, (B) conjugate crenulation cleavage develops along the margin of the porphyroblast in response to the continued shortening of the matrix, (C) second stage porphyroblast growth resulting in the inclusion of crenulation cleavage in the margin of the porphyroblast.

mechanism to produce the S_1 vergence changes characteristic of millipede microstructure. This is in contrast to the bulk inhomogeneous shortening model of Bell (1981) where porphyroblast growth occurs only in low strain domains in the developing millipede foliation pattern with the porphyroblasts having little influence over its development. Bell et al. (1992) argue that the development of millipede microstructure does not require the presence of rigid porphyroblasts, a notion clearly not supported by the localisation of S_3 crenulation cleavage along the margins of both pre- and syn-kinematic porphyroblasts in the Back River area.

Central to the model presented here is the non-linear, syn-kinematic growth of the andalusite porphyroblasts. The development of the millipede microstructure requires two stages of andalusite growth. Initial relatively rapid growth in comparison with the deformation rate, followed by a period of decreased or negligible relative growth rate during conjugate S_3 crenulation cleavage development represents a realistic growth history. It may be that the strain rate varied rather than the growth rate, although there is little supporting textural evidence. The late andalusite growth resulted in the inclusion of the quartz-rich S_1 as the S_3 muscovite–biotite septa were consumed, producing the observed millipede microstructure. To this end, Bell and Rubenach (1980) also suggest two stages of porphyroblast growth during millipede development.

From the observations presented here, the continuation of the deformation to a point where the matrix is penetratively crenulated would obscure these early conjugate crenulations and their role in the development of the microstructures. The result could be similar to Fig. 1 of Bell and Rubenach (1980). Fortunately, the deformation in the Back River area ceased shortly after the development of the S_3 conjugate crenulations, freezing in a possible intermediate stage to those described by other authors. Although it must be conceded that millipede microstructures may form by other processes, the similarity between the porphyroblast growth histories and foliation geometry of the Back River millipedes and those described by Bell and Rubenach (1980) suggests that both may have developed in the manner outlined here.

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