Relationships between foliation development, porphyroblast growth and large-scale folding in a metaturbidite suite, Snow Lake, Canada

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Abstract—Complex relationships exist between cleavage development, metamorphism and large-scale folding in the well-bedded, polydeformed, staurolite-grade metaturbidite of the Burntwood Suite, internal Palaeoproterozoic Trans-Hudson Orogen at Snow Lake, Manitoba, Canada. It is demonstrated: (a) that cleavage in anisotropic pelitic rock develops whenever microfolding is possible and that, commonly, initiation of a cleavage, which is pervasive on the scale of a fold, predates folding; (b) how a new axial planar fabric can develop on one fold limb of a symmetrical fold and not on the other; and (c) how two cleavages of different generations can be present in adjacent beds. It is further shown that porphyroblasts rotate with respect to geographical coordinates during folding. Finally, dissolution of cleavage septa is suggested here as an alternative mechanism for the generation of schistosity. The Burntwood Suite is exposed on the dismembered limb of a macroscopic isoclinal F3 structure and preserves a domal cleavage (S_2), which locally grades into a schistosity. S_2 developed from crenulation of a generally bedding-parallel S_1 cleavage that is axial planar to F1 isodienal folds formed at 1.84 Ga. Porphyroblast growth coincided with crenulation of S_1 early during F2 folding at 1.81–1.8 Ga. Early stages of S_2 development are recorded by inclusion trails (S_i) in the porphyroblasts. During F2, flexural-flow folding, variations in magnitude of bedding-parallel shear in lithologies of different competency resulted in a strong S_2 refraction and thus heterogeneous strains between beds. Independent of shear magnitude and resulting S_i/S_2 angle, S_i and S_2 remained sub-orthogonal everywhere, and thus porphyroblasts and the enveloping S_2 rotated by equal amounts with respect to S_1. As the different magnitudes of porphyroblast rotation in different beds could not be exactly balanced by the counteracting rotation of the fold limbs (same magnitude for all beds) during fold tightening, most porphyroblasts also rotated with respect to geographical coordinates. S_2 was crenulated prior to F3 large-scale folding, where favourably oriented. F3 crenulations were tightened on the eastern F3 limb and unfolded by sinistral layer-parallel shear on the western limb, where F2 and F1 layer-parallel shears were of opposite and the same sense, respectively. As a result, the initial developmental stages of an S_3 were developed only on the eastern F3 limb, and there only in incompetent layers, whereas S_3 is preserved in the competent layers. On the western limb, S_3 is preserved and appears axial planar to the F3 structure. The S_3 domal fabric was locally transformed into a schistosity by dissolution of the septa during widespread fluid activity, which endured until syn- or post-F_3. © 1998 Elsevier Science Ltd.

INTRODUCTION

Cleavage formation in strongly anisotropic micaceous pelitic rocks is regarded essentially as a crenulation process (e.g. Williams, 1972, 1977, 1979, 1990; Weber, 1976, 1981; Knipe and White, 1977). Microfolding of a sedimentary or tectonic foliation leads to a crenulation fabric. Crenulation is believed to initiate prior to or during the initial stages of large-scale folding. Thus, if the earlier fabric was approximately bedding-parallel, the crenulations form with their axial planes at a high angle to bedding (e.g. Kienow, 1942; Williams, 1972, 1979; Knipe and White, 1977; Nickelsen, 1979; Weber, 1981; Williams and Schoneveld, 1981; Henderson et al., 1986; Wright and Henderson, 1992).

During cleavage development, one or more of three competing metamorphic processes are generally operative to varying degrees: (1) solution transfer, (2) recrystallization and (3) neo-crystallization (e.g. Rickard, 1961; Williams, 1972, 1977, 1990; Marlow and Etheridge, 1977; Knipe, 1981). As a result, the final fabric might be a domalinal fabric such as differentiated crenulation cleavage, differentiated layering (e.g. Williams, 1972, 1990), dominal slaty cleavage (e.g. Hoepener, 1956; Hobbs et al., 1976, p. 222), or a penetrative fabric such as a penetrative slaty cleavage (e.g. Williams, 1972, 1977; Hobbs et al., 1976, p. 222) or a schistosity (e.g. Williams, 1977, 1985). Undifferentiated crenulation cleavages (not to be confused with crenulation that has not developed into a true cleavage) appear to be the exception.

Cleavage-forming mechanisms and the relationship between fabric development and folding are commonly studied in low-grade rocks, where the phyllosilicates do not experience coarsening. Low-grade rocks, unfortunately, generally lack porphyroblasts, which are useful for establishing the relative timing of deformation and metamorphism. Particularly useful are synkinematic porphyroblasts, which preserve stages of fabric development as inclusion trails (S_i). The relationship between S_i and the foliation external to the porphyroblast (S_e) is in some cases ambiguous, especially where S_i and S_e are discontinuous. This relationship has therefore been the subject of extensive discussion (e.g. Zwart, 1960, 1962; Spry, 1969; Vernon, 1977, 1978, 1988, 1989; Bell, 1985; Williams, 1985; Bell et al., 1986, 1992c; Passchier et al., 1992; Johnson and Vernon, 1995). Since the early 1980s, many of the microfabric studies in medium-grade pelitic
rocks have focused on (1) porphyroblast-matrix relationships per se in order to correlate metamorphic events with stages of foliation formation, and (2) the question of whether porphyroblasts rotate or not with respect to the enveloping fabric and/or geographical coordinates (e.g. Bell, 1985; Vernon, 1988; Bell et al., 1992a-c; Passchier et al., 1999). In most of these studies the porphyroblast-cleavage relationships were not considered in the context of associated mesoscopic and macroscopic structures. However, we regard such relationships as important tools for the delineation of the tectonometamorphic history of an area. Evaluating porphyroblast-matrix relationships around a fold can also help eliminate at least some S1/S2 ambiguities, as demonstrated by Williams (1985).

In the present paper we establish complex relationships between the development and overprinting of the regional S2 cleavage, porphyroblast growth and two phases of large-scale folding (F2 and F3) in a well-bedded metaturbidite sequence at Snow Lake, Canada. In order to extract the maximum information from the rock, the porphyroblast-matrix relationships were studied across a portion of heterogeneously deformed layering, which shows strong cleavage refraction. Selective overprinting of the cleavage, where favourably oriented, by subsequent F3 crenulation, is helpful in eliminating ambiguous porphyroblast-matrix relationships and gives evidence of cleavage initiation during layer-parallel shortening prior to, or in the early stages of, F2 folding. It is further shown how an axial planar cleavage may develop on one fold limb only and how different generations of cleavage may be present in adjacent beds. Moreover, it can be demonstrated that dissolution of S2 cleavage septa defined by muscovite during widespread fluid activity on the retrograde metamorphic path is responsible for the local transition of a dominal cleavage into a schistosity.

GEOLOGICAL SETTING

The Snow Lake area is situated in a transitional zone in the Paleoproterozoic Trans-Hudson Orogen (Lewry and Stauffer, 1990) of Manitoba, Canada (Fig. 1), in which the Snow Lake assemblage (part of the previous Flin Flon-Snow Lake greenstone belt) and the Kisseynew domain, a former marginal basin, were interleaved during the Hudsonian Orogeny (Fig. 2) (Kraus and Williams, 1994b). The Snow Lake area (Fig. 2) is characterized by a large, symmetrical F3 Threehouse synform largely controls the map-scale pattern in the Snow Lake area (Fig. 2).

In the Snow Lake area, the metamorphic grade is staurolite-grade, containing the assemblage younger than ~1.859 Ga for the Burntwood Suite (David et al., 1996) and ~1.845 Ga for the Missi Suite (Ansdell, 1993). SW-movement of Kisseynew sedimentary basin over the Snow Lake arc (e.g. Kraus and Williams, 1994a; Connors, 1996) resulted in two phases of isocinal folding, F1 and F2, and related thrusting, which led to multiple repetition of the contact between the two domains (Kraus and Williams, 1994b; Connors, 1996). F1 folds are truncated by 1.84-1.83 Ga granitoid plutons (Kraus and Williams, 1995; Connors, 1996; David et al., 1996).

Peak thermal conditions were reached at 1.815-1.8 Ga (Gordon et al., 1990; Parent et al., 1995; David et al., 1996) coeval with F2 in the study area (Kraus and Menard, 1997; Menard and Gordon, 1997). Post 1.8 Ga sinistral-oblique collision of the Superior Province with the Trans-Hudson Orogen along the Thompson Nickel Belt (Hoffman, 1988; Bleeker, 1990) generated NNE-trending open F3 folds of the tectonostratigraphy (Kraus and Williams, 1994b). The bounding faults are the Snow Lake fault below and the McLeod Road thrust above (Fig. 2), which are of F1 and F2 age, respectively (Kraus and Williams, 1994a; Connors, 1996). Detailed structural mapping has revealed that the slice is the dismembered lower limb of a macroscopic F2 fold (McLeod Lake fold), which was truncated along the McLeod Road thrust in the tightening stages of F2 folding (Fig. 2; see also Fig. 6c) (Kraus and Williams, 1994a). The F2 structure overprints macroscopic F1 folds and, together with the thrusts, is open fold refolded by the symmetrical F3 Threehouse synform (Fig. 7). In the core of the F3 Threehouse synform at Snow Lake, all linear features are broadly coaxial plunging moderately to steeply to the NE (Fig. 3) (Kraus and Williams, 1994b). On the eastern and western limbs, bedding dips moderately to steeply in northerly and easterly directions, respectively (Fig. 3).

Metamorphism

In the Snow Lake area, the metamorphic grade increases to the N, towards the upper tectonostratigraphic levels, from chlorite-grade at Wekusko Lake to partial melting at the southern margin of the Kisseynew domain (Figs 1 & 2) (e.g. Froese and Gasparri, 1975; Bailes and McRitchie, 1978; Kraus and Menard, 1997; Menard and Gordon, 1997). Around the F3 Threehouse synform at Snow Lake, the turbidites are metamorphosed at staurolite-grade, containing the assemblage...
staurolite + biotite + garnet + muscovite + plagioclase + graphite ± chlorite, with minor ilmenite, rutile, pyrrhotite, tournaline, magnetite, zircon and monazite. Chlorite is abundant only as inclusions in porphyroblasts and as a retrograde phase partially replacing biotite, and rims of garnet and staurolite. Temperatures of 560–570°C at an associated pressure of 4–4.5 kbar were calculated on representative samples (Kraus and Menard, 1997) using the following methods: the TWQ 1.02 program (Berman, 1991) with thermodynamic data.

Fig. 1. Lithotectonic domains of the internal Trans-Hudson Orogen (after Hoffman, 1988). SFKD = southern flank of Kisseynew domain.
Fig. 2. Simplified geological map of the Threehouse synform area at Snow Lake.

The Burntwood suite metaturbidites

The metaturbidite sequence is composed of greywacke beds, up to 1 m thick, alternating with mudstones and siltstones. The greywacke beds have preserved grading and other primary features such as scours, rip-up clasts, calcareous concretions and rare flame structures. Locally, the Burntwood Suite appears as a pelitic schist up to several metres thick. The compositional change within graded greywacke beds is reflected in reversed grading (due to coarser grain size of metamorphic minerals in the more pelitic parts). At the base of the beds biotite (up to 2 mm) is the dominant porphyroblast phase. With increasing Al-content towards the top, euhedral to subhedral pinhead garnet (1–3 mm in diameter), and large staurolite (up to 14 cm long) become abundant.

CLEAVAGE DESCRIPTION

In the sequence, there is only one discrete cleavage, S2, which appears as a small-scale differentiated layering (dominal cleavage) or a penetrative schistosity that is strongly refracted across lithological layering (Fig. 4a). In hand specimen, S2 is defined by trails of dimensionally and crystallographically well aligned, lensoid to angular biotite of variable aspect ratio (Fig. 4a). The biotite grains are locally enveloped by thin films of muscovite. S2 streamlines around garnet and staurolite. Locally, staurolite is also aligned parallel to the cleavage, but it is commonly a magnitude larger than the cleavage domains. Many biotite and staurolite porphyroblasts are pulled apart and extended in S, the stretching direction being at a high angle to the S0/S2 intersection (Fig. 4a; see also Fig. 8a). There is no cleavage in mica-poor portions of the greywackes. In thin section (all thin sections described in this paper are cut perpendicular to the S0/S2 intersection), S2 shows a variety of microstructures. The dominal character of the cleavage indicates its origin as a crenulation cleavage (Fig. 4) (cf. Williams, 1972, 1990). Garnet and biotite are confined to quartz-rich domains, which constitute the microlithons (Fig. 4; see also Fig. 7). An earlier fabric (S1) is preserved as S1 in the porphyroblasts, the significance of which will be discussed below. S2 is
defined by a quartz shape fabric in the quartz-rich domains, where, in rare cases, the matrix quartz is not annealed. Thin muscovite films, which constitute the S₂ septa, anastomose around the porphyroblasts (Fig. 4b–d). The basal planes of the muscovite grains are parallel to S₂ in both the films and quartz-rich domains (Fig. 4b–d). Locally, closely spaced porphyroblastic biotite fish are separated by thin anastomosing muscovite films and the overall cleavage morphology resembles that of a domal schistosity (Figs 4b & 5) (cf. Hobbs et al., 1976, p. 227). The films are commonly accentuated by graphite trails, which probably resulted from passive concentration by the dissolution of quartz from the developing septa (Fig. 4c & d). At the scale of a thin section, these muscovite films are preserved in some domains of a micro-bed but may have been dissolved to varying degrees in others so that the domal character of the fabric locally gives way to a more homogeneous distribution of aligned muscovite in the matrix (Fig. 4d). In domains strongly affected by muscovite dissolution, the overall appearance of the fabric approaches one of a penetrative schistosity (Fig. 5). Here, the former septa are locally tracked by trails of the less soluble graphite. The removal of muscovite is discussed in more detail below. Toward the base of the greywacke beds, which were initially poor in muscovite, the rare muscovite is randomly oriented or less orderly crenulated.

**CLEAVAGE–FOLD RELATIONSHIPS**

*Distribution and overprinting of cleavage in the Threehouse synform*

The deformation sequence in the study area was previously considered to comprise two phases of folding (Russell, 1957; Froese and Moore, 1980; Galley et al., 1988). A first generation of isoclinal folds (F₁) was believed to be refolded by the open Threehouse synform (F₂; *ibid.*). The prominent regional S₂ was considered to be axial planar to the Threehouse synform (*ibid.*). Our detailed structural mapping showed that the regional S₂ cuts mesoscopic and macroscopic F₁ folds, is axial planar to a second generation of macroscopic isoclinal folds (F₂) (Kraus and Williams, 1994a), and is deformed by the F₃ Threehouse synform (Fig. 2). Mesoscopic F₂ folds are very rare. Further evidence for this deformation sequence is given by the constant sinistral asymmetry of S₂ on the exposed limb of the F₂ McLeod Lake fold around the F₃ Threehouse synform. (*Note: all asymmetries and shear senses given in this paper refer to the F₃ profile plane looking down the NE-plunging S₀/S₂ intersection; the asymmetry is sinistral, if the clockwise intersection angle between S₀ and S₂ is < 90°; it is dextral, when the dihedral angle is > 90°.)*

On both F₃ limbs, S₀/S₂ dihedral angles vary significantly in adjacent beds from close to 90° in competent
Fig. 4. (a)-(d) Bedding-cleavage-porphyroblast relationships on the Threehouse east limb (Fig. 2). (a) Refraction of domainal fabric (S₂) across layer interface (S₀). Upper bed: S₂ and pressure-shadows of biotites (fine white strings) are refolded into Z-asymmetric open F₁ crenulations. Lower bed: The high-angle S₀ is undeformed. Geometrical relationships are as in Fig. 6d. (b) Photomicrographs of (a). S₀ is parallel to bases of photomicrographs. (b) Lower bed: S₀ domainal schistosity at high angle to S₀. Biotite fish contain planar S₁ (= S₀) of elongate quartz grains. Base is 1.7 mm. (c) Upper bed: The biotite blast overgrew S-asymmetric F₂ crenulations of S₁. Note the graphitic residue (double arrow) and the depleted muscovite films. Opaque phase is ilmenite. Base is 1.1 mm. (d) Upper bed, same thin section as (c): Varying degrees of matrix homogenisation. Graphite-enriched S₂ septa are preserved locally. Quartz pressure-shadows of biotite are recrystallised. Base is 4.2 mm. (e) Relict S-asymmetric F₂ crenulations, Threehouse west limb.
Fig. 5. Photomicrograph of porphyroblast-matrix relationships in hinge of minor \( F_1 \) fold on the Threehouse east limb. Refracted \( S_2 \) cuts the \( F_1 \) axial surface at intermediate to high angles. Straight \( S_0 \) in garnet and biotite are suborthogonal to \( S_2 \). Quartz as inclusions in garnet are elongate and smaller than in the matrix. Left hand side of photomicrograph: \( S_2 \) is developed as a domainal schistosity. Right hand side: \( S_2 \) septa are not preserved. Base is 6.4 mm.
greywackes to 10° in some incompetent mudstones. On the east limb, wherever S0/S2 angles are small, S2 is refolded by Z-asymmetrical tight to open F2 crenulations or, in micaceous portions, by kinks, whose wavelengths exceed the spacing of S2 domains considerably (Fig. 4a; see also Fig. 8a). These crenulations, which do not constitute a true cleavage, were not noted by previous writers. The axial surfaces of the crenulations are approximately axial planar to the Threehouse synform, dipping steeply ESE and containing the approximately axial planar to the Threehouse synform, because the net effect is that where S2 was inclined to S0 at an angle approaching 90° it was not folded by F3 shear.

**Timing of crenulation initiation with respect to folding**

So far, we have assumed, that crenulations form early in the folding history with axial planes at a high angle to the earlier fabric, if this earlier fabric was parallel to or at a low angle to bedding (cf. Kienow, 1942; Williams, 1972, 1979; Knipe and White, 1977; Nickelsen, 1979; Weber, 1981; Henderson et al., 1986; Wright and Henderson, 1992). This assumption fits the experiments and models of fold development in multilayer systems (Ramberg, 1963, 1964; Riot, 1964; see also Williams and Schoneveld, 1981), in which small-scale folds develop in fine layering prior to larger-scale buckling. It has been indirectly verified in the field with the help of strain markers such as sand volcanoes or organic borings parallel to the new cleavage (Nickelsen, 1979; Henderson et al., 1986; Wright and Henderson, 1992).

We are able to present further evidence based on the local overprinting of a low-angle S2 by tight–gentle, S-asymmetrical F3 crenulations on the western Threehouse limb (Fig. 4e). During sinistral layer-parallel F2 and F3 shearing, S2 was always in the instantaneous extensional field (Fig. 6d), and thus no crenulations could develop in response to layer-parallel shear. However, as pointed out above, crenulations do occur locally on the western limb. We believe that this crenulation of low-angle S2 could only have resulted from F1 layer-parallel shortening prior to major F3 folding. During subsequent large-scale buckling, when layer-parallel shear became effective in the incompetent layers, F1 crenulations were tightened and forced to become asymmetrical on the eastern limb and crenulations on the western limb were mostly unfolded (cf. Williams and Schoneveld, 1981, p. 329). The unfolded S2 continued rotation towards parallelism with lithological layering. We regard this timing of crenulation formation as generally applicable in anisotropic rocks with a penetrative cleavage on the scale of a macroscopic fold, including the initiation of S2 in the Snow Lake area.

For the following determination of the timing of metamorphism with respect to deformation, only samples and locations from the eastern Threehouse limb are considered, since this is the only place where F2 and F3 strains can be distinguished.

**SEQUENCE OF PORPHYROBLAST GROWTH—EVIDENCE FROM INCLUSION TRAILS**

In the Burntwood Suite, the presence of S1 in the
porphyroblasts makes it possible to establish the sequence of porphyroblast growth and also to examine early increments of $S_2$ development. Generally, there are two independent lines of evidence for the order of porphyroblast growth, (1) variations in $S_1$ morphologies in different porphyroblast phases adjacent to each other, and (2) metamorphic textures, such as inclusions of one index mineral in another, dissolution of grain boundaries by metamorphic reactions, and pseudomorphic relationships. Based on metamorphic textures, the following reaction sequence for the Burntwood Suite at Snow Lake during heating was inferred (Froese and Gasparini, 1975; Kraus and Menard, 1995):

\[
\text{Chl} + \text{Bt} + \text{Pl} + \text{Gr} = \text{Grt} + \text{Ms} + \text{H}_2\text{O} \quad (1)
\]

\[
\text{Chl} + \text{Ms} + \text{Grt} = \text{St} + \text{Bt} + \text{Qtz} + \text{H}_2\text{O} \quad (2)
\]

\[
\text{Chl} + \text{Ms} = \text{St} + \text{Bt} + \text{Qtz} + \text{H}_2\text{O} \quad (3)
\]

(mineral abbreviations after Kretz, 1983). This order of porphyroblast growth was tested on the $S_1$ geometries. $S_1$ is defined by graphite and/or deformed quartz and is generally sub-parallel in adjacent porphyroblast phases (Figs 4b–d, 5, 7b & c). Quartz-inclusions have a shape fabric and are smaller than matrix quartz (Fig. 7b). Locally, $S_1$ appears parallel to bedding, however it is inclined at high angles to $S_0$ in the hinges of minor $F_1$
folds (Fig. 5). Therefore, \( S_1 \) is a tectonic fabric (\( S_t \)), which appears to have been axial planar to \( F_1 \) structures. Euhedral–subhedral garnet lacks graphite as inclusions and as concentrations around the rims suggesting that graphite was a reactant in reaction (1). In most garnets, the quartz-\( S_1 \) is planar (Figs 5 & 7b). The generally undeformed biotite grains contain a straight to smoothly curved \( S_1 \) mainly of graphite (Figs 4c, d, 5 & 7c). In the quartz-rich, competent beds, where \( S_2 \) is sub-orthogonal to \( S_0 \), biotite dimensions and wavelengths of included crenulations are generally larger than in incompetent beds (Fig. 4a). Euhedral to strongly corroded staurolite varies from highly poikiloblastic to inclusion-free depending on the matrix it overgrew. Due to the large staurolite dimensions, \( S_t \), where present, describes several crenulations within each grain. The \( S_t \) in staurolite is identical in wavelength and composition to the \( S_1 \) in the adjacent biotite suggesting simultaneous growth of both phases by reactions (2) and (3).

The different stages of \( F_2 \) crenulation development recorded by \( S_t \) in the different porphyroblast phases are in accord with the above inferred sequence of metamorphic growth and imply that the porphyroblasts grew synkinematically. The constant curvatures of the included crenulations from core to rim further suggest that the porphyroblasts grew rapidly with respect to strain rates. The asymmetry of \( S_t \) in some but not all porphyroblasts indicates that growth occurred when the crenulations in some incompetent beds were constrained to become asymmetrical. Such stages of the \( S_t \) development coincided with \( F_2 \) bulk layer-parallel shortening preceding folding and/or during the earlier stages of large-scale fold amplification.

Growth of the porphyroblasts during early \( F_2 \) can be confirmed by the timing of their overprinting with respect to folding, the latter giving an upper limit for porphyroblast growth. This is illustrated in Fig. 8(a). In the lower bed, quartz pressure-shadows of some staurolites which are located close to the layer boundary across which cleavage refraction occurs, extend into the adjacent bed, continue tracking the low-angle \( S_0 \), and are crenulated by \( F_3 \). This deflection across lithological boundaries indi-
Fig. 8. Selective overprinting of $S_2$ on east limb of the Threehouse synform. (a) Lower bed: Staurolite aligned and pulled apart parallel to $S_2$. Note the pressure-shadows along $S_2$ being refracted across the layer boundary. Middle bed: Z-asymmetric $F_3$ crenulations deforming quartz pressure-shadows of staurolite grains. Upper bed: Strongly poikiloblastic staurolite at base of greywacke bed. For further explanation see text. Younging of beds is to the N. (b) Photomicrograph of $F_3$ crenulation hinge from (a). High-angle $S_3$/$S_2$ relationships are preserved after crenulation. $S_2$ septa are missing. Note the relict stylolitic residue tracking the former septa. Base is 4.2 mm.

icates that pressure-shadows developed prior to significant $S_2$ refraction and therefore early during $F_3$.

**INCLUSION TRAIL-CLEAVAGE RELATIONSHIPS—PORPHYROBLAST NON-ROTATION WITH RESPECT TO GEOGRAPHICAL COORDINATES?**

Independent of $S_0$/$S_2$ dihedral angles, $S_1$ and $S_2$ in garnet and biotite are discontinuous and at a high angle to each other everywhere in the Burntwood Suite around Snow Lake (Figs 4b-d, 5, 7b & c). This suggests that garnet and biotite porphyroblasts did not rotate or rotated very little with respect to $S_2$ during $F_2$ and $F_3$. Such lack of relative rotation between porphyroblast and enveloping cleavage has been interpreted by some workers as indicative of porphyroblast non-rotation with respect to geographical coordinates (e.g. Bell, 1985, 1986; Bell et al., 1992a–c). Nonetheless, in this case, most porphyroblasts rotated in space during folding, because (a) they rotated with respect to $S_0$ by the same amount as $S_2$ wherever cleavage refraction occurred in response to $F_2$ layer-parallel shear, and (b) $S_0$ itself rotated with respect to geographical coordinates. Thus, different amounts of $S_2$ refraction resulted in variable $S_1$ orientations relative to $S_0$ across layering; however on a small-scale, $S_1$ in adjacent porphyroblasts remained more or less parallel (Figs 5, 7 & 9). It may be argued that the garnet and biotite overgrew $S_2$ after folding and therefore did not rotate with respect to any reference frame. This possibility can be ruled out, because the planar geometry of $S_1$ in many beds, which show small $S_0$/$S_2$ dihedral angles, indicates that locally no significant shortening of $S_1$ had occurred prior to porphyroblast growth (Fig. 7b & c). Whether staurolite rotated relative to $S_0$ and $S_2$ cannot be determined with certainty, as most of the specimens do not contain $S_0$. In places, where $S_2$ was subsequently crenulated by $F_3$, $S_1$ remained sub-orthogonal to the enveloping $S_2$-septa everywhere in the crenulations (Fig. 8b). Non-rotation of porphyroblasts with respect to their enveloping cleavage can therefore not be an argument for non-rotation with respect to geographical coordinates.

**VEIN-FOLD RELATIONSHIPS**

Quartz veins (sub-)parallel to $S_2$ are ubiquitous throughout the layered sequence. They cut through staurolite porphyroblasts and are locally folded by $F_3$ crenulations. Depending on the $S_0$/$S_2$ angles and thus on lithology, these veins are stubby in the quartzose beds and are rather spindly and locally boudinaged in the mudstones (Fig. 10). In the light of the above observations, we attribute these veins to layer-parallel extension in the advanced stages of $F_2$ folding (Fig. 10c). Layer-parallel extension was controlled by the $S_2$ anisotropy and thus was accommodated differently in different lithologies. Rigid competent layers were simply torn apart along high-angle $S_2$, whereas pelitic layers were extended by slip along $S_2$ septa. The large thickness of the stubby veins is a consequence of the relatively low ductility of the competent beds.

**DEVELOPMENT OF SCHISTOSITY FROM DIFFERENTIATED LAYERING—AN ALTERNATIVE MODEL**

As mentioned above, the $S_2$ morphologies in the metaturbidites record gradations from differentiated layering to a coarse schistosity defined by aligned biotite. This aspect requires further discussion. Schistosity in metamorphosed micaceous pelitic rocks has been reported to develop in several ways. For example, a schistosity which is defined by coarse-grained micas is assumed to have developed during growth of these minerals (Voll, 1960; Tobisch et al., 1970; Dallmeyer...
Fig. 9. Schematic summary of bedding-cleavage-porphyroblast relationships during $F_2$ folding. (a) Garnet and biotite porphyroblasts overgrew an $S_0$-parallel $S_1$ during early $F_2$ and thus contain straight to smoothly curved $S_2$. (b) During fold amplification and $S_2$ rotation (stippled), the porphyroblasts did not rotate with respect to $S_1$ in incompetent beds. In competent greywacke (white), $S_2$ and porphyroblasts did not rotate with respect to $S_0$.

Microfabrics, metamorphic textures and phase petrology suggest that the schistosity in the Burntwood Suite developed from the destruction of the domainal cleavage by muscovite removal, preferentially from cleavage septa. Loss of muscovite is indicated by the different preservation states of adjacent cleavage septa in the same micro-bed on the scale of a thin section. Locally, septa (adjacent to well-preserved septa) may have been completely destroyed so that porphyroblasts 'float' freely in a quartz matrix that shows no anisotropy (Fig. 5; see also Figs 7c & 8b). In such domains now devoid of muscovite, the graphite-$S_1$ in biotite porphyroblasts is identical in shape and geometry to biotite $S_1$ in adjacent domains.
Fig. 10. Late-$F_2$ quartz veins parallel to $S_2$. (a) Spindly, boudinaged veins on Threehouse west limb record continual sinistral $F_2$ and $F_3$ layer-parallel shear. Anticlockwise rotation of veins is indicated by $S$-folds in the competent calc-silicate layer at their base. Note stubby vein within the competent layer at the left hand side. (b) Stubby veins with $S_0$ tightened around them, Threehouse east limb. (c) Sketch showing vein developed during $F_2$ folding.
where the septa are preserved (Fig. 5) suggesting that a layered anisotropy existed in both types of domain during porphyroblast growth. Here, the schistosity is defined by trains of well-aligned biotite, which are the loci of the former microlithons, in a coarsened quartz matrix (Figs 4a, 5 & 7c). The local demise of $S_2$ septa indicates that schistosity developed after $S_2$ differentiation and after growth of the prograde metamorphic assemblage. Muscovite dissolution endured until syn- or post-$F_3$ as recorded by skeletal $F_4$ crenulations, in which only the aligned biotite porphyroblasts are preserved (Fig. 8b). We believe that muscovite was dissolved by fluids and was flushed out of the system. During fluid infiltration, $S_2$ septa acted possibly as channels of enhanced fluid flow in a way described by Williams (1990). Evidence of fluid activity is given by the deficiency of matrix muscovite in many samples and by the local corrosion of biotite and staurolite rims in the absence of a higher grade aluminosilicate forming reaction. Chlorite and muscovite participated in reactions (2) and (3), and muscovite must have been left over when the reactions stopped. The presence of these phyllosilicates prior to reactions (2) and (3) is also indicated by their inclusion in porphyroblasts. Although Al, as contained in the muscovite, is considered to be relatively immobile (Carmichael, 1969), it is suggested that Al was flushed out of the system by high-pH fluids (Kraus and Menard, 1995; see also Glen, 1979 and Mancktelow, 1994). This interpretation correlates with a widespread fluid activity in the adjacent Snow Lake assemblage during $F_2$ and $F_3$ causing syntectonic alteration of volcanic-hosted massive sulphide deposits (Menard and Gordon, 1995, 1997).

SYNTHESIS AND CONCLUSIONS

In the Burnwood Suite metaturbidites at Snow Lake, a single penetrative cleavage, $S_2$, is ubiquitously developed as a dominal fabric, which shows all gradations into a schistosity. The fabric developed from crenulation of a bedding-parallel $S_1$, which formed during $F_3$ isoclinal folding at 1.84 Ga. Such crenulations are included as $S_1$ in porphyroblasts of staurolite and biotite. These porphyroblasts grew between 1.815 Ga and 1.8 Ga, when $F_2$ crenulations were constrained in some incompetent layers to become asymmetrical prior to $F_2$ fold tightening during a very small deformation increment. Associated peak conditions of metamorphism were 560–570°C and ~4-4.5 kbar. Local transformation of the differentiated layering into a schistosity by muscovite dissolution endured until syn-or post-$F_3$ after 1.8 Ga. In incompetent beds, $S_2$ and porphyroblasts rotated with respect to $S_0$ during $F_2$ tightening on the presently exposed limb of the $F_2$ McLeod Lake fold. However, they did not rotate relative to one another (in micro-beds on the scale of a thin section) and remained more or less stationary with respect to $S_0$ in competent beds. Layer-parallel extension during the later stages of $F_2$ was accommodated by separation along $S_2$ in the competent beds, resulting in quartz vein formation. $S_2$ and porphyroblast pressure-shadows, where favourably oriented, were crenulated prior to $F_3$ large-scale folding. $F_3$ crenulations were accentuated by dextral layer-parallel shear on the eastern limb of the Threehouse synform and unfolded by continued sinistral layer-parallel shear on the western limb. As a result, the initial developmental stages of an $S_3$ is preserved on the eastern $F_3$ limb only. On the other limb, $S_3$ was largely unaltered, and after rotation associated with $F_3$ appears axial planar to the $F_3$ structure.

Our work supports the hypothesis that in areas of polydeformed anisotropic micaceous pelitic rocks, cleavage may start to develop prior to folding. In general, dominal cleavage develops whenever microfolding is possible. Whether and when microfolding takes place during large-scale folding strongly depends on the orientation of the anisotropy to be crenulated with respect to layering. In special circumstances, a cleavage may develop late. For example, in a setting such as the west limb of the Threehouse synform, where a pervasive new cleavage does not form because of the orientation of the old cleavage, a local cleavage may form late during folding in the hinges of minor folds. The Threehouse synform example also shows that a dominal cleavage may develop locally, for example on one fold limb only, and there only in selected layers depending on the orientation of the previous fabric. As crenulation and differentiation involve the destruction of the previous fabric (e.g. Tobisch and Paterson, 1988; this work) the only foliation present in alternating lithologies may be of different generations. This has implications for other areas, for example the Slave Province, Canada, where, in the Yellowknife Supergroup metaturbidite sequence, two subsequent, however morphologically similar fabrics alternate in adjacent beds, displaying a chevron pattern (Fyson, 1982, 1984; Henderson, 1997). This pattern possibly formed by the same mechanisms operating in the Threehouse synform area with the difference that, in the Yellow Knife supergroup, the later fabric experienced complete differentiation.

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