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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 Paleoproterozoic 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 F_2 structure and preserves a domainal 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 F_1 isoclinal folds formed at 1.84 Ga. Porphyroblast growth coincided with crenulation of S_1 early during F_2 folding at 1.815–1.8 Ga. Early stages of S_2 development are recorded by inclusion trails (S_i) in the porphyroblasts. During F_2 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_0/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_0. 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 F_3 large-scale folding, where favourably oriented. F_3 crenulations were tightened on the eastern F_3 limb and unfolded by sinistral layer-parallel shear on the western limb, where F_2 and F_3 layer-parallel shears were of opposite and the same sense, respectively. As a result, the initial developmental stages of an S_3 are developed only on the eastern F_3 limb, and there only in incompetent layers, whereas S_2 is preserved in the competent layers. On the western limb, S_2 is preserved and appears axial planar to the F_3 structure. The S_2 domainal 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) neocrystallization (e.g. Rickard, 1961; Williams, 1972, 1977, 1990; Marlow and Etheridge, 1977; Knipe, 1981). As a result, the final fabric might be a domainal fabric such as differentiated crenulation cleavage, differentiated layering (e.g. Williams, 1972, 1990), domainal slaty cleavage (e.g. Hoeppener, 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 focussed 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.*, 1992; Johnson and Vernon, 1995). 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 S_i/S_e ambiguities, as demonstrated by Williams (1985).

In the present paper we establish complex relationships between the development and overprinting of the regional S_2 cleavage, porphyroblast growth and two phases of large-scale folding (F_2 and F_3) 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 F_3 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, F_2 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 S_2 cleavage septa defined by muscovite during widespread fluid activity on the retrograde metamorphic path is responsible for the local transition of a domainal 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, 1994a; Connors, 1996). This zone of interleaving is referred to as the Snow Lake allochthon (Kraus and Menard, 1997). The Snow Lake assemblage comprises rocks of island arc affinity that formed at ~1.9 Ga (Stern *et al.*, 1995; Lucas *et al.*, 1996; David *et al.*, 1996). The Kisseynew domain consists of metamorphosed metaturbidites (*Burntwood Suite*), which are intercalated with their terrestrial facies correlative (*Missi Suite*) (Bailes, 1980; Stauffer, 1990; Zwanzig, 1990). U–Pb geochronology of detrital zircons has yielded a sedimentation age 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 isoclinal folding, F_1 and F_2, and related thrusting, which led to multiple repetition of the contact between the two domains (Kraus and Williams, 1994b; Connors, 1996). F_1 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 F_2 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 F_3 folds of the tectonostratigraphy (Kraus and Williams, 1994b). The large, symmetrical F_3 Threehouse synform largely controls the map-scale pattern in the Snow Lake area (Fig. 2).

The rocks discussed here form a slice of Burntwood Suite metaturbidites (previously referred to as File Lake Formation by Bailes, 1980) that are exposed around the town of Snow Lake (Fig. 2). The northerly to easterly dipping slice (Fig. 3a) varies in thickness from several hundred metres to 4–5 km and is in structural contact above and below with rocks of the arc assemblage. The bounding faults are the Snow Lake fault below and the McLeod Road thrust above (Fig. 2), which are of F_1 and F_2 age, respectively (Kraus and Williams, 1994a; Connors, 1996). Detailed structural mapping has revealed that the slice is the dismembered lower limb of a macroscopic F_2 fold (McLeod Lake fold), which was truncated along the McLeod Road thrust in the tightening stages of F_2 folding (Fig. 2; see also Fig. 6c) (Kraus and Williams, 1994a). The F_2 structure overprints macroscopic F_1 folds and, together with the thrusts, is openly refolded by the symmetrical F_3 Threehouse synform (Fig. 2). In the core of the F_3 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 Gasparrini, 1975; Bailes and McRitchie, 1978; Kraus and Menard, 1997; Menard and Gordon, 1997). Around the F_3 Threehouse synform at Snow Lake, the turbidites are metamorphosed at staurolite-grade, containing the assemblage

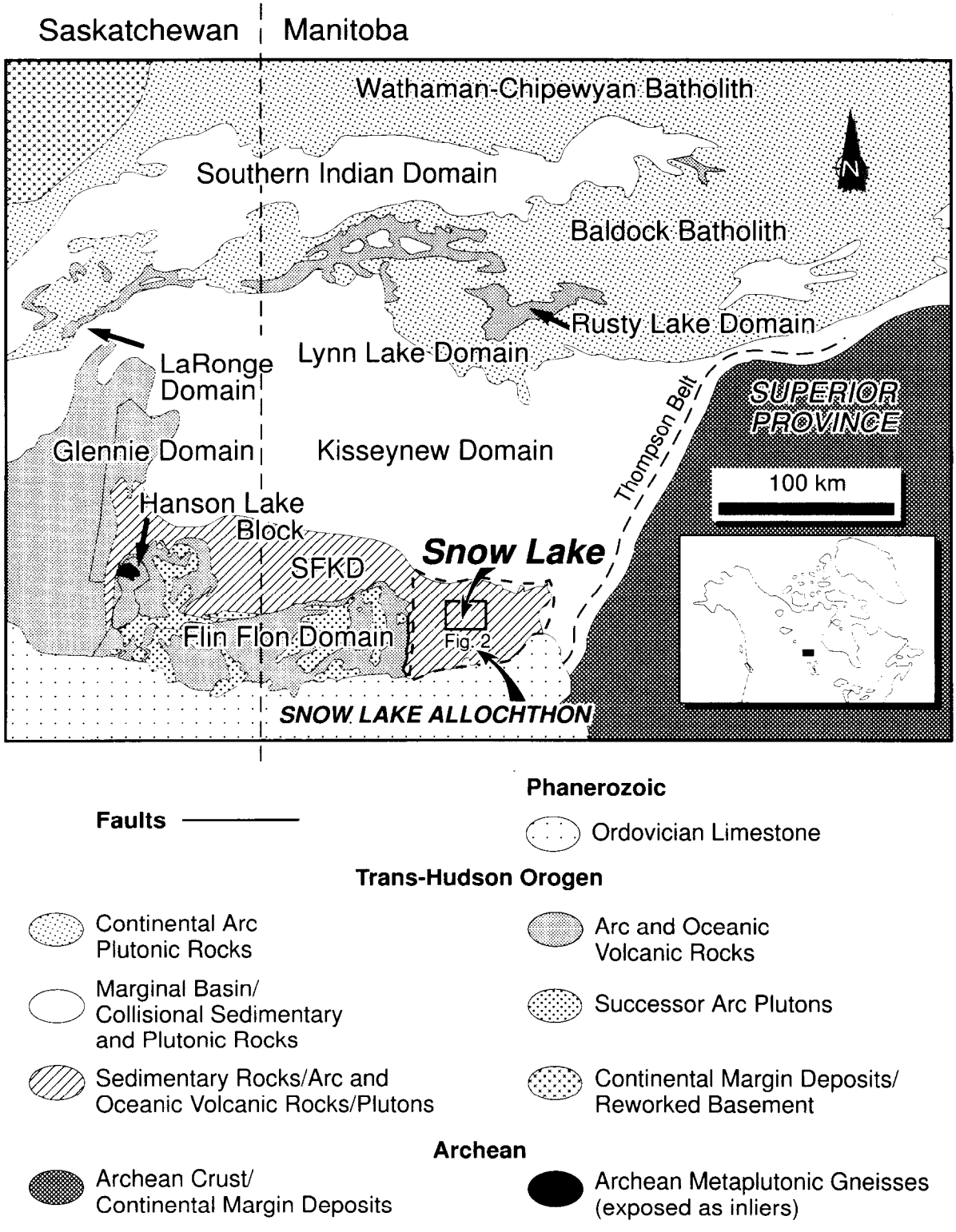

Fig. 1. Lithotectonic domains of the internal Trans-Hudson Orogen (after Hoffman, 1988). SFKD = southern flank of Kisseynew domain.

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

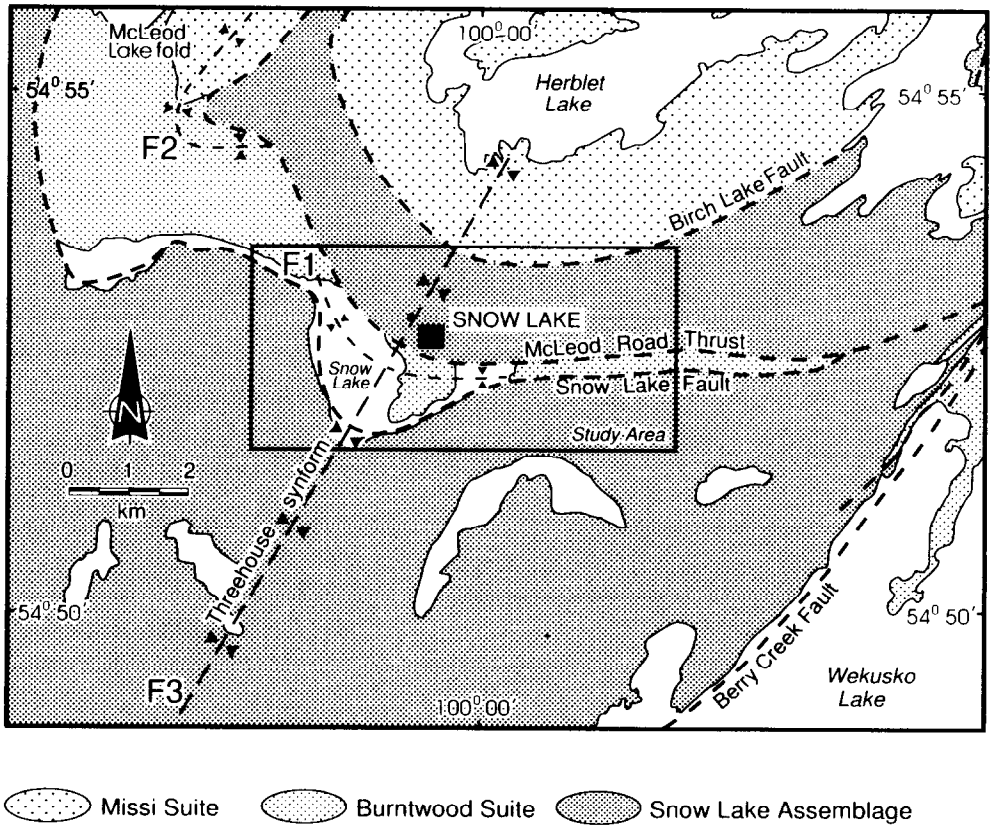

Fig. 2. Simplified geological map of the Threehouse synform area at Snow Lake.

from Berman (1988, 1990), Fuhrman and Lindsley (1988), Berman and Koziol (1991), McMullin *et al.* (1991), and Mäder *et al.* (1994); the garnet–biotite thermometer (Kleemann and Reinhardt, 1994); and the garnet–biotite–muscovite–plagioclase barometer (Hodges and Crowley, 1985; Powell and Holland, 1988; Hoisch, 1990). These results were interpreted as representing peak metamorphic conditions (Kraus and Menard, 1997).

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, S_2, which appears as a small-scale differentiated layering (domainal cleavage) or a penetrative schistosity that is strongly refracted across lithological layering (Fig. 4a). In hand specimen, S_2 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. S_2 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_2, the stretching direction being at a high angle to the S_0/S_2 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 S_0/S_2 intersection*), S_2 shows a variety of microstructures. The domainal 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 (S_1) is preserved as S_i in the porphyroblasts, the significance of which will be discussed below. S_2 is

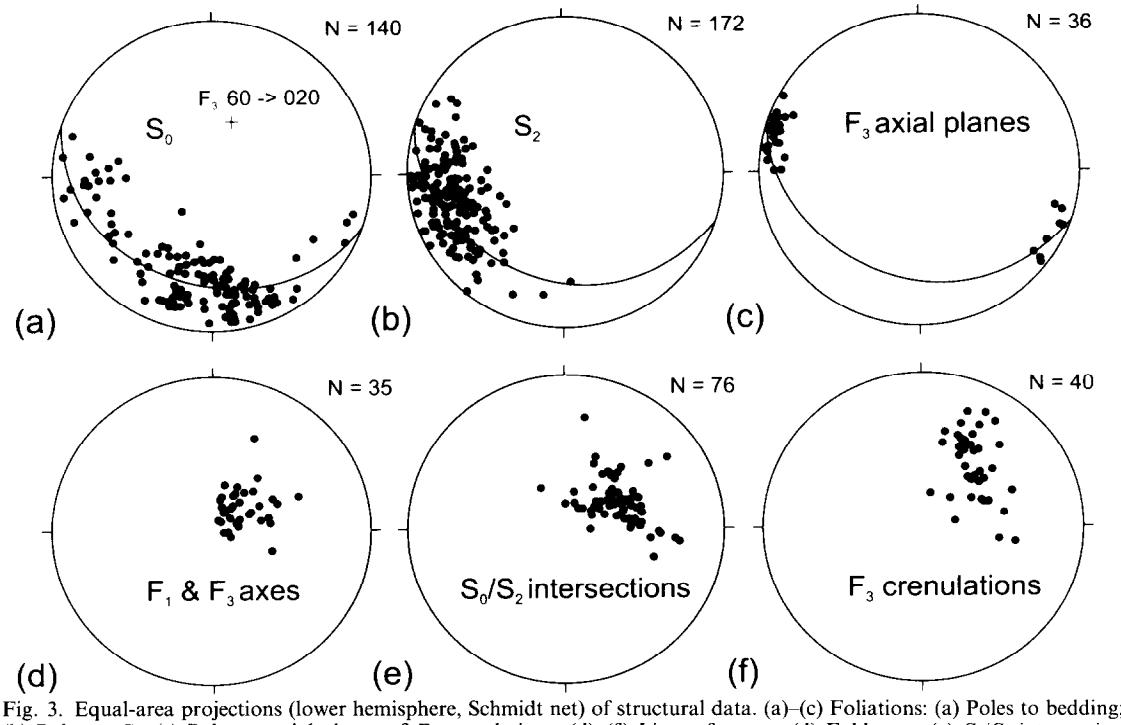

Fig. 3. Equal-area projections (lower hemisphere, Schmidt net) of structural data. (a)–(c) Foliations: (a) Poles to bedding; (b) Poles to S_2; (c) Poles to axial planes of F_3 crenulations; (d)–(f) Linear features: (d) Fold axes; (e) S_0/S_2 intersection lineations (calculated); (f) F_3 crenulation axes on S_2.

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 S_2 septa, anastomose around the porphyroblasts (Fig. 4b–d). The basal planes of the muscovite grains are parallel to S_2 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 domainal 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 domainal 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 (F_1) was believed to be refolded by the open Threehouse synform (F_2; *ibid.*). The prominent regional S_2 was considered to be axial planar to the Threehouse synform (*ibid.*). Our detailed structural mapping showed that the regional S_2 cuts mesoscopic and macroscopic F_1 folds, is axial planar to a second generation of macroscopic isoclinal folds (F_2) (Kraus and Williams, 1994a), and is deformed by the F_3 Threehouse synform (Fig. 2). Mesoscopic F_2 folds are very rare. Further evidence for this deformation sequence is given by the constant sinistral asymmetry of S_2 and S_0 on the exposed limb of the F_2 McLeod Lake fold around the F_3 Threehouse synform. (*Note: all asymmetries and shear senses given in this paper refer to the F_2 profile plane looking down the NE-plunging S_0/S_2 intersection; the asymmetry is sinistral, if the clockwise intersection angle between S_0 and S_2 is $<90°$; it is dextral, when the dihedral angle is $>90°$.*)

On both F_3 limbs, S_0/S_2 dihedral angles vary significantly in adjacent beds from close to 90° in competent

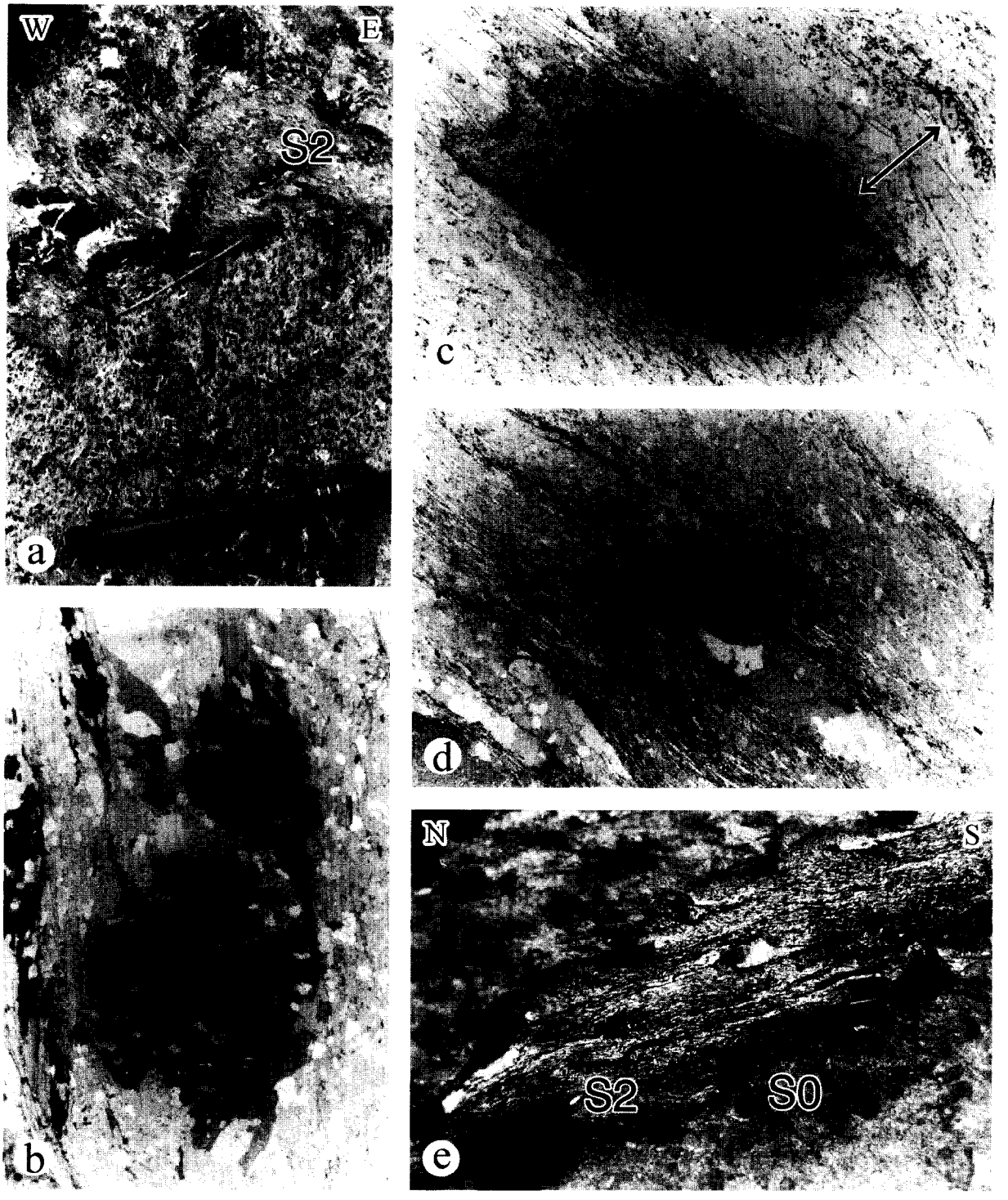

Fig. 4. (a)–(d) Bedding–cleavage–porphyroblast relationships on the Threehouse east limb (Fig. 2). (a) Refraction of domainal fabric (S_2) across layer interface (S_0). Upper bed: S_2 and pressure-shadows of biotites (fine white strings) are refolded into Z-asymmetric open F_3 crenulations. Lower bed: The high-angle S_2 is undeformed. Geometrical relationships are as in Fig. 6d. (b)–(d) Photomicrographs of (a). S_0 is parallel to bases of photomicrographs. (b) Lower bed: S_2 domainal schistosity at high angle to S_0. Biotite fish contain planar S_i ($= S_1$) of elongate quartz grains. Base is 1.7 mm. (c) Upper bed: The biotite blast overgrew S-asymmetric F_2 crenulations of S_1. 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 S_2 septa are preserved locally. Quartz pressure-shadows of biotite are recrystallised. Base is 4.2 mm. (e) Relict S-asymmetric F_3 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_1 ($= S_1$) 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 S_0/S_2 angles are small, S_2 is refolded by Z-asymmetrical tight to open F_3 crenulations or, in micaceous portions, by kinks, whose wavelengths exceed the spacing of S_2 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 F_3 fold axis. S_2 is undeformed, where it is at a high angle to S_0.

On the west limb, S_0/S_2 dihedral angles are generally smaller than in comparable lithologies on the east limb. Here, S_2 is not overprinted except at three localities, where tight–gentle, S-asymmetrical F_3 crenulations are developed (Fig. 4e).

Interpretation

The reconstruction of the cleavage and folding history during F_2 and F_3 based on these geometrical relationships is shown in Fig. 6. It is assumed that S_2 formed originally at a high angle to S_0 during F_2 layer-parallel shortening (Fig. 6a). This assumption is discussed below. S_2 refraction occurred due to differential sinistral layer-parallel shear on the exposed lower limb of the F_2 McLeod Lake fold during F_2 fold development (Fig. 6b). The mudstones and incompetent portions of the graded beds maximised F_2 layer-parallel shear or shear induced vorticity (Lister and Williams, 1983); the competent portions maximised F_2 spin (Lister and Williams, 1983). The large-scale F_2 fold was subsequently dismembered along the McLeod Road thrust (Fig. 6c). The constant sinistral S_0/S_2 asymmetry across the Threehouse synform indicates that the turbidite sliver represents the southern limb of the easterly closing F_2 McLeod Lake fold (Fig. 6c). During F_3 folding, layer-parallel shear was of opposite sense on the opposite limbs of the Threehouse synform (Fig. 6d). Continued sinistral layer-parallel shearing on the west limb resulted in further decrease in S_0/S_2 dihedral angles. Here, S_2 appears to be axial planar to the Threehouse synform, because the exposed limb of the F_2 structure has the same asymmetry as the western limb of the F_3 synform and thus the F_2 asymmetry of S_0 and S_2 is preserved. It is important to note that F_2 and F_3 must be approximately coaxial or S_2 would not appear to be axial planar to F_3. This coaxiality is indicated by the poles to S_0, S_2 and the axial planes of F_3 crenulations plotting on approximately the same great circle (Fig. 3a–c).

On the Threehouse east limb, the shear sense reversed from F_2-related sinistral shear to F_3-related dextral shear following initial layer-parallel shortening (Fig. 6d). S_2 was in the shortening sector of the instantaneous F_3-related shear strain and, where it was at a shallow angle to S_0, the finite strain was sufficient to result in well developed open–tight crenulations. As shearing continued the crenulations were constrained to become Z-asymmetrical. Where S_2 was at a high angle it started in the shortening field but after accumulating only a small amount of shear strain it was rotated into the extensional sector. Any crenulation developed in response to the initial shortening would be unfolded. Thus the net effect is that where S_2 was inclined to S_0 at an angle approaching 90° it was not folded by F_3 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; Biot, 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 S_2 by tight–gentle, S-asymmetrical F_3 crenulations on the western Threehouse limb (Fig. 4e). During sinistral layer-parallel F_2 and F_3 shearing, S_2 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 S_2 could only have resulted from F_3 layer-parallel shortening prior to major F_3 folding. During subsequent large-scale buckling, when layer-parallel shear became effective in the incompetent layers, F_3 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 S_2 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 S_2 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 F_2 and F_3 strains can be distinguished.

SEQUENCE OF PORPHYROBLAST GROWTH—EVIDENCE FROM INCLUSION TRAILS

In the Burntwood Suite, the presence of S_i in the

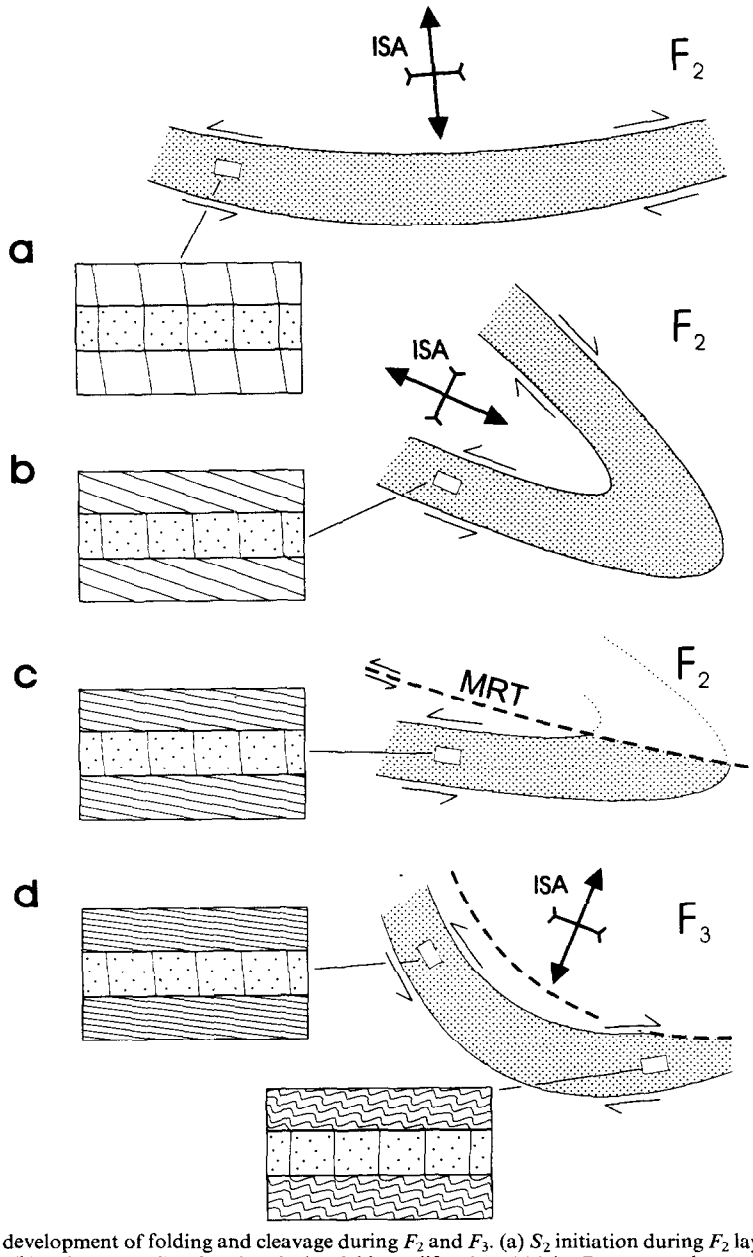

Fig. 6. Sequential development of folding and cleavage during F_2 and F_3. (a) S_2 initiation during F_2 layer-parallel shortening and early buckling. (b) Subsequent S_2 refraction during fold amplification. (c) The F_2 structure becomes dismembered by the McLeod Road thrust. (d) The relict lower F_2 limb is refolded by the F_3 Threehouse synform. During (d) the low-angle S_2 experiences differential overprinting on both F_3 limbs. ISA = instantaneous stretching axes of the bulk flow.

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_i 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 Gasparrini, 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_i geometries. S_i 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_i appears parallel to bedding; however it is inclined at high angles to S_0 in the hinges of minor F_1

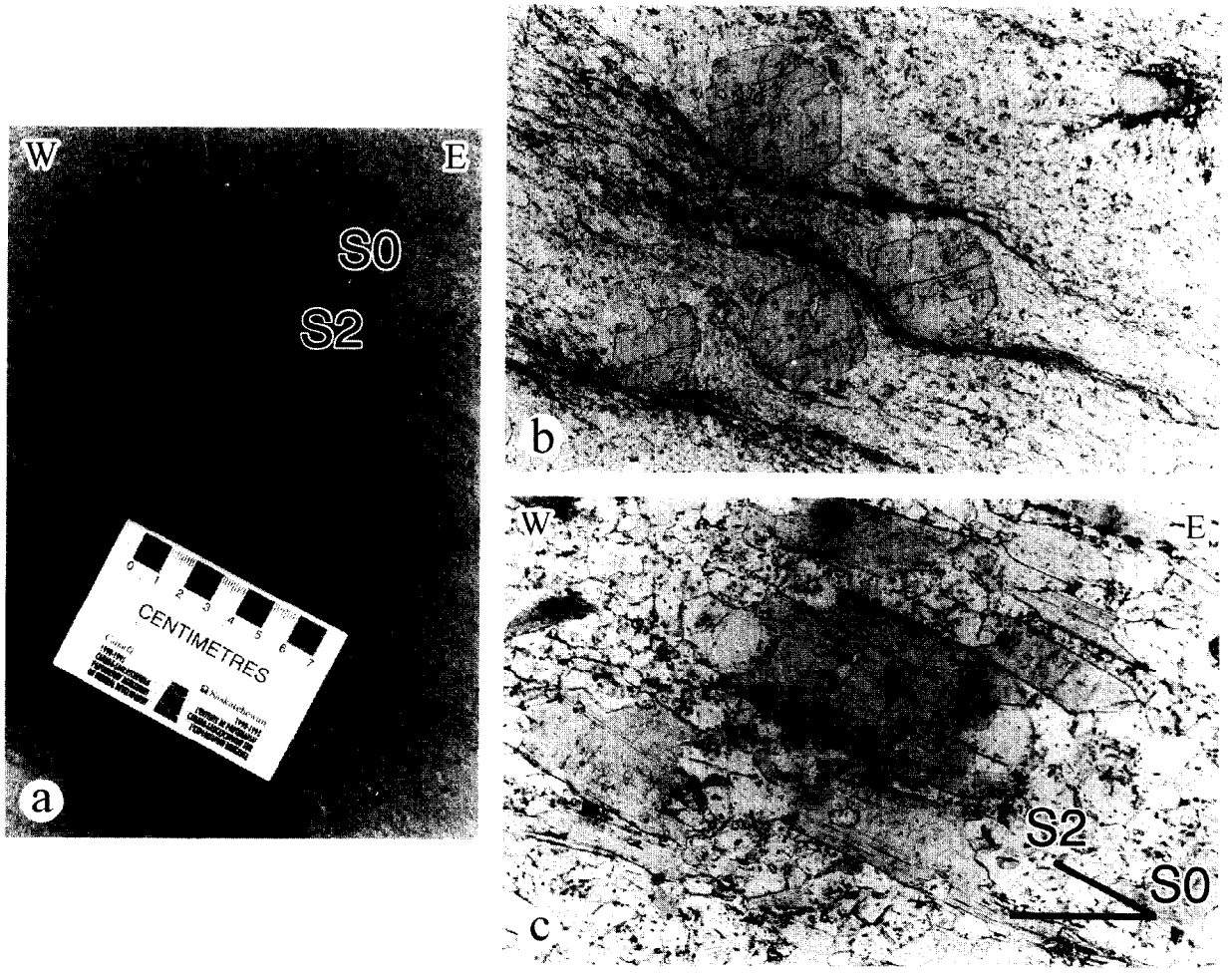

Fig. 7. Bedding–cleavage–porphyroblast relationships on Threehouse east limb. (a) Domainal fabric (S_2) in garnetiferous siltstone, only weakly affected by F_3 crenulation. (b) Photomicrograph of (a). Garnet contains planar S_i ($= S_1$). S_2 septa are partly dissolved. Base is 1 cm. (c) Crystallographically aligned biotites form a low-angle S_2 schistosity. Enveloping muscovite films are not preserved. S_0 is parallel to base of photomicrograph. Base is 1.7 mm. The context of a low S_0/S_2 dihedral angle and planar S_i at a high angle to S_2 in (b) and (c) indicates rotation of S_2 and porphyroblasts with respect to S_0. For further explanation see text.

folds (Fig. 5). Therefore, S_i is a tectonic fabric (S_1), 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_i is planar (Figs 5 & 7b). The generally undeformed biotite grains contain a straight to smoothly curved S_i 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_i, where present, describes several crenulations within each grain. The S_i in staurolite is identical in wavelength and composition to the S_i 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_i 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_i 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_2 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_2, and are crenulated by F_3. This deflection across lithological boundaries indi-

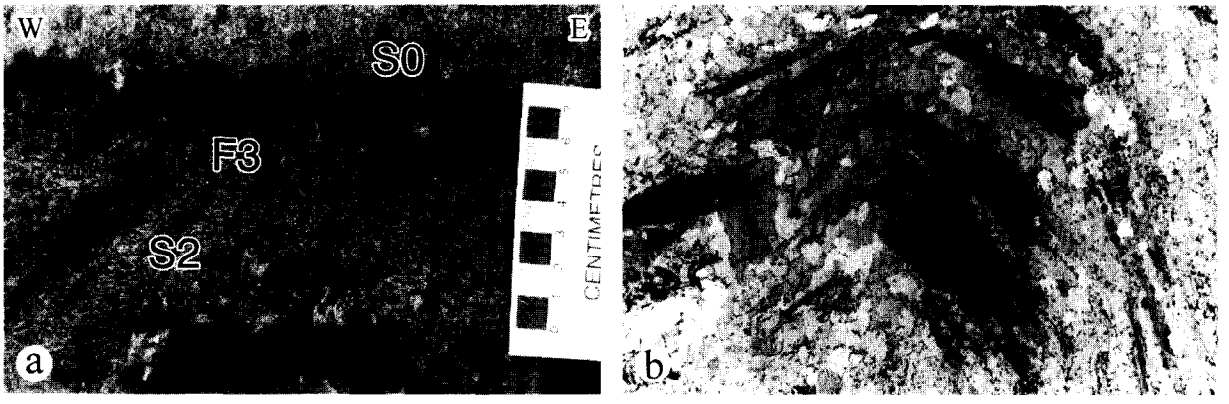

Fig. 8. Selective overprinting of S_2 on east limb of the Threehouse synform. (a) Lower bed: Staurolite aligned and pulled apart parallel to S_2. Note the pressure-shadows along S_2 being refracted across the layer boundary. Middle bed: Z-asymmetric F_3 crenulations deforming quartz pressure-shadows 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_i/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.

cates that pressure-shadows developed prior to significant S_2 refraction and therefore early during F_2.

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

Independent of S_0/S_2 dihedral angles, S_i 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_i orientations relative to S_0 across layering; however on a small-scale, S_i 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_i 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_e cannot be determined with certainty, as most of the specimens do not contain S_i. In places, where S_2 was subsequently crenulated by F_3, S_i 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

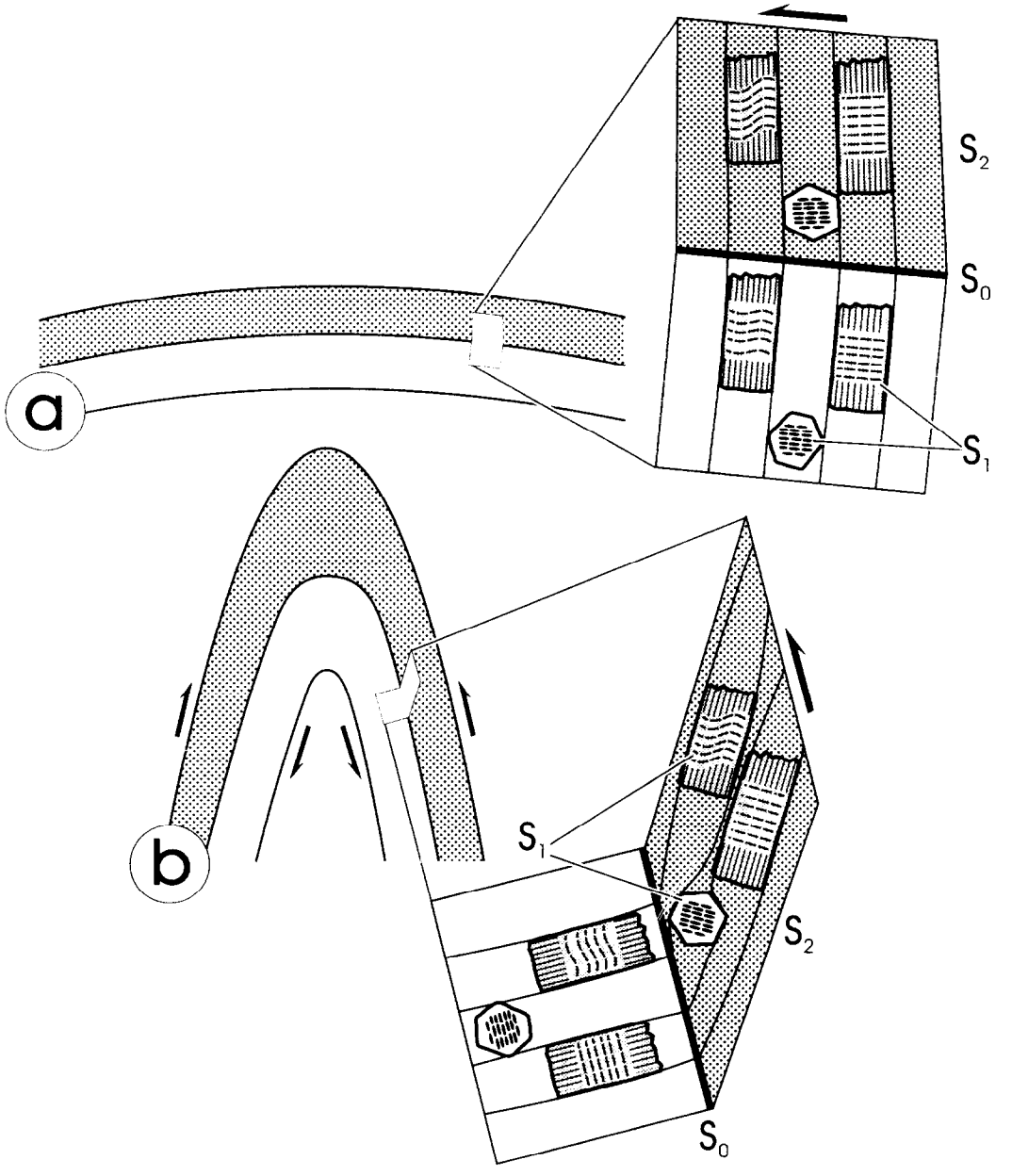

Fig. 9. Schematic summary of bedding–cleavage–porphyroblast relationships during F_2 folding. (a) Garnet and biotite porphyroblasts overgrew an S_0-parallel S_1 during early F_2 and thus contain straight to smoothly curved S_i. (b) During fold amplification and S_2 rotation (stippled), the porphyroblasts did not rotate with respect to S_2 in incompetent beds. In competent greywacke (white), S_2 and porphyroblasts did not rotate with respect to S_0.

et al., 1983). If the bulk of the mica growth predates the cleavage forming event, as in the Burntwood Suite, other mechanisms must account for schistosity formation. Mathematical theories of rigid body rotation of randomly distributed single grains have been proposed by Jefferey (1922) and March (1932). However, their models cannot explain the locally domainal fabric. Alternatively, schistosity may grow from a coarsening crenulation cleavage (e.g. Williams, 1977, 1985) or involve kinking of an earlier foliation (Williams, 1977; Williams *et al.*, 1977; Williams and Compagnoni, 1983) but the continuous S_i in biotite (see above) also rules out these possibilities (Figs 4b–d & 7c).

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_i in biotite porphyroblasts is identical in shape and geometry to biotite S_i in adjacent domains

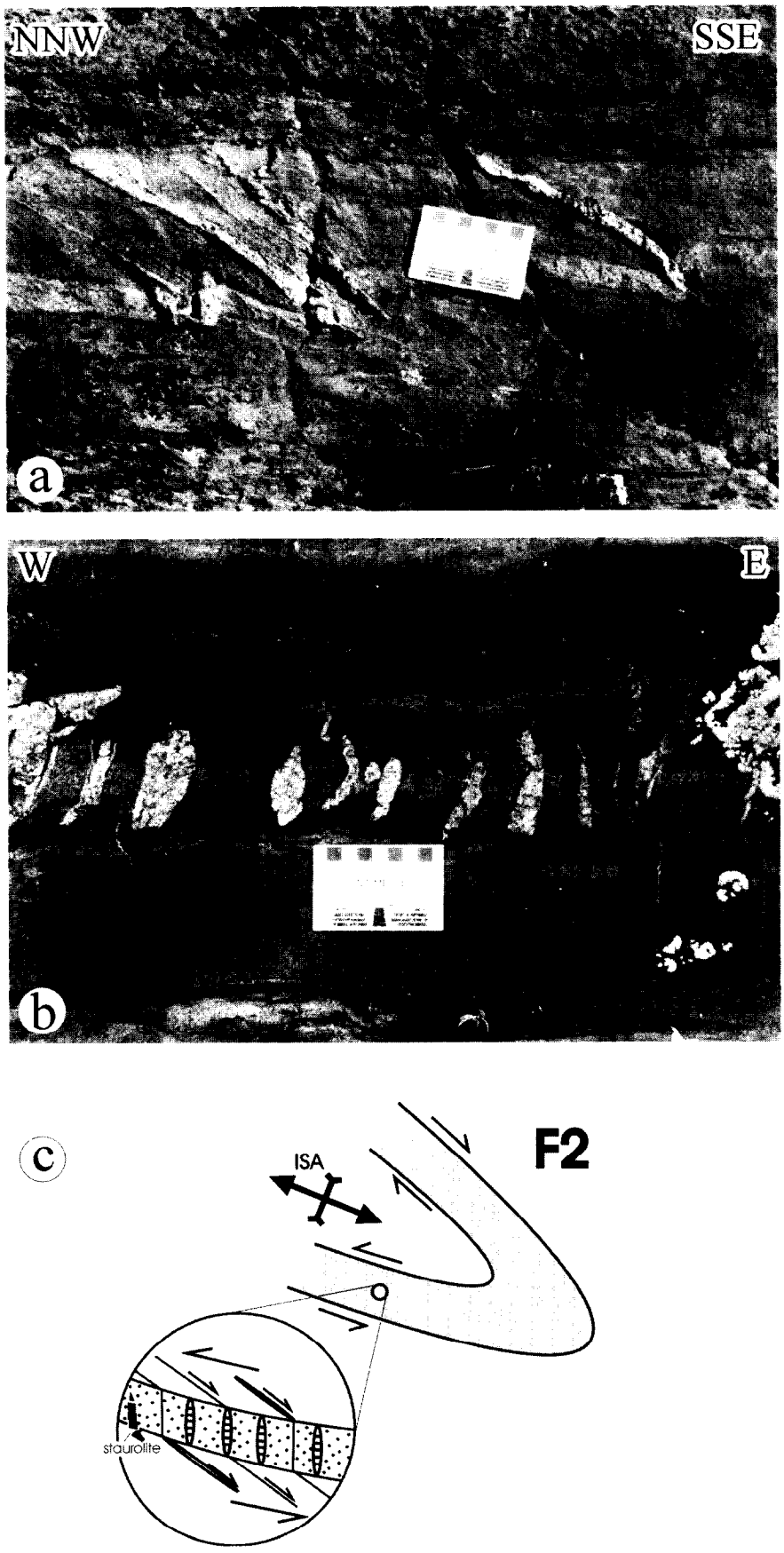

Fig. 10. Late-F_2 quartz veins parallel to S_2. (a) Spindly, boudinaged veins on Threehouse west limb record continual sinstral F_2 and F_3 layer-parallel shear. Anticlockwise rotation of veins is indicated by S-folds in the competent calcsilicate layer at their base. Note stubby vein within the competent 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_3 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 Burntwood Suite metaturbidites at Snow Lake, a single penetrative cleavage, S_2, is ubiquitously developed as a domainal fabric, which shows all gradations into a schistosity. The fabric developed from crenulation of a bedding-parallel S_1, which formed during F_1 isoclinal folding at 1.84 Ga. Such crenulations are included as S_i 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_2 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, domainal 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 domainal 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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