Cleavages developed in mudstone during diagenesis and deformation: an example from the Carboniferous (Tournaisian), southeastern New Brunswick, Canada

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ABSTRACT

The Weldon Formation of the Lower Carboniferous (Tournaisian) Sussex Group of southeastern New Brunswick consists of red mudstone intervals interbedded with red siltstone and fine-grained sandstone. Some of the mudstone intervals exceed 50 m in thickness and are deformed in such a way as to render bedding ambiguous. At two localities south of Moncton, these thick mudstone intervals carry two fracture cleavages that are almost perpendicular to each other, and perpendicular to bedding. In the Weldon Creek section these cleavages are particularly well preserved, and a clear timing relationship can be established. The second cleavage crenulates and transposes the first, which typically carries a slicken lineation where lithons are deformed by crenulation. Thin section and scanning electron microscope images reveal that these cleavages are defined by microveins of calcite, gypsum, and montmorillonitic clays with hematite and vivianite, and that there is some evidence for silica dissolution. At Belliveau Village, these two cleavages are largely disrupted by layer-parallel shear planes in the limb of the Belliveau syncline, indicating that they predated folding. The presence of primary diagenetic gypsum, primary carbonate cement in interbedded sandstone, and low equivalent vitrinite reflectance (%R) values in underlying oil shale (0.65–0.77) indicate that these cleavages formed below 100 °C during diagenesis rather than under anchizone conditions. Their presence reflects a bulk shortening parallel to bedding prior to fold development, and layer-parallel deformation during folding progressively destroyed them. These early cleavages are not precursors to slaty cleavage, and are essentially ephemeral features, though they could provide another anisotropy on which later cleavages might nucleate.

RÉSUMÉ

La formation de Weldon du Carbonifère inférieur (Tournaisien) du Groupe de Sussex, dans le sud-est du Nouveau-Brunswick se compose d’intervalles de mudstone dans des stratifications de siltite rouge et de grès à grain fin. Certains de ces intervalles de mudstone ont plus de 50 m d’épaisseur et présentent une déformation telle que le litage semble ambigu. Dans deux localités au sud de Moncton, ces intervalles épais de mudstone comportent deux schistosités de fracture se présentant pratiquement à la perpendiculaire, l’une par rapport à l’autre, et également à la perpendiculaire de la stratification. Dans la section du ruisseau Weldon, ces schistosités sont particulièrement bien préservées et on peut en déduire très nettement une corrélation de périodicité. La deuxième schistosité donne lieu à une crénulation reportée à partir de la première schistosité, laquelle comprend une linéation de glissement classique dont les lithons ont été déformés par crénulation. Les images de lame mince et de MEB (microscope électronique à balayage) indiquent que ces schistosités se caractérisent par de petits filonnets de calcite, de gypse, et d’argiles de montmorillonite assortis d’hématite et de vivianite, et on peut également observer des traces de dissolution de silice. Au village de Belliveau, ces deux schistosités sont altérées de manière importante par des plans de cisaillement parallèles au litage dans le flanc du pli synclinal Belliveau, ce qui porte à croire que les schistosités sont antérieures à la formation du synclinal. La présence de gypse diagénétique primaire, de ciment carbonaté primaire dans le grès intercalaire, et d’une réflectance de vitrinite de faible équivalence (%R) dans le schiste bitumineux sous-jacent (0.65–0.77) semble indiquer que la formation de ces schistosités s’est opérée à une température inférieure à 100 °C au cours de la diagénèse, plutôt que pendant l’anchizone. Cette présence rend compte d’un raccourcissement des matières meubles parallèlement au litage, survenu avant la formation du synclinal, et d’une déformation parallèle au litage pendant la formation du synclinal, ce phénomène ayant entraîné leur destruction graduelle. Ces premières schistosités ne sont pas des indices d’un clivage ardoisier, car il s’agit pour l’essentiel de formations de nature éphémère, qui pourraient néanmoins produire une autre anisotropie susceptible de donner lieu à la nucléation d’autres schistosités.

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INTRODUCTION AND GEOLOGICAL BACKGROUND

Fabrics defined by the alignment of clay particles are widely reported from mudstones, and generally attributed, if they are bedding-parallel or sub-parallel, to compaction during dewatering and diagenesis (see review in Kisch 1991 and papers by Oertel and Curtis 1972, Moon 1972, Krizek *et al*. 1975, Curtis *et al*. 1980, and Maltman 1981). Discordant fabrics are generally attributed to early tectonic deformation and considered to represent incipient cleavage development under conditions transitional from high-temperature diagenesis into anchizone and greenschist-facies metamorphism, and in such cases, fabric geometry can be related to finite strain (e.g., Dunoyer de Segonzac 1966; Kubler 1967a, 1967b; Piqué 1975, 1982; Weber 1976; Siddans 1977; Dandois 1981; Kisch 1989; Glasmacher *et al*. 2004). What is described in this paper is a pair of cleavages, highly discordant to bedding, in a mudstone where diagenetic history and thermal maturation data (vitrinite reflectance and spore coloration) indicate conditions that were well below the anchizone-diagenesis transition. The geometric relationship of these cleavages to bedding and regional structures (folds and thrust faults) suggests that they formed during a very early phase of bedding-parallel shortening, and were progressively obliterated by layer-parallel slip and shear. Not only were these cleavages formed under exceptionally low-grade conditions, but they are also ephemeral features of these mudstones, largely destroyed by subsequent deformation.

The Lower Carboniferous sedimentary rocks in the area south of Moncton, New Brunswick, are contained in a series of northeast-southwest anticlines and synclines in the Hillsborough area, that are part of a fold-thrust belt along the southern edge of the Moncton sub-basin (Figs 1, 2; Park and St. Peter 2005; Park *et al*. in press). These features all lie beneath the unconformity at the base of the late Tournaisian to Visean Hillsborough Formation (Park and St. Peter 2005; Park *et al*. in press; St. Peter and Johnson 2009). The pre-Visean (Fammenian–Tournaisian) rocks below the Hillsborough Formation are included in two stratigraphic units: Horton Group and Sussex Group. The Horton Group is subdivided into a basal Memramcook Formation (absent locally) and an overlying Albert Formation. An unconformity separates the Horton Group from the overlying Sussex Group. The Sussex Group is in turn subdivided into a conglomeratic Round Hill Formation, a red mudstone-dominated Weldon Formation, and a grey-red shale - evaporite Gautreau Formation. The three formations are partly lateral equivalent, but in the area of this study the Round Hill Formation is overlain by, and interbed-

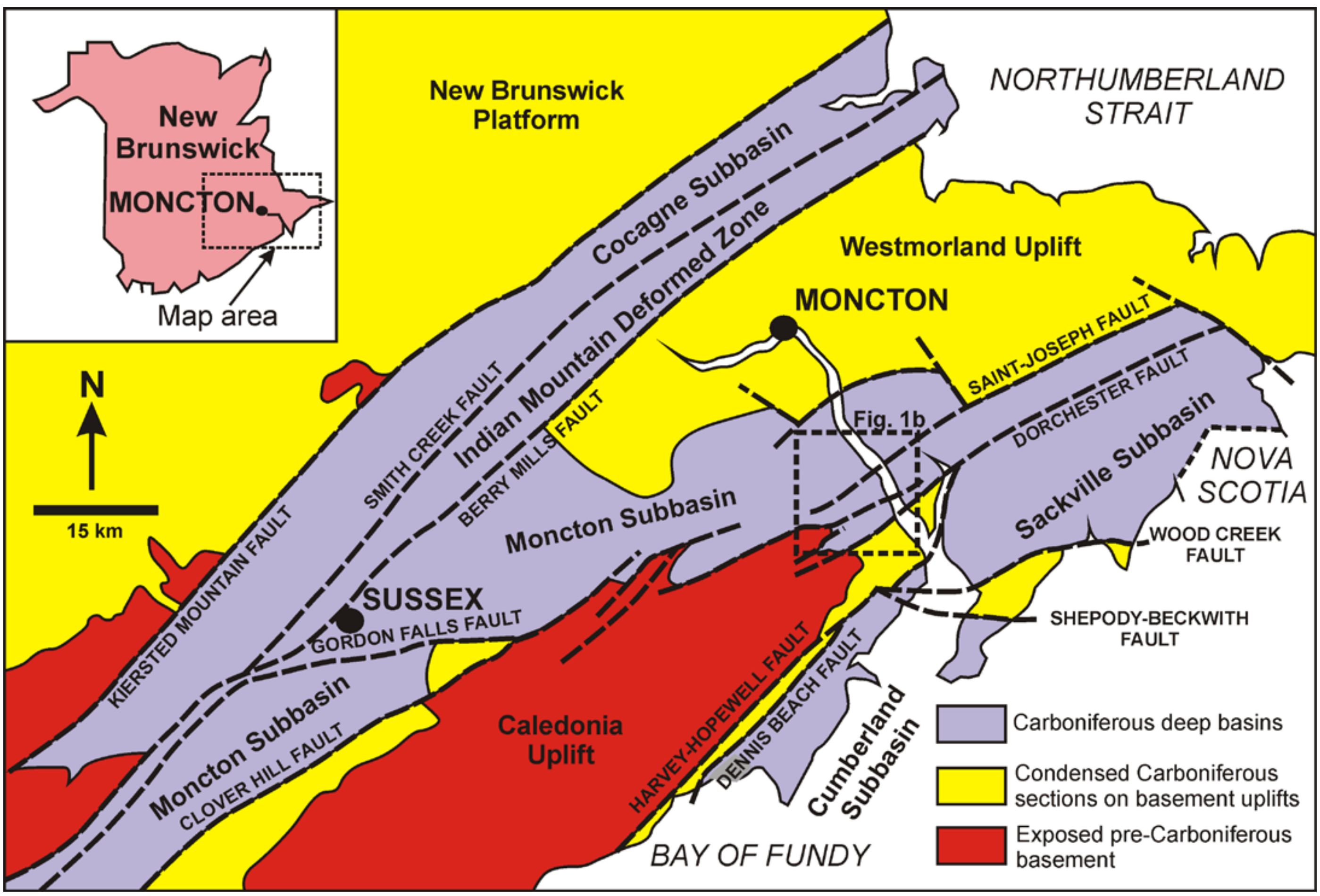


Fig. 1. Outline map of Lower Carboniferous subbasins in southeastern New Brunswick (after St. Peter 2001).

ded with, the Gautreau Formation, and both are overlain by the Weldon Formation (Park and St. Peter 2005; Park *et al.* in press; St. Peter and Johnson 2009).

The Weldon Formation is a thick succession of mudstone interbedded with red siltstone and red to brown sandstone, for which a thickness of at least 300 m is proven from boreholes. Mudstone is the dominant lithology, and locally comprises intervals in excess of 50 m with no siltstone or sandstone interbeds and with very poorly defined bedding. Gypsum rosettes are present in much of this mudstone, and iron-reduction spots and fracture-related iron-reduction zones are ubiquitous. Siltstone and sandstone beds are generally less than 10

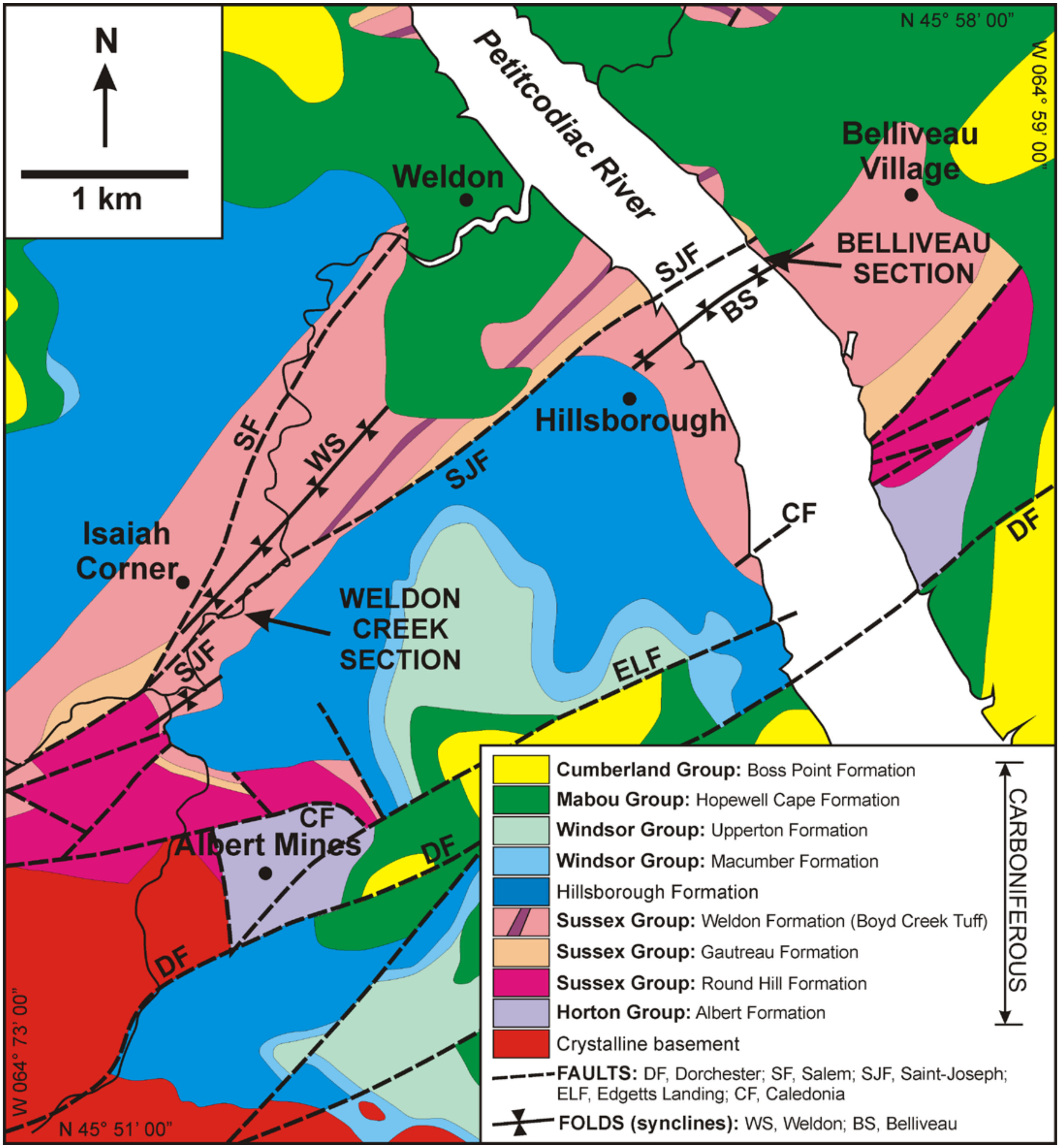


Fig. 2. Geological map of parts of Westmorland and Albert counties, southeastern New Brunswick, with the location of the Belliveau Village and Weldon Creek sections (after Park and St. Peter 2005).

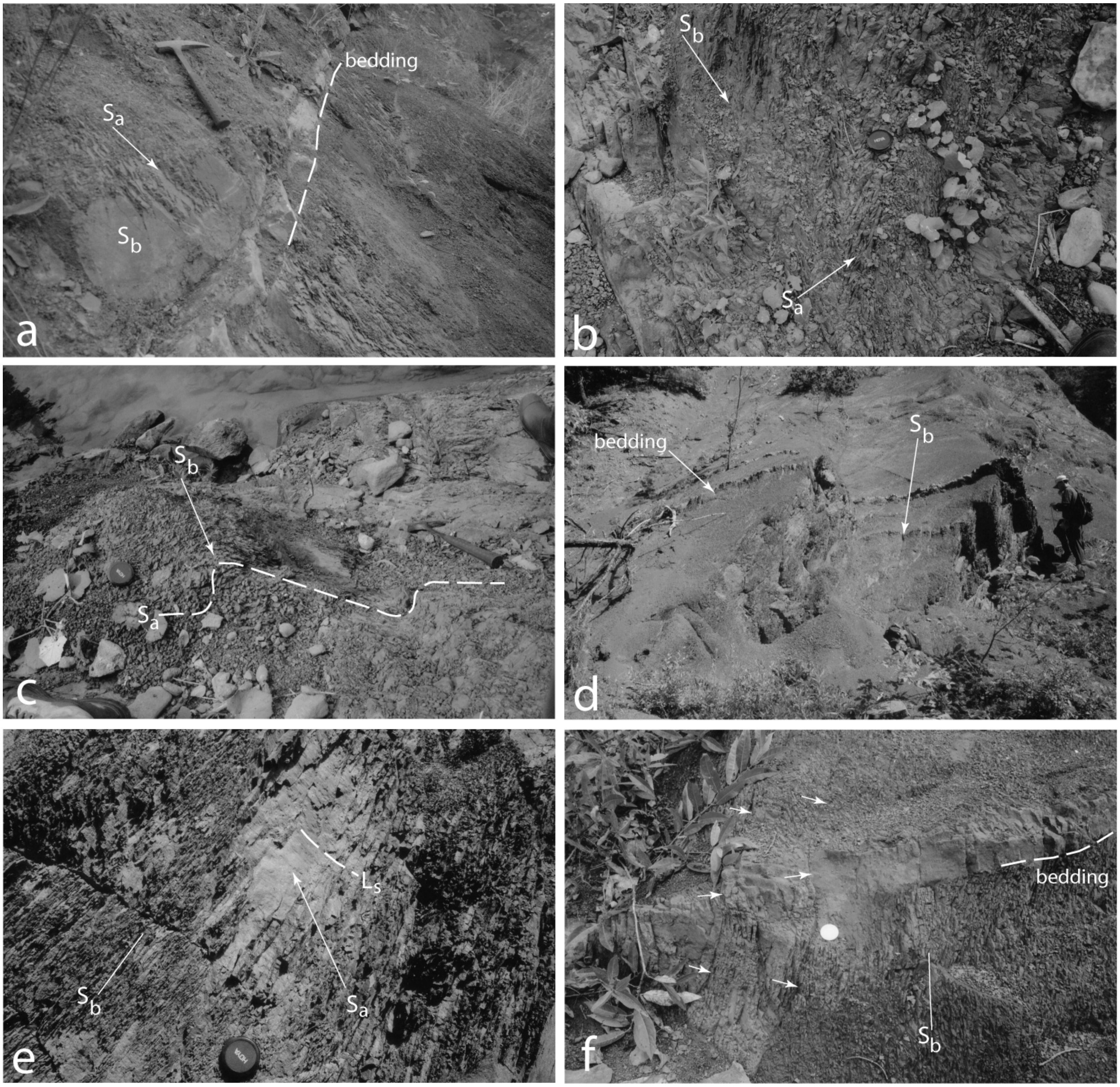


Fig. 3. Photographs of the Weldon Creek locality. (a) Bedding (S_0) and the two cleavages, S_a and S_b in mudstone. Hammer shaft = 25 cm. (b) S_a and S_b cleavages and their intersection, forming $L^a{}_b$ in mudstone. Both cleavages are perpendicular to bedding. Lens cap = 50 mm diameter. (c) S_b cleavage, with crenulation of S_a cleavage in mudstone. Hammer shaft = 25 cm. (d) Bedding (S_0) and the S_b cleavage in mudstone. Apparent folding of bedding is a surface cut effect, all bedding here dips uniformily into the plane of the photograph. Field assistant for scale (1.8 m). (e) Enclaves of S_a cleavage, with L_s slickenside lineation preserved in lithons that are defined by the S_b cleavage. Note the curvature of the S_a surface and L_s lineation. Lens cap = 50 mm. (f) Bedding (S_0) defined by siltstone layer in mudstone. S_b cleavage is strongly expressed in the mudstone. Notice that there is no offset of the bedding by S_b. The offsetting fractures picked out by arrowheads are a later feature. Coin = 2.4 cm diameter.

cm thick, and are typically laminated or cross-laminated on a sub-centimetre scale. Channels, scours and rippled surfaces are common, reflecting the floodplain to lake-margin depositional environment that is inferred for these rocks (see, for instance, St. Peter 2006).

CLEAVAGES IN MUDSTONE OF THE WELDON FORMATION

Early cleavages are best preserved in the mudstone that is exposed in a large section along Weldon Creek near Isaiah Corner (Albert County). The progressive destruction of early cleavages is best observed in the cliff section and tidal platform along the Petitcodiac River estuary at Belliveau Village (Westmorland County). These two localities are described in detail below.

Weldon Creek, Isaiah Corner

A succession of at least 50 m of red mudstone with very few sandstone/siltstone interbeds is exposed in 150 m of continuous section along the southern bank of Weldon Creek, 1 km south of Isaiah Corner. The bedding, as defined by the sparse interbeds, dips south at approximately 30° (Fig. 3a). According to McLeod (1980) these mudstones lie between the main Saint-Joseph Fault and a southern splay, and in the northwestern limb of the Belliveau syncline, although neither is exposed in the creek section (Fig. 1). The mudstones are very fissile, breaking into a steeply plunging 'pencil' structure that is formed by the intersection of two steeply dipping cleavages (Fig. 3b). The definition of 'pencil structure' used here differs from the more restricted 'prolate strain'-defined pencil structure of Ramsay (1981) and Kligfield *et al*. (1983). It more closely conforms to the 'intersection' structure of Reks and Gray (1982) and Ferrill (1989). The development of the second cleavage is variable, and lithons several metres wide define zones in which the first cleavage is preserved with minimal development of the second (Figs. 3a–e). The transition from these lithons into the zones of intense and well-defined pencil structures affords evidence of overprinting and the transposition of the first cleavage (S_a) by the second cleavage (S_b) (Figs. 3b–e). Both cleavages can be traced continuously through the full 50+ m mudstone interval exposed in Weldon Creek, demonstrating that they are not paleosol structures or 'peds' (Retallack 1988) developed during deposition of the Weldon Formation. Peds are seen within the Weldon Formation but do not extend more than a few metres below well-defined paleosol surfaces.

The first cleavage (S_a) is a spaced, smooth cleavage (Kisch 1991), with lithons ranging in width between 0.25 and 1.0 cm. The fractures are commonly defined by growths of illite, hematite (some specularite), and vivianite (hydrated iron phosphate - $Fe_3(PO_4)_2.8H_2O$) giving the surface a 'metallic' sheen and bluish-grey appearance. Within the macro-lithons, in the absence of penetrative S_b, this first cleavage surface is typically unadorned, but within the macro-lithons and near their margins, S_a carries a slickenside lineation (L_a) that is especially pronounced when hematite and/or vivianite are present (Fig. 3e). In thin section, the expression of S_a by aligned fine-grained phyllosilicates is very weak, and unless hematite and/or vivianite are present the septae are diffuse (Figs. 4a, b). In some cases microveins are present, and there is a distinct zone up to 0.1 mm on either side of such veins in which quartz clasts are rare, suggesting that some silica dissolution has occurred in relationship to these features. These narrow zones are also markedly less reddened than the mudstone in general. In its undisturbed state, S_a is nearly vertical and strikes west-southwest. The slickenside lineation (L_a) is close to horizontal.

The second cleavage (S_b) has a close superficial resemblance to S_a in being a spaced, smooth fracture cleavage with lithons ranging in width between 0.25 and 1.0 cm. The cleavage itself has a very clear expression in thin section. It is defined by aligned phyllosilicates along the immediate margins of septae, and re-inforced locally by gypsum and calcite veinlets (Fig. 4c). Some hematite is present in the septae, but not as much as that which typically adorns some of the septae of S_a. Some evidence of silica dissolution is also present in selvages along the S_b cleavage (Fig. 4c).

Overprinting relationships between S_b and S_a commonly take on two forms, depending on the spacing of the S_b septae. Where S_b septae are widely spaced, or form clusters of closely spaced septae separated by zones with few S_b septae, the S_a cleavage is asymmetrically folded, with wavelength approximating twice the amplitude. One limb typically shows stronger S_b development than the other, and in the limb that is more closely aligned to the S_b direction, S_a is transposed (Figs. 3b, c). On the other limb, crenulation of S_a by S_b is evident. The fold axes plunge parallel to the intersection lineation (L^a_b), forming the 'pencil structure' noted above.

Where the development of S_b is more uniformly intense, S_a is preserved only within the S_b lithons, forming a pronouncedly curved surface (turning into parallelism with S_b), and showing the strongest development of the slickenside lineation L_s (Fig. 3e). There is an evident correlation between the degree of curvature on the S_a relics and the intensity of L_s.

The relationship to bedding is a striking feature of these cleavages in the Weldon Creek section. At the eastern end of the outcrops in Weldon Creek, siltstone-sandstone interbeds are more numerous than elsewhere in this section. Both S_a and S_b are almost perpendicular to bedding, and yet there are very few places in which bedding shows any obvious displacement along either cleavage (Fig. 3f). Indeed, the first real disruption of bedding noted in this section is along a set of shear planes that seem almost parallel to S_b on the outcrop surface, but that differ from it by about 30° in strike (Fig. 3f). These same shear planes disrupt the S_b cleavage (offset by less than 2 cm) and are clearly younger features.

Stereographic representation of this geometry makes it clear that the cleavages are close to perpendicular to each other and to bedding (Fig. 6a). The slickenside lineation (L_s) on the S_a cleavage lies close to the strike of bedding, and crucially, when this lineation shows signs of having been rotated during

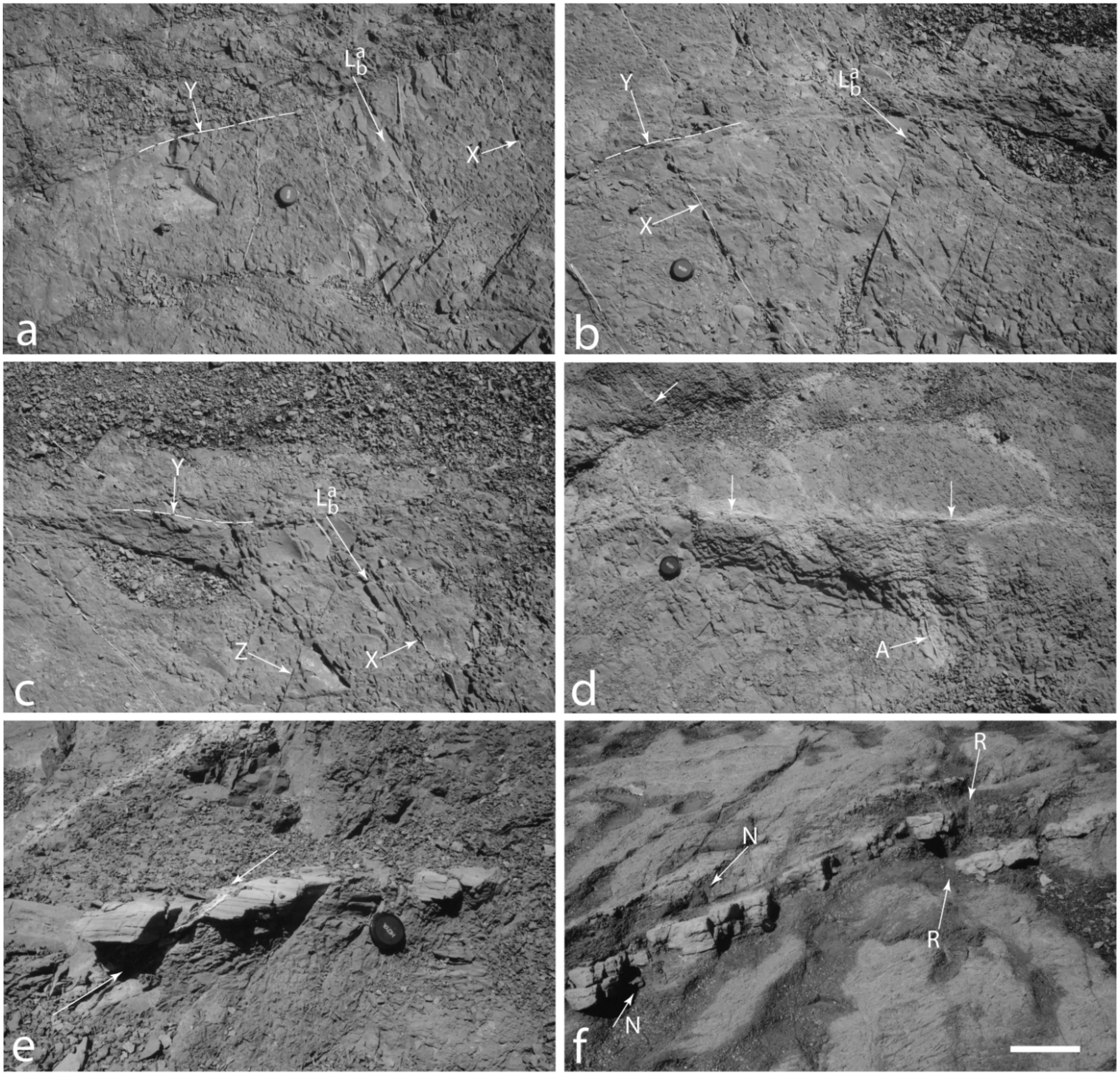


Fig. 4. Photographs of the Belliveau Village locality. (a) Relics of the L^a_b pencil structure formed by intersection of the S_a and S_b cleavages in mudstone. X is a later fracture with calcite fill, and Y is a bedding-parallel fracture with displacement offsetting L^a_b and X. The rock surface is horizontal. Lens cap = 50 mm. (b) Relics of L^a_b in mudstone, with the calcite-filled later X fractures and the bedding-parallel Y fractures. Surface is horizontal. Lens cap = 50 mm. (c) L^a_b relics in mudstone, with calcite-filled fractures X and Z, and the bedding-parallel fracture Y. X and Z here are the two conjugate joints associated with normal and reverse displacement in text. Surface is horizontal. Lens cap = 50 mm. (d) Selection of later fractures (post-L^a_b lineation) in mudstone. A has a calcite-fill, and it and the other fractures picked out by arrowheads are associated with grey-green iron reduction zones. The fracture running across the centre of the image is close to being bedding-parallel. Horizontal surface. Lens cap = 50 mm. (e) Fine-grained sandstone layer in mudstone showing one of the fractures with normal sense offset. Vertical surface, looking north. Lens cap = 55 mm. (f) Fine-grained sandstone layer in mudstone with both normal and reverse sense offset on minor fracture. Vertical surface looking north. Scale bar = 20 cm.

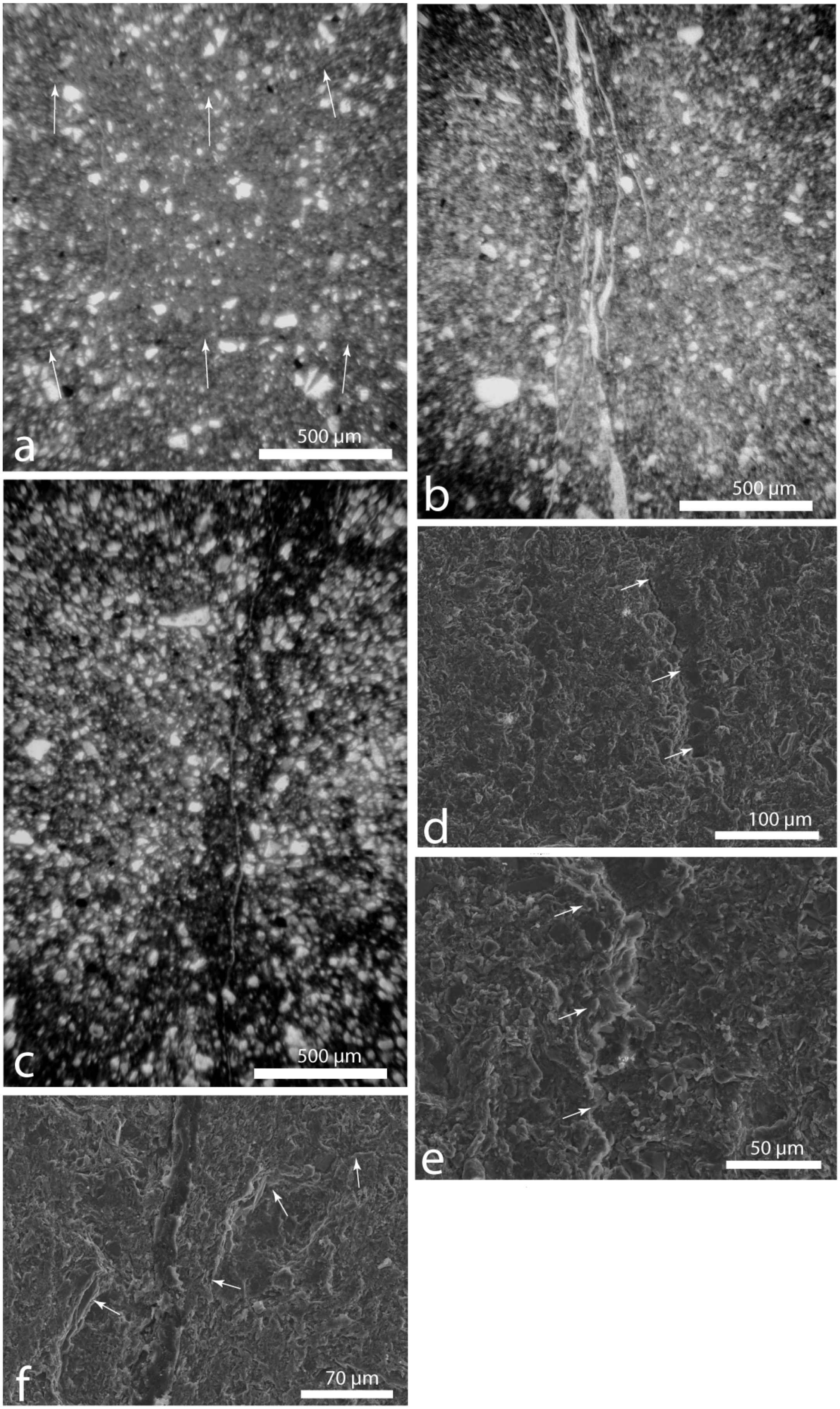
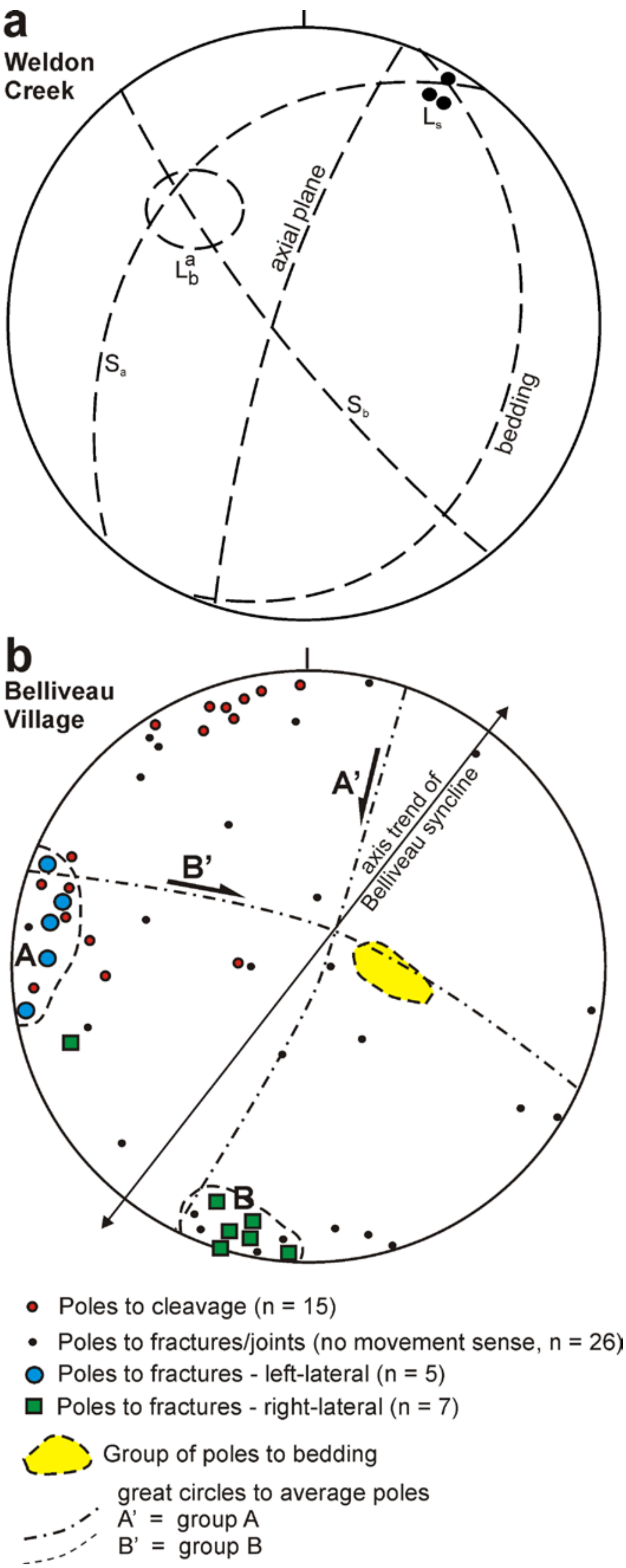


Fig. 5. Micrographs and SEM images. (a) Silty mudstone with two hematitic septae picked out by arrow heads, representing S_a cleavage. Bedding in this image runs top to bottom. Plane polarized light. (b) Silty mudstone with calcite-clay veinlets parallel to the S_a cleavage. Bedding runs left to right. Plane polarized light. (c) S_b cleavage picked out by calcite-clay hematized veinlets running top to bottom. Note the apparent removal of quartz grains from the immediate selvage of the veinlets. The left to right septae at the top and bottom of the image are the S_a cleavage. This section is parallel to bedding. Plane polarized light. (d) SEM back scattered image of the S_a cleavage picked out by calcite-clay septae in mudstone. Arrowheads indicate one of several examples in this image. Bedding runs left to right. (e) SEM back scattered image of clay flakes aligned along a calcite-clay septae defining the S_a cleavage (indicated by arrowheads) in mudstone. Bedding runs left to right. (f) SEM back scattered image of clay flakes and calcite-clay veinlet following the S_a cleavage (arrowheads), offset and deflected along an S_b cleavage-parallel calcite-clay veinlet (running top to bottom) in mudstone. This view is perpendicular to bedding.



the transposition of S_a into S_b, the rotation is in a plane that is almost parallel to bedding (Fig. 6b). This implies that any movement across these cleavage planes, and indeed any associated deformation, involved only bedding-parallel motion.

Morphology of these cleavages is very similar to those described in the Mabou Group or slightly younger (Visean or possibly Serpukhovian) mudstone-siltstone in southwestern New Brunswick (Stringer and Lajtai 1979: note that these authors considered the rocks in question to be Triassic, but subsequent workers have ascribed them to the Carboniferous following the discovery of Windsor Group at the bottom of the succession, see Park *et al.* 1994 and references therein).

Belliveau Village – Petitcodiac River section

Some 150 m of the Weldon Formation are exposed along just over a kilometre of cliff and foreshore outcrop at Belliveau Village on the eastern shore of the Petitcodiac River estuary (Fig. 1). The southern third of the section is a red mudstone with a few interbeds of sandstone/siltstone, whereas the rest of the section contains roughly equal amounts of mudstone and sandstone-siltstone units. This latter part of the section defines the closure of the Belliveau syncline (Fig. 6a), whereas bedding in the southernmost third of the section is ambiguous.

The part of the section of most interest lies in the southern (northward-dipping) limb of the syncline around a large headland where the first sandstone-siltstone interbeds appear above the lower, uniform red mudstone. South of this headland the mudstone outcrop is broken up into polygonal domains (polygons on outcrop surfaces that are planar - polyhedra in the third dimension) by at least four sets of shear planes, some of which are associated with greenish iron-reduction zones (Figs. 5a–d). Within the polygons, there is a sporadic preservation of two cleavages (S_a and S_b) with intersection that create a pencil structure - $L^a{}_b$. Both are fracture cleavages with lithons 0.25–1.5 cm wide, as at Weldon Creek, but without the specularite-vivianite that is seen there. Where the first siltstone-sandstone units appear in the section, bedding is disrupted by the same

Fig. 6. **Stereonets. (a) Stereographic synopsis of the S_a and S_b cleavages and bedding in mudstone at Weldon Creek. Also shown are the projection of the axial plane of the Weldon Syncline, the L_s slickenside lineation on the S_a cleavage, and the pencil structure-intersection lineation $L^a{}_b$. Lower hemisphere equal area projection. (b) Stereographic synopsis of poles to cleavages, poles to bedding, poles to joints and shear planes in the southern end of Belliveau Village cliff section. Only two groups of shear planes (A, B) with movement sense are plotted, chosen because they are clearly cross-cut by shears with associated iron-reduction features. Whereas the shear planes showing left- or right-lateral movement form two coherent groups, the two cleavages show far more scatter (see text for explanation). Lower hemisphere equal area projection.**

shear planes that define the polygons in the mudstone (Figs 5e, 4f). When vestiges of the pencil structure L^a_b and the two cleavages (S_a and S_b) are present and where bedding is defined by siltstone-sandstone layers, no offsets are visible congruent with these cleavage planes. Post-S_b shear planes disrupt both bedding and the earlier cleavages (Figs. 5a–d).

In contrast to the Weldon Creek section, the section at Belliveau Village is dominated by post-S_b shear planes (labelled X, Y, Z, A in Figs. 5a–d). These shear planes are plentiful enough to consider their relationship to the relatively well-defined and exposed Belliveau syncline. The S_a, S_b and L^a_b relics show little coherence in their geometry in stereographic projections, which is consistent with the disruption that is seen in outcrop (Fig. 6b). Evidently much rotation and shearing were involved in the creation of the polygonal pattern in the mudstones, and the orientation data set for these features is too small to define a broader pattern. The shear planes are a different matter, especially those which are cut by, and therefore predate, those shear planes associated with iron reduction. Though there is much scatter, two sets (A and B in the stereonets, Fig. 6b) appear to define a conjugate pair symmetrically oblique to the axial plane of the Belliveau syncline (Fig. 6b). They seem to be symmetrically disposed about the a-c plane of the syncline - see Hobbs *et al*. (1976, Fig. 7.4), and are comparable the R' and R'' joints of Price and Cosgrove (1990, Fig. 14.20). Though the intersection of this conjugate pair does not coincide with the pole to bedding, it is close to this point. Movement evident on some of these joints as indicated by slickensides, is evidently more complex than that of a simple conjugate pair, yet it is movement on these joints, now shear planes (Y in Figs 5a–d), that created the first substantial disruption of bedding. The acute angle of the conjugate shear planes suggests a response to north-south shortening that also created the Belliveau syncline and the Saint-Joseph Fault (when it moved as a thrust). This implies that disruption of bedding is created by displacement on structures that have a consistent geometrical relationship to folding, and as a corollary, it also implies that the earlier pair of cleavages (S_a and S_b) predate that folding (or rotation of the limb on which they are located). The acute intersection of conjugate pairs of joints that are symmetrically disposed about the a-c planes of the Belliveau synform indicate shortening along a north-south direction (Fig. 6b). The scatter in the poles to cleavages implies more rotation (Fig. 6b), probably a consequent of layer-parallel shear in the rotating limb of the syncline. Both the Belliveau and Weldon synclines, to which these cleavages have a geometrical and genetic relationship, predate the unconformity below the Hillsborough Formation (see Fig. 1, also Park and St. Peter 2005, Park *et al*. in press).

It should also be noted that the later shear planes associated with iron-reduction features are also associated with hydrocarbon migration. No bitumen has been observed or reported in the Belliveau Village section, but similar iron-reduced shears and sandstones within the Weldon and Gautreau formations at Boudreau Village, 1.5 km south of this location, carry pyrite and bitumen (Park and St. Peter 2005). This indicates that hydrocarbon migration from the underlying Albert Formation (Horton Group) post-dated cleavage formation and its initial disruption.

SCANNING ELECTRON MICROSCOPY OF CLEAVAGES

Scanning Electron Microscopy (SEM) was undertaken on samples from Weldon Creek. The mudstone is exceptionally difficult material to sample on account of its fissility, friability and the presence of vivianite, which is hygroscopic and decrepitates in moist air. Samples had to be diamond-sawn out of outcrop and encased in surgical plaster before removal, then oven-dried and impregnated with polyvinyl acetate prior to cutting in order to prevent complete disintegration. Optical examination of thin sections revealed a close association between veinlets and both the S_a and S_b cleavages (Figs. 4a–c), but aside from confirming the presence of hematite and vivianite along the S_a and S_b cleavages, iron-staining and extremely fine grain-size precluded more detailed analysis. SEM images reveal more detail of both fabrics, and confirm the presence of veinlets that reinforce diffuse clay mineral septae (Figs. 4d, e). Both deformed detrital illite grains, and authigenic clay grains with preferred orientation are present, defining both S_a and S_b. In both cases, veinlets of an irresolvable fine mixture of clay, gypsum, and calcite are present (Figs. 4d–f). Cross-cutting relationships are also made apparent by the transposition of clay septae, where S_b-related veinlets cut the S_a cleavage (Fig. 4f). Qualitative data (EDAX spectra) imply that the detrital clays are largely illite (with negligible peaks for Ca, Na or Mg), whereas the authigenic orientated grains, and the material that is mixed with ultra-fine calcite, have a more montmorillonitic composition (Ca and Na peaks appear alongside K peaks in qualitative EDAX spectra). The presence of such clay with swelling properties may account for why the two cleavages form such good partings near weathered surfaces. SEM images did not reveal any clay mineral fringes on the detrital quartz or feldspar grains that are sporadically present in these mudstones.

SEM is the only microtextural analytic technique practically applicable to this material. Attempts to assess illite crystallinity by X-ray diffraction (XRD) proved ambiguous as the mudstones are still dominated by detrital clays. Difficulties in obtaining standard thin sections from such friable material precluded attempts to prepare wafers and apply transmission electron microscopy (TEM).

TIMING OF CLEAVAGE FORMATION

Timing of cleavage formation in these rocks relates to: (1) formation of the cleavages relative to the formation of folds, and (2) formation of cleavages in relation to the diagenetic history of these rocks. Three observations in the immediate environment of these cleavages pertain to the relationship with the diagenetic history. First, the mudstones contain gypsum rosettes with no trace of anhydrite (a development similar to that seen in the cleavage micro-veins), implying that conditions (especially temperature) have been consistent with gypsum stability ever since the rosettes (and micro-veins) formed. Second, the first evidence for reducing fluids percolating through the mudstones is iron-reduction haloes around shear planes that all cross-cut the two early cleavages and the conjugate pair of shear planes. There is no iron-reduction associated directly with either S_a or S_b (both the hematite and vivianite associated with S_a and S_b at Weldon Creek are oxidized phases). Elsewhere in the area these iron-reduction features are associated with hydrocarbon migration, implying a later stage of maturation-diagenesis. Third, the sandstone layers within the mudstone sections have their primary carbonate cement intact with no evidence of secondary porosity formation or silica overgrowth. These three characteristics imply that an early stage of diagenetic history is preserved in these rocks, and that the highest temperatures they have experienced lie in the range 60–100 °C. Depending on when the gypsum rosettes grew, the lower end of this range is more probable. This observation places severe constraints on depth of burial. It also places these rocks below the range for conditions consistent with 'anchimetamorphism' (see Kisch 1989, 1991).

Such conditions for maximum burial depth and thermal maturation do not rule out the formation of cleavage. Indeed, the appearance of a fissile fabric in claystone particularly is well documented (Kisch 1989, 1991 for reviews; see also Oertel and Curtis 1972; Curtis *et al.* 1980, Krizek *et al.* 1975; Maltman 1978, 1981). However, these early cleavage-like fabrics are produced by compaction and dewatering, and the resultant single fabric is always bedding-parallel, or close to being in this orientation. This situation is in marked contrast to the case described at Weldon Creek, where the two cleavages are both perpendicular to bedding. Furthermore, the fabrics that are created by compaction and dewatering are generally described as 'fissility' (a penetrative fabric) rather than as a spaced, domainal foliation (Moon 1972). There may well be a continuum between the two, but the end-members of shaly fissility and domainal cleavage are morphologically quite distinct.

Bedding-parallel fissility forms during compaction and may be associated with deformation as well (Curtis *et al.* 1980), but this deformation generally resolves to a shortening perpendicular to bedding. Deformation associated with S_a and S_b in these mudstones is quite distinct in this respect. Veinlets parallel to S_b, and also perpendicular to bedding, show no evidence of shortening along their lengths, strongly suggesting that these veinlets were emplaced after the compaction associated with dewatering. Similarly, neither cleavage is deformed in a fashion that could be attributed to compaction, placing another constraint on timing with respect to diagenesis. The most marked deformation features associated with these cleavages are the development of the slickenside lineation on S_a (L_s), and the subsequent rotation of L_s and curvature of S_a when it was transposed into S_b, none of which can be resolved by simple loading with a maximum principal stress that would be perpendicular to bedding. Here the fabric geometry suggests a bulk shortening parallel to bedding.

In summary, two cleavages formed perpendicular to bedding in these mudstones after compaction and dewatering, but prior to folding-related deformation associated with the Weldon and Belliveau synclines. Indirect evidence suggests that both cleavages formed during the early stages of diagenesis (prior to iron-reducing fluid and hydrocarbon migration), probably at temperatures less than 100 °C in rocks that were never deeply buried. Geometry of the fabrics does imply a relationship to bulk shortening of the layers parallel to bedding, possibly an early response to the same shortening that generated the folds. Critically, both cleavages predated the folds themselves.

CONDITIONS OF CLEAVAGE FORMATION

The conditions under which the S_a and S_b cleavages formed are constrained by two sets of independent data from either the Weldon Formation itself, or from underlying oil shale of the Albert Formation. Diagenetic minerals in the red mudstone of the Weldon Formation include gypsum, occurring as veinlets within the second cleavage (S_b), or as rosettes in the matrix with an ambiguous relationship to either cleavage (S_a and S_b). Petrographically, there is no evidence of the presence or former presence of anhydrite, indicating that these red mudstones have never been buried sufficiently since an early stage of diagenesis to pass through the gypsum - anhydrite transition. Given that this reaction involves a very large molar volume change, it is pressure sensitive, but occurs at around 50 °C at atmospheric pressure. This temperature will fall with increasing pressure through burial, placing a severe constraint on depth of maximum burial (certainly less than 1.5 km).

Direct temperature estimates are also available from studies of the oil shales in the Albert Formation (Chowdhury 1995). Equivalent % vitrinite reflectance (%R) data from around Weldon Creek and Belliveau Village give values between 0.65 and 0.75 (with a maximum of 0.77 from a borehole at the albertite mine site, Albert Mines, 2 km from the Weldon Creek site). Thermal Alteration Index (TAI) from spore coloration has also been determined for rocks at Albert Mines, with values averaging 2.00 (Chowdhury 1995; MacIntosh and St. Peter in press). These data translate to a maximum temperature in the 70 to 90 °C range, and critically, the lower figures come from the top of the Albert Formation typically 100 to 150 m below the level of the exposed Weldon Formation in which these cleavages are observed. These data imply that maximum temperatures in the Weldon Formation of Weldon Creek and Belliveau Village were no higher than 50 °C – consistent with the observations regarding diagenetic gypsum as rosettes or micro-veins in the cleavages.

It is useful to compare these conditions to those generally associated with early cleavage formation, namely the higher temperature diagenetic anchizone regime transitional to prehnite-pumpellyite metamorphic facies (Dunoyer de Segonzac *et al*. 1966; Weber 1976, 1981; Piqué 1975, 1982; Siddans 1977; Dandois 1981; Kisch 1989, 1991, 1998; Gutiérrez-Alonso and Nieto 1996; Glasmacher 2004). These authors described conditions well above %R of 1.0 (as high as 3.0) for conditions of early cleavage formation and incipient metamorphism in the anchizone.

Although they are interpreted as tectonic features, these two cleavages and the resultant pencil structure cannot be related to any measurable strain (cf., Reks and Gray 1982). This is due to a number of factors, not least of which is the absence of reliable strain markers in these red mudstones. Thin section and SEM examination of the mudstones has not revealed any pressure fringes on detrital grains, despite the abundance of quartz and feldspar grains in some samples. Veinlets parallel to the cleavages (S_b mainly) show no evidence of shortening or elongation, though in the case of S_a there is some evidence of quartz dissolution along the cleavage septae. If silica from detrital grains was being mobilized during S_a formation, then the absence of fringes around other detrital grains may indicate very low strain, or at least strain that is well below the threshold defined by Reks and Gray (1982), and certainly less than the 40–60% shortening generally cited for conditions of incipient slaty cleavage formation (Kisch 1989, 1991). Though there is overwhelming evidence in these rocks that strain cannot be constant volume, fluid-mediated mass transfer on a scale necessary to accommodate 40–60% shortening is highly unlikely.

Finally, though now somewhat scattered, the two cleavages may have originated as a conjugate pair. Unlike the disruptive shear planes seen in the Belliveau section, such a pair would have no obvious relationship to the axial plane of any recognized fold. As an element of shear rather than simple shortening is implied by this orientation, 'fracture' cleavage is the preferred term for these features, rather than 'slaty' cleavage or incipient 'slaty' cleavage.

DISCUSSION AND CONCLUSIONS

The presence of cleavages in the mudstones of the Weldon Formation is significant for a number of reasons.

1. Timing relationships demonstrate that these cleavages formed later than compaction-dewatering but very early in the diagenetic history of these rocks (prior to hydrocarbon migration). Their geometry suggests that they are related to a local deformation that affected these rocks shortly after deposition and by the end of the Tournaisian (prior to the unconformity beneath the overlying Hillsborough Formation; Park and St. Peter 2005; Park *et al*. in press). The demonstration of a tectonic relationship for a very early pair of cleavages here implies that mechanisms other than dewatering-compaction may be important elsewhere.

2. Relationships of these cleavages to folding are particularly revealing: the rotation of beds during folding was partly accommodated on the very shear planes responsible for the progressive obliteration of both early cleavages. Although related to the deformation that ultimately produced the folds (a bedding-parallel bulk shortening), these two cleavages predate the folds themselves. S_a and S_b formed as an early response to bedding-parallel bulk shortening, and were subsequently disrupted and progressively obliterated as folding began and bulk shortening gave way to layer-parallel shear and rotation.

3. Both cleavages (S_a and S_b) are essentially ephemeral features of these mudstones that were preserved locally where favourable factors prevailed. They were probably far more widespread than current preservation suggests. Several authors have indicated the importance of pre-existing fabrics in the nucleation of new cleavages (Williams 1972; Cosgrove 1976; Gray and Durney 1979; Maltman 1981; Craig *et al*. 1982; Ho *et al*. 1996), though this is tacitly assumed to be an early fissility, caused by compaction-dewatering. The presence of cleavages in the Weldon Formation mudstones that are not compaction-dewatering features, and yet still ephemeral (and not axial planar) suggests that fabrics other than compaction-dewatering related fissility may form earlier than folding, and that they too provide anisotropies that can be recycled as new cleavages nucleate in an evolving rock mass during deformation.

4. The pencil structure created by the intersection of S_a and S_b is also unusual (see review in Reks and Gray 1982) in so far as such a structure is generally considered to be an intersection of a cleavage or incipient cleavage with a primary shale fissility, therefore an L^1_0 intersection lineation, close to, if not perfectly parallel to a fold axis. At neither locality in which this pencil structure is preserved is it bedding-parallel, or anything other than close to being perpendicular to bedding. It also bears little relationship to the geometry of the large-scale folds.

5. The ephemeral nature of S_a and S_b in the Weldon Formation is critical. They are preserved locally where conditions permit, but the evidence from the Belliveau Village section suggests that once folding began layer-parallel slip and shear obliterated these features. This is in marked contrast to most anchizone cleavages described in the literature (see Kisch 1991), which are regarded as the precursors to the slaty cleavage that is more fully developed in higher grade anchizonal and greenschist facies pelites. The early cleavages described here are fracture cleavages with evidence of shear, rather than true 'slaty' cleavages or their precursors. Other than providing another planar anisotropy at the scale of clay grains, on which subsequent cleavages may nucleate, the cleavages in the Weldon Formation mudstones cannot be considered precursors to anything seen at higher grades of recrystallization.

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REFERENCES

Chowdhury, A.H. 1995. Sedimentology, diagenesis and organic geochemistry of the Albert Formation, Moncton Subbasin, New Brunswick, Canada. Unpublished Ph.D. Thesis, University of New Brunswick, Fredericton, New Brunswick, Canada, 249 p.

Cosgrove, J. W. 1976. The formation of crenulation cleavage. Journal of Geological Society of London, 132, pp.155–178. doi:10.1144/gsjgs.132.2.0155

Craig, J., Fitches, W. R., and Maltman, A. J. 1982. Chlorite-mica stacks in low strain rocks from central Wales. Geological Magazine, 119, pp. 243–256. doi:10.1017/S0016756800026066

Curtis, C. D., Lipshie, S. R., Oertel, G., and Pearson, M. J. 1980. Clay orientation in some Upper Carboniferous mudstones, its relationship to quartz content and some inferences about fissility, porosity and compactional history. Sedimentology, 27, pp. 333–339. doi:10.1111/j.1365-3091.1980.tb01183.x

Dandois, P. 1981. Diagenèse et métamorphisme des domaines caledonien et hercynien de la vallee de la Meuse entre Charleville-Mézières et Namur (Ardennes franco-belges). Bulletin de la Société Belge de Géologique, 90, pp. 299–316.

Dunoyer de Segonzac, G. 1966. Sur une transformation de minéraux argileux dans les 'terres noires' du bassin de la Durrance: influence de l'orogénie alpine. Comptes Rendus des Séances de l'Académie des Sciences, 262, pp. 2401–2404.

Ferrill, D. A. 1989. Primary crenulation pencil cleavage. Journal of Structural Geology, 11, pp. 457–461. doi:10.1016/0191-8141(89)90022-9

Gray, D. R., and Durney, D. W. 1979. Investigations on the mechanical significance of crenulation cleavage. Tectonophysics, 58, pp. 35–79. doi:10.1016/0040-1951(79)90321-4

Glasmacher, U. A., Matenaar, I., Bauer, W., and Puchkov, V. N. 2004. Diagenesis and incipient metamorphism in the western fold-and-thrust belt, SW Urals, Russia. International Journal of Geology, 93, pp. 361–383.

Gutiérrez-Alonso, G.,, and Nieto, F. 1996. White-mica 'crystallinity', finite strain and cleavage development across a large Variscan structure, NW Spain. Journal of the Geological Society of London, 153, pp. 287–300. doi:10.1144/gsjgs.153.2.0287

Ho, N-C., Peacor, D. R., and van der Pluijm, B. A. 1996. Contrasting roles of detrital and authigenic phyllosilicates during slaty cleavage development. Journal of Structural Geology, 18, pp. 615–623. doi:10.1016/S0191-8141(96)80028-9

Hobbs, B. E., Means, W. D., and Williams, P. F. 1976. An Outline of Structural Geology, Wiley, New York, 569 pp.

Kisch, H. J. 1989. Discordant relationship between degree of very low-grade metamorphism and the development of slaty cleavage. *In* Evolution of Metamorphic Belts. *Edited by* J. S. Daly, R. A. Cliff, and B. W. D. Yardley. Geological Society of London, Special Publication 43, pp. 173–185.

Kisch, H. J. 1991. Development of slaty cleavage and degree of very low grade metamorphism: a review. Journal of Metamorphic Geology, 9, pp. 735–750. doi:10.1111/j.1525-1314.1991.tb00562.x

Kisch, H. J. 1998. Criteria for incipient slaty and crenulation cleavage development in Tertiary flysch of the Helvetic zone of the Swiss Alps. Journal of Structural Geology, 40, pp. 601–615. doi:10.1016/S0191-8141(97)00111-9

Kligfield, R., Lowrie, W., Hirt, A., and Siddans, A. W. B. 1983. Effect of progressive deformation on remanant magnetization of Permian redbeds from the Alpes Maritimes (France). Tectonophysics, 97, pp. 59–85. doi:10.1016/0040-1951(83)90211-1

Krizek, R. J., Tuncer, B. E., and Ozaydin, I. K. 1975. Preparation and identification of clay samples with controlled fabric. Engineering Geology, 9, pp. 13–38. doi:10.1016/0013-7952(75)90025-3

Kubler, B. 1967a. La cristallinité de l'illite et les zones tout à fait supérieures du métamorphisme. *In* Étages Tectoniques - Colloque de Neuchâtel avril 1966, A la Baconnière, Neuchâtel (Suisse), pp. 105–122.

Kubler, B. 1967b. Anchimétamorphisme et schistosité. Bulletin du Centre de Recherches de Pau SNPA, 1, pp. 259–278.

MacIntosh, J. A., and St. Peter, C. J. in press. Maritimes Basin Thermal Maturation Project: Carboniferous Organic Geochemical (NB COG) Database for New Brunswick. New Brunswick Department of Natural Resources, Minerals, Policy and Planning Division, Geological Surveys Branch Open File.

Maltman, A. J. 1978. Experimentally deformed sediments and the early deformation of cleavage (abstract). *In* Deformation of soft-sediments. *Edited by* W. R. Fitches and A. J. Maltman, Conference Report, Journal of Geological Society of London, 135, pp. 249–250.

Maltman, A. J. 1981. Primary bedding-parallel fabrics in structural geology. Journal of Geological Society of London, 138, pp. 475–483.

McLeod, M. J. 1980. Geology and mineral deposits of the Hillsborough area, map area V-22 and V-23 (Parts of 21H/15E and 21H/15W). New Brunswick Department of Natural Resources, Mineral Resources Branch, Map Report 79-6, 35 p.

Moon, C. F. 1972. The microstructure of clay sediments. Earth Science Reviews, 8, pp. 303–321. doi:10.1016/0012-8252(72)90112-2

Oertel, G., and Curtis, C. D. 1972. Clay-ironstone concretions preserving fabrics due to progressive compaction. Bulletin Geological Society of America, 83, pp. 2597–2606. doi:10.1130/0016-7606(1972)83[2597:CCPFDT]2.0.CO;2

Park, A. F., and St. Peter, C. J. 2005. Deformation of Lower Carboniferous rocks in the Rosevale to Saint-Joseph area (NTS 21 H/15), Albert and Westmorland counties, southeastern New Brunswick. *In* Geological Investigations in New Brunswick for 2004. *Edited by* G. L. Martin. New Brunswick Department of Natural Resources; Minerals, Policy and Planning Division, Mineral Resources Report 2005-1, pp. 45–98.

Park, A. F., St. Peter, C. J., Keighley, D. G., and Wilson, P. in press. Tectonic inversion along a sidewall ramp and its relationship to a hydrocarbon play in the Tournaisian rocks of southeastern New Brunswick: the Peck Creek section, Albert Mines, Albert County. Canadian Society of Petroleum Geologists Bulletin.

Park, A. F., Williams, P. F., Ralser, S., and Leger, A. 1994. Geometry and kinematics of a major shear zone segment in the Appalachians of southern New Brunswick. Canadian Journal of Earth Sciences, 31, pp. 1523–1535.

Piqué, A. 1975. Répartition des zones d'anchimétamorphisme dans les terrains dinantiens du Nord-Ouest du Plateau central (Meseta marocaine). Bulletin de la Société Géologique de France, 17, pp. 416–420.

Piqué, A. 1982. Relations between stages of diagenetic and metamorphic evolution and the development of a primary cleavage in the northwestern Moroccan Meseta. Journal of Structural Geology, 4, pp. 491–500. doi:10.1016/0191-8141(82)90039-6

Price, N. J., and Cosgrove, J. W. 1990. Analysis of Geological Structures, Cambridge University Press, Cambridge, UK, 502 p.

Ramsay, J. G. 1981. Tectonics of the Helvetic nappes. *In* Thrust and Nappe Tectonics. *Edited by* K. R. McClay and N. L. Price. Geological Society of London Special Publication 9, pp. 293–309.

Reks, I. J., and Gray, D. R. 1982. Pencil structure and strain in weakly deformed mudstone and siltstone. Journal of Structural Geology, 4, pp. 161–176. doi:10.1016/0191-8141(82)90025-6

Retallack, G. J. 1988. Field recognition of paleosols. *In* Paleosols and weathering through geologic time. *Edited by* J. Reinhardt and W. R. Sigleo. Geological Society of America Special paper 216, pp. 1–20.

Siddans, A. W. B. 1977. The development of slaty cleavage in a part of the French Alps. Tectonophysics, 39, pp. 533–557. doi:10.1016/0040-1951(77)90152-4

St. Peter, C. J. 2001. Petroleum geology in the Carboniferous of southeastern New Brunswick. *In* Guidebook to Field Trips in New Brunswick and western Maine. *Edited by* R. K. Pickerill and D. R. Lentz. New England Intercollegiate Geological Conference, 93rd Annual Meeting, September 2001, Fredericton, New Brunswick, pp. A4-1–A4-30.

St. Peter, C. J. 2006. Geological relationships between the Cocagne subbasin and Indian Mountain Deformed Zone, Maritimes Basin, New Brunswick. *In* Geological Investigations in New Brunswick for 2005. *Edited by* G. L. Martin. New Brunswick Department of Natural Resources; Minerals, Policy and Planning Division, Mineral Resources Report 2006-3, pp. 103–183.

St. Peter, C. J., and Johnson, S. C. 2009. Stratigraphy and structural history of the late Paleozoic Maritimes Basin in southeastern New Brunswick, Canada. New Brunswick Department of Natural Resources, Geological Surveys Branch, Memoir 3, 348 p.

Stringer, P., and Lajtai, E. Z. 1979. Cleavage in Triassic rocks of southern New Brunswick, Canada. Canadian Journal of Earth Sciences, 16, pp. 2165–2180.

Weber, K. 1976. Gefügeuntersuchungen an transversalgeschieferten Gesteinen aus dem östlichen Rheinischeen Schiefergebirge (ein Beitrag zur Genese der transversalen Schieferung). Geologisches Jahrbuch, Reihe D, Heft 15, 98 p.

Weber, K. 1981. Kinematic and metamorphic aspects of cleavage formation in very low-grade metamorphic slates. Tectonophysics, 78, pp. 291–306. doi:10.1016/0040-1951(81)90018-4

Williams, P. F. 1972. Development of metamorphic layering and cleavage in low grade metamorphic rocks at Bermagui, Australia. American Journal of Science, 272, pp. 1–47.

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