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FOLDS IN THE CARBONIFEROUS ROCKS NEAR WALTON, NOVA SCOTIA

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ABSTRACT. The main folds in a shale-siltstone succession plunge at low angles southwest and are variably overturned toward the southeast. Steeply-plunging cross folds occur in a few localities. The largest cross folds are S-shaped as viewed in plan profile and refold small main folds. Near the S folds, inverted folds plunge at moderate angles. The axial planes of both the inverted and S folds dip southward. Conjugate or box-shaped folds plunge at all angles; thus regardless of plunge, the general fold style is similar throughout.

It is suggested that the main folds were initiated during the overriding movements of upper beds toward the southeast and that continued movement toward a more southerly direction led to the inversion of some of these folds. North-south compression concurrent with the southerly movement was effective across the main northeast-southwest axes, and the resultant sinistral shear on the steep limbs led to the development of the S cross folds.

INTRODUCTION

Folded Carboniferous rocks are well exposed in cliffs and extensive intertidal areas in the 11 miles between Cheverie and Walton, South Minas Basin, Bay of Fundy, Nova Scotia (fig. 1). Low-dipping Triassic conglomerates unconformably overlie and mask the folded rocks northeast of Walton and in three small areas between Walton and Cheverie. The Triassic beds are cut by northeast-striking faults which developed after the folding of the underlying rocks. Boyle (1963) has mapped these and other faults in some detail; they are not further considered here. Crosby (1963) has mapped and described the rocks of the Cheverie-Walton area.

Inland, exposures are poor. About 15 miles south of the coast, Carboniferous beds unconformably onlap against the metamorphic Meguma Group (Ordovician and older?) and associated Devonian granite masses.

Along the coast, most of the Carboniferous rocks are thinly interbedded dark shales, laminated siltstones, and minor limestones of the Lower Mississippian Horton Group. Sedimentary structures, particularly sole casts, are well developed in the siltstones and permit the determination of stratigraphic tops. Apart from a closely spaced cleavage which is present locally, the rocks are virtually unmetamorphosed.

Thick-bedded coarse sandstones occur toward the top of the Horton Group, for instance near Cheverie. These pass conformably upward into limestones, gypsum, and red clastics of the Windsor Group, also commonly thick-bedded. The thick beds of the Windsor Group and the upper part of the Horton Group are not as tightly folded as the thin-bedded underlying rocks which contain most of the structures described in this paper.

Most large and small folds along the coast plunge at low angles. These are the main folds. In addition, in a few localities there are cross folds with steep plunges and folds intermediate in plunge. The shapes of all these folds, regardless of plunge, are very similar; hence the folds appear to have developed when the rocks were subjected to essentially the same physical conditions, that is probably during the same period of deformation. The main problem is thus to demonstrate the geometric relationship between the main and cross folds and

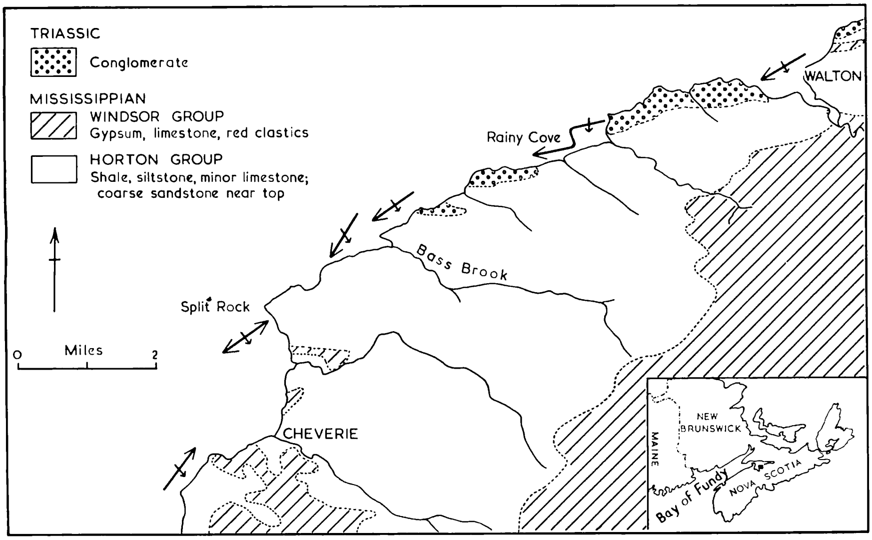

Fig. 1. Average directions of plunge of folds in the Carboniferous between Cheverie and Walton. Black square over "S" of Nova Scotia indicates location of area studied. The short cross-arrows indicate the average direction of overturning. The outcrop pattern is modified from R. W. Boyle (1963).

to indicate the sequence of tectonic events that could have led to the penecontemporaneous development of these structures.

GENERAL FOLD STYLE

The shapes and sizes of variably plunging folds and associated structures are indicated in figures 2, 3, 4, and 5. In general, the folds tend to be parallel (concentric) within the siltstones, but considerable changes in thickness in the interbedded shales commonly result in disharmonic folding.

In the siltstones, many of the smaller folds that affect only a few beds have converging axial planes, so that they form conjugate pairs of folds (Johnson, 1956, p. 346) or "box" folds, and these plunge at both low and high angles (fig. 2, c, d). The axial planes of conjugate pairs usually form angles of 70° to 80° about the general direction of shortening indicated by the shape of the folds. That is, the axial planes form an acute angle about the direction of compression and thus may lie parallel to shear planes. This relationship is also suggested by the presence of small thrusts (fig. 4) and steeper faults parallel to the axial planes of the low-plunging folds. Small strike-slip and normal faults are also apparent in the siltstones, but too few are exposed for a detailed analysis.

The presence in the siltstones of the parallel and conjugate folds and associated shear planes suggests that these rocks were relatively rigid or brittle during the development of both the low and steeply plunging folds (see also Ramsay, 1962, p. 525).

MAIN FOLDS

The main folds plunge at low angles northeast or southwest, approximately parallel to the coast, with, except near Cheverie and at Rainy Cove, a pre-

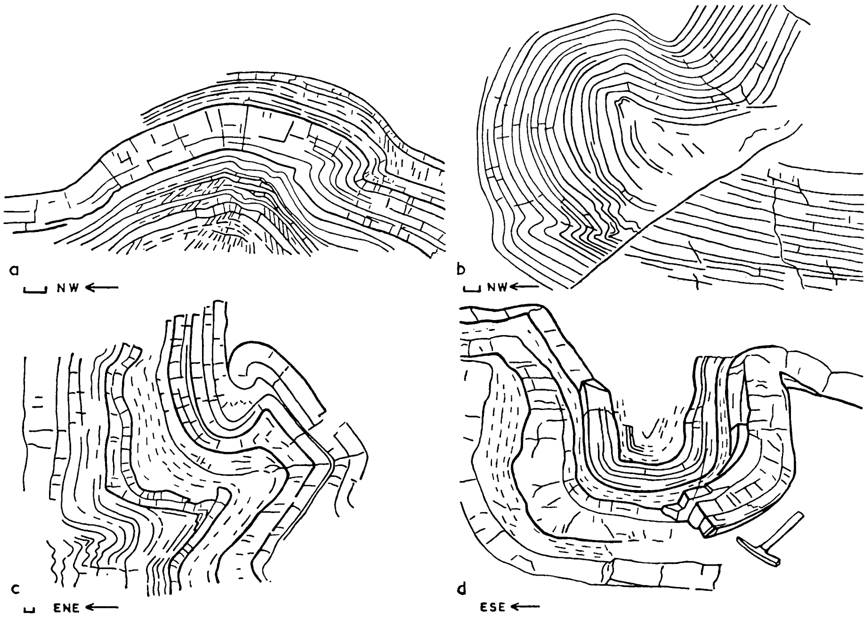

Fig. 2. Profiles of folds in laminated siltstones and shales (dashed lines). One foot scale shown.

a. South Split Rock. Cleavage locally developed in the thicker argillites converges toward the crest of the inclined anticline. The shape of the small overturned fold on the southeast limb suggests that there was movement of upper beds toward the southeast.

b. North Walton. The upper fold, synclinal in shape, is an inverted anticline with older beds in the core. The fold axes in (a) and (b) are low-plunging; the axial planes vary considerably in dip, but all folds face southeast.

c. West Rainy Cove. Low-plunging "box" fold facing east-northeast. The siltstone bed in the core of the fold is ruptured indicating relative rigidity during folding.

d. West Rainy Cove. "Box" fold plunging 40° SSW, almost down the dip of inverted beds.

dominance of southwesterly plunges (figs. 1 and 7, a). Although a general direction of plunge is often apparent in single outcrops, in detail the hinges are commonly curved and variable in plunge. Perhaps the curving of the hinges is partly an expression of cross folding, but it is also in part due to the irregular folding of beds of variable thickness.

The fold axes shown in figure 7 are mostly those of the smaller folds that are readily measured in the field. The axes of the larger folds, that is, those that affect all the exposed beds and that have limbs tens of feet in length, are not usually directly measurable. However, in all areas the intersections of bedding planes, as shown in β diagrams, exhibit the same patterns of concentration as the small fold axes. Thus the axes of both the small and large folds are similar in attitude.

The main folds are dominantly inclined, overturned, or in more general terms, face towards the southeast, that is stratigraphically higher beds are encountered when following along the axial planes toward the southeast regard-

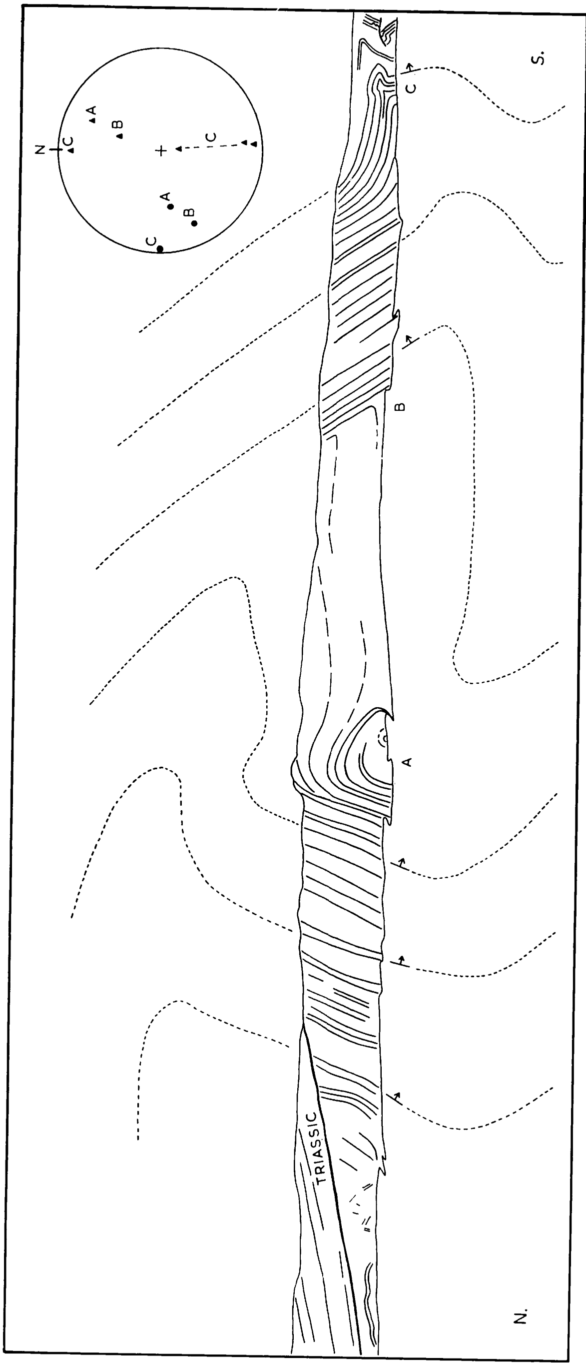

Fig. 3. Inverted folds (A) and (B) in Horton Group beneath unfolded Triassic conglomerate, North Rainy Cove. North-south cliff section about 1000 feet long. Sedimentary tops shown by arrows. Lower hemisphere equal-area projection of fold axes (circles) and poles to axial planes (triangles).

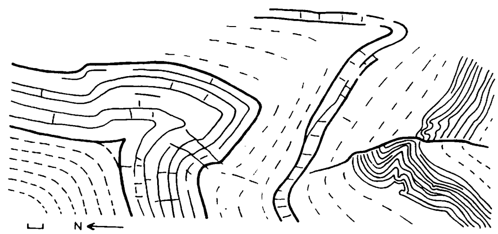

Fig. 4. Detail of southern end of figure 3. One foot scale bar. Folds vary from upright to recumbent. The shales show marked thickening in the hinge areas, but the siltstone layers remain parallel. The small thrust affecting the siltstone beds dies out abruptly in the adjacent shales. Movement along the thrust was not necessarily in the plane of the paper.

less of whether these planes are horizontal or nearly vertical. Most commonly, the axial planes dip northwest, as shown in figure 7, a, where the poles are clustered in the southeast quadrant. In overall shape, folds with these axial planes are asymmetric with short steep limbs on the southeast sides of anticlines and longer limbs which dip gently northwest. Some folds have axial planes which dip southeast; these are generally the "back folds" of conjugate pairs.

Partly because of the conjugate folding apparent in single outcrops, the axial planes of many of the folds fan about the average axis plunging gently southwest. The fanning, however, is also due to the changes in attitude from one area to another. Thus near Cheverie the larger folds are nearly upright, and an axial-plane cleavage which dips steeply northwest is formed locally in the thick argillites (fig. 2, a). In contrast, northeast in the Walton area the folds are generally more recumbent, and some are inverted (fig. 2, b). No axial-plane cleavage has been observed in either the overturned main folds with axial

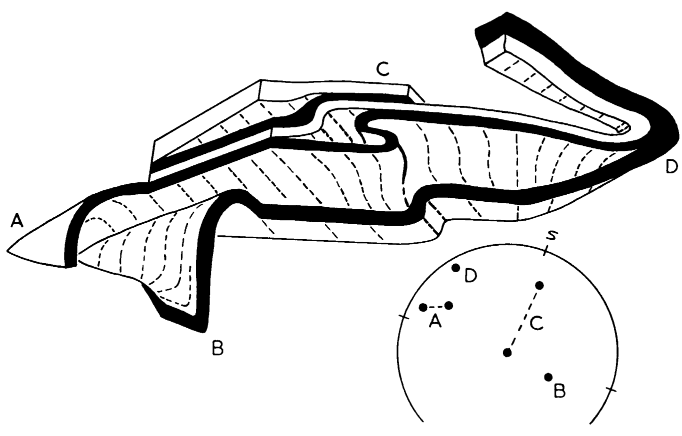

Fig. 5. Variably plunging folds, West Rainy Cove. Block diagram simplified from photograph of 50-foot cliff section, with lower hemisphere projection of the fold axes. Diagram viewed south and projection with similar orientation. Three separate beds are shown edged in black, but at the low-plunging fold (D) the edges of adjacent beds merge. The stratigraphic bottoms of beds are largely displayed (except close to (B) and above (D)). The axial planes of the folds all dip southerly. At (C) the fold axes and axial planes (more accurately "axial surfaces") are curved and locally vertical.

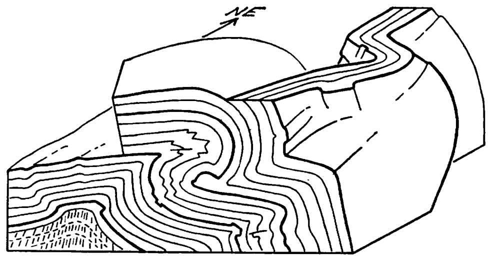

Fig. 6. Composite block diagram showing style of folds in the Cheverie-Walton area. The folds with steep axes plunge variably in southerly directions.

planes dipping less than 55° NW or the cross folds described below. This absence could be related to the later development of these folds, but the local occurrence of the cleavage within the nearly upright folds precludes the use of its presence or absence as a distinguishing structural feature.

On the north side of Rainy Cove, there are large inverted folds (fig. 3). These folds are intermediate in plunge (the antiform at A in figure 3 plunges up to 45° WSW), and as with folds that plunge at similar and steeper angles

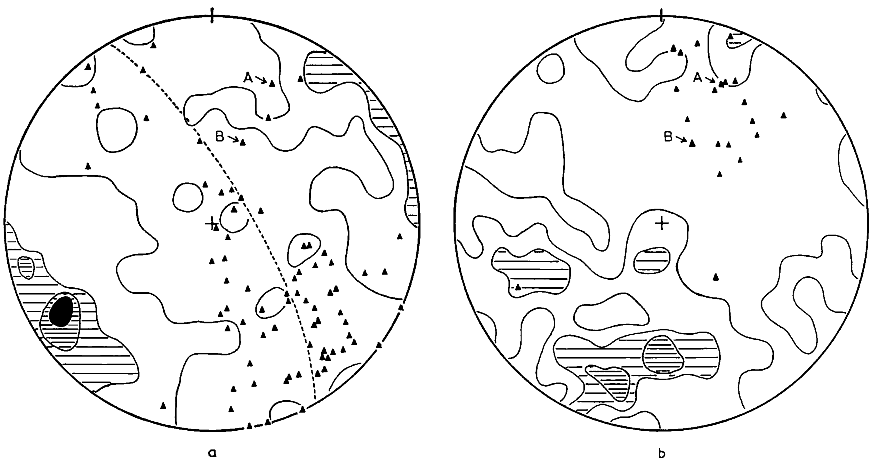

Fig. 7. Lower hemisphere equal-area projections of fold axes (contoured) and poles to axial planes (triangles).

a. Cheverie to Walton, excepting West Rainy Cove. 142 fold axes (contours at 0.5%, 4%, 8%, and 12% per 1% area) and poles to 74 axial planes (mostly calculated from attitudes of limbs of larger folds). (A) and (B) are axial planes of inverted folds at North Rainy Cove (see fig. 3). A well-defined maximum of fold axes plunges 15° SW, but there is also a considerable spread in directions and a few folds plunge almost vertically. Most axial-planes dip variably northwest (the poles are in the southeast quadrant) but some dip southeast. The poles to many of the axial planes tend to lie in a NW-SE plane with a normal corresponding to the maximum fold axis. The axial planes are thus fanned about the fold axis.

b. West Rainy Cove. 75 fold axes (contours at 1%, 4%, and 7% per 1% area) and 19 poles to axial planes plus (A) and (B) as in figure 7, a. The axes plunge variably, mostly in southerly to westerly directions; the steep axes (45°+) are of S folds. The axial planes dip variably south-southwest.

on the west side of the cove, the axial planes dip southward (fig. 7, b). On the lower hemisphere projection in figure 3, the poles to the axial planes of the inverted and adjacent low-plunging folds lie fairly closely on a north-south plane, that is the axial planes appear to fan about an axis trending east-west rather than northeast-southwest as elsewhere along the coast. As interpreted in the cross section, the inverted folds have been rotated about the east-west axis.

In figure 7, a, the spread of the axial planes away from a fanned position about the southwest-plunging axis is partly due to the tendency to fan about an east-west axis, not only on the north side of Rainy Cove, but also elsewhere.

CROSS FOLDS

On the west side of Rainy Cove, folds plunge at all angles up to 90° (figs. 5 and 7, b). The steeply plunging folds (>45° plunge) are designated as cross folds, but folds of intermediate plunge cannot readily be classified as either cross or main folds. The largest cross folds, viewed in plan profile, are S-shaped with steep inverted middle limbs which are up to 100 feet in length and face east-northeast. Regardless of axial plunge, the axial planes (or where curved, axial surfaces) of nearly all the main, intermediate, and cross folds here dip south-southwestward (fig. 7, b).

Small low-plunging folds can be traced around some of the subvertical hinges of the cross folds with no apparent change in the amount of plunge. Hence these small folds have been refolded by the cross folds, which are thus later in origin. The asymmetrical S-shape and the steepness of the axes suggest that the cross folds are the result of sinistral (left-handed) strike-slip movements, possibly along the main fold axes.

In other localities, the cross folds are not as well developed or exposed. Inland to the southeast, the outcrop pattern of the Horton and Windsor rocks is displaced in the general form of an S (fig. 1), and although obscured by faults (described by Boyle, 1963, p. 22) steeply-plunging folds are evident in quarry workings (G. Kent, personal communication).

Elsewhere along the coast, for example half a mile northeast of Split Rock, small cross folds affect only a few thin beds on the steep limbs of the larger main folds. These cross folds are both S- and Z-shaped, or they form conjugate pairs or box folds. Because of the variable shapes and few exposures, no overall sense of asymmetry is apparent.

Large, but poorly exposed, cross folds with steep axes occur near the coastal outcrops of Windsor limestone and gypsum at Cheverie. In the gypsum just north of Cheverie Creek, steep silty layers strike northeast parallel to the main fold axes and form boudinage and pinch-and-swell structures with subvertical axes. These structures indicate subhorizontal extension and thus movement parallel to the main fold axes. Possibly this movement took place during the development of the cross folds.

Slickensides are preserved on calcite films between bedding surfaces at several localities along the coast. In addition to slickensides aligned perpendicular to the main fold axes (that is as if due to flexural slip between beds), some slickensides lie approximately parallel to these axes, for example on the north side of Bass Brook near an anticlinal hinge which steepens in plunge.

Movement along the main fold axis is thus indicated, and this movement may have accompanied the development of the steeply plunging cross folds noted elsewhere. The steepening in plunge of the main fold at Bass Brook could be an incipient expression of the cross folding.

The general style of the folds between Cheverie and Walton is shown in figure 6.

DISCUSSION

A theory that explains the development of the structures described must take into account the following features:

1. The main folds plunge at low angles, are overturned (face) toward the southeast, and are generally asymmetric with short steep limbs on the southeast sides of anticlines. The axial planes of most of these folds dip northwest, but they also fan about the average fold axis plunging gently southwest.

2. Steeply-plunging cross folds and folds intermediate in plunge are formed in some localities. At Rainy Cove, the steep folds are S-shaped with axial planes that dip southward.

3. Adjacent to the S folds at Rainy Cove, inverted folds occur that are intermediate in plunge, with axial planes that dip, like those of the S folds, southward. Possibly these axial planes tend to fan about an east-west axis.

4. The S folds refold small main folds and thus are later in origin.

In addition, the similarity in style shown by the conjugate folds which plunge at both low and high angles suggests that all the folds formed during a single period of deformation. A continuous sequence of movements is therefore envisaged.

Possibly the folding movements, which took place toward the end of the Palaeozoic, were as follows:

A. At the start of deformation there was an overriding movement of upper beds toward the southeast. This led to the development of the asymmetric main folds trending northeast with axial planes that dip dominantly northwest (fig. 8, a). Boyle (1963, p. 12) has suggested similar "thrust" movements to account for the main folds.

B. The overriding movements veered toward a more southerly direction (fig. 8, b). Where this movement was most pronounced, as at Rainy Cove, some of the main folds with axial planes dipping northwest were refolded and

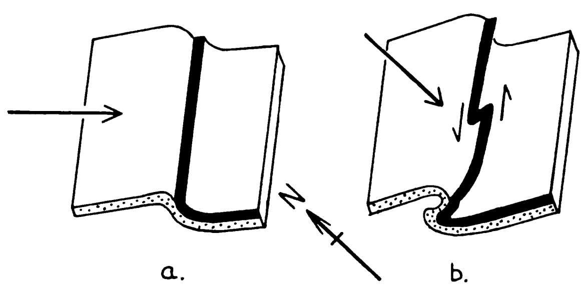

Fig. 8. Proposed sequence of tectonic events.
a. Initial overriding movement toward the southeast and folding about NE-SW axes.
b. Later movement toward the south, inversion of folds, and S-folding on steep beds.

rotated about east-west axes to recumbent and then inverted positions so that the axial planes dipped southward and the fold axes were steepened to plunge southwest to westward. The dominant southwest plunge of the main folds throughout the coastal section could also be due to a similar, but less pronounced, rotation. The north to south movements caused compression oblique to the main fold axes, and this led to oblique and sinistral strike-slip movements along these axes. Cross folds of variable plunge developed in response to these movements, and steeply-plunging S folds formed on the steep limbs of the main folds.

If the cross folds were formed in response to north-south compression, their axial planes should dip either north or south, the dip depending to a large extent on the initial attitude of the refolded limbs. At Rainy Cove, the southerly dips of the axial planes are probably due to the formation of the cross folds on the steep southeasterly dipping limbs of the main folds.

Perhaps to summarize logically the folds in the Walton area, they should be divided into three classes:

1. The main low-plunging folds with axial planes that dip dominantly northwest. These are first generation folds.

2. The inverted and other folds at Rainy Cove with low and intermediate plunges and axial planes that dip dominantly southward.

3. The steeply-plunging cross folds with axial planes that dip southward as in (2).

Classes (2) and (3) obtained their present attitudes together after the development of class (1). Folds with variable plunges but parallel axial planes are typically formed contemporaneously on a non-planar surface, that is, a surface previously folded (Turner and Weiss, 1963, p. 135). The plunge depends on the intersection of the surface with the axial plane, and in the simplest case with concentric folds, this plane is perpendicular to the direction of maximum compression. At Walton, however, this relationship is complicated by the development of conjugate folds and the effects of rotation so that the axial planes tend to form a fan. Second generation fold axes cannot, therefore, be expected to lie in a single plane (Turner and Weiss, 1963, p. 139).

Classes (2) and (3) are not considered together as one class of second generation folds because some of the folds in class (2) (for example the inverted folds) were initiated at the same time as class (1) and only later rotated to their present positions concurrently with the development of class (3). They are refolded folds (Clifford and others, 1957, p. 8). Folds in class (2), in fact, have geometric properties of both classes (1) and (3), and although some were initiated with the former, others probably developed with the latter class.

Too few folds have been measured to advance a more rigorous analysis or to consider the regional implications of the fold style at Walton. However, it is notable that a preliminary investigation elsewhere in the Carboniferous rocks of Nova Scotia has revealed folds with both low and steep plunges, and as at Rainy Cove, at some localities these folds have closely parallel axial planes regardless of the variation in axial plunge.

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