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The Acadian fold belt in the Meguma Terrane, Nova Scotia: Cross sections, fold mechanisms, and tectonic implications

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[1] Structural data and cross sections from the eastern part of the Devonian-Carboniferous fold belt of the Meguma Terrane give insight into its structural development and crustal tectonics. The sandy Goldenville Formation, the active competent member during buckling, formed a multilayer several kilometers thick that lay beneath the denser, softer muds and silts of the Halifax Formation. Cross sections reveal 2 orders of folds: 11–18 km wavelength folds are interpreted as resulting from buckling under the influence of gravity; 4–6 km wavelength folds reflect the thickness of the multilayer with buckle shortening in the range 32–44%. Depth to detachment derived from the sections (11–13.5 km below present erosion surface) is such that given the depth of the detachment below the paleosurface during the main phase (pre-Devonian granite) of folding, it would likely have been a relatively soft and thick shear zone that would have influenced profile geometry of the main phase folds at this stage of fold belt development. Granite production that may have been triggered by mantle delamination during continuing convergence accompanying terminal Pangean assembly and ocean basin closure was followed by rapid exhumation. Later localized deformation (Late Devonian–Carboniferous) in the fold belt took place as the Meguma Terrane was displaced along the terrane-bounding Cobequid-Chedabucto fault system. The characteristic asymmetric cross sections of structures of this phase are attributed to cooling and strengthening of the detachment that was a consequence of the postgranite uplift and exhumation. **Citation:** Culshaw, N., and S. K. Y. Lee (2006), The Acadian fold belt in the Meguma Terrane, Nova Scotia: Cross sections, fold mechanisms, and tectonic implications, *Tectonics*, *25*, TC3007, doi:10.1029/2004TC001752.

1. Introduction

[2] The Meguma Terrane is the most outboard terrane in the Canadian Appalachians (Figure 1), lying south of the Chedabucto-Cobequid fault system (CCFS) that separates it from the Avalon Terrane (Figure 1). An Acadian fold belt affects its sedimentary component, the Cambrian–Early Ordovician Meguma Group and latest Ordovician-Devonian White Rock, Kentville, and Torbrook formations. The fold belt is notable for its apparent simplicity: the locally periclinal folds have mostly upright axial surfaces and horizontal hinges, with kilometric spacing between axial traces that are up to several tens of kilometers in length. Given the external position of the Meguma Group relative to the Appalachian orogen, the simple geometry of the Acadian fold belt is of interest, for, although resembling an external foreland fold and thrust belt, thrusts are absent at the present level of exposure. Also, the presence or absence of a detachment zone separating the fold belt from a basement, and therefore the relationship of the fold belt to crustal tectonics, are by no means clear.

[3] In this paper we present new cross sections of the Acadian fold belt from east of the city of Halifax (Figure 1). The cross sections give insight into the geometry and genesis of the fold belt and constrain speculations about tectonics of the Meguma Terrane.

2. Geological Background

[4] The Cambrian-Ordovician metasandstones of the Goldenville Formation, the overlying slates and metasiltstones of the Halifax Formation (together, the Meguma Group) and Devonian granites comprise most of the Meguma Terrane (Figure 1). The less extensive latest Ordovician–Devonian sediments and rift-related volcanic rocks of the White Rock, Kentville and Torbrook formations predate the Devonian granites and lie unconformably on the Meguma Group. Late Devonian and Carboniferous sediments that overstep the terrane boundary (CCFS) and postdate the Devonian granites, are, together with Mesozoic rocks related to formation of the proto-Atlantic, of restricted extent within the Meguma Terrane.

[5] There are differing views of the relationship of the Meguma Group to the neighboring Avalon Terrane. In one view, the Meguma Group was situated on the passive margin of Gondwana (NW Africa) and the Meguma and Avalon terranes were unrelated prior to docking against Laurentia in the Devonian [*Schenk*, 1991]. An alternate hypothesis is that the Meguma Group has, throughout its history, remained on Avalon basement [*Keppie and Krogh*, 2000]. Two variants of this are possible: that the Meguma Terrane was a passive margin to an Avalon continent laterally continuous with West Africa [*Murphy et al.*, 2004]; or, the Meguma Terrane was deposited in a Japan Sea-like back arc; the arc potentially represented by mag-

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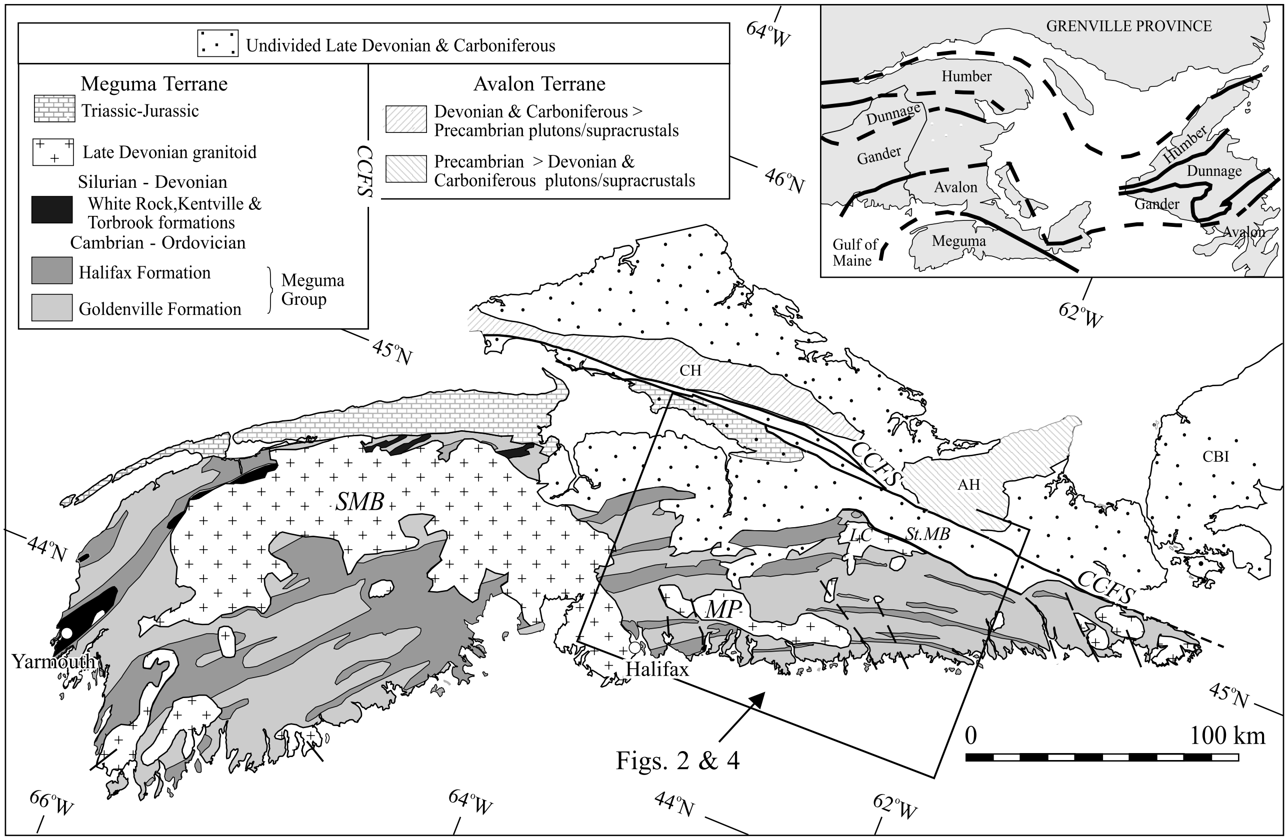


Figure 1. Geology of the Meguma Terrane. CCFS, Chedabucto-Cobequid fault system; CH, Cobequid Highlands; AH, Antigonish Highlands; CBI, Cape Breton Island; SMB, South Mountain Batholith; LC, Liscomb Complex; MP, Musquodoboit Pluton; St. MB, Saint Marys Basin. Box, location of Figures 2 and 4. Inset, terranes comprising the Appalachians of Atlantic Canada (and part of the United States).

matic rocks from Cape Breton Island that have ages [*Bevier et al.*, 1993; *Barr et al.*, 1990; *Dunning et al.*, 1990] similar to youngest detrital zircons in the Goldenville Formation [*Krogh and Keppie*, 1990]. This idea is also consistent with latest Ordovician to earliest Silurian rifting of the Meguma (White Rock Formation volcanic rocks), which may, in fact, have been continuous from Goldenville deposition onward [*White and Barr*, 2004]. A third possibility is that Avalon and Meguma were separate until the Ordovician when detrital zircon populations in sediments of both terranes are comparable [*Murphy et al.*, 2004]. Whether the Meguma was a passive margin or back arc, the ramp-like Avalon-Meguma contact visible on seismic lines at the northeast [*Marillier et al.*, 1989b; *Jackson et al.*, 2000] and southwestern [*Keen et al.*, 1991] extremities of Nova Scotia may be a remnant of the transition from stretched to unstretched Avalon crust reactivated during Paleozoic convergence and Mesozoic extension.

[6] Estimates of the thicknesses of the Goldenville Formation vary between >5500 m [*Krogh and Keppie*, 1990] to ~7000 m [*Schenk*, 1971; *Henderson et al.*, 1986], and for the Halifax Formation, from 500–4000 m [*Krogh and Keppie*, 1990] up to 8000 m [*Schenk*, 1991]. The rift related metasedimentary and metavolcanic rocks of the Ordovician–Lower Devonian White Rock, Kentville, and Torbrook formations are 2300–4500 m thick [*Keppie and Dallmeyer*, 1995]. These are restricted to the northwest part of the Meguma Terrane and do not appear at similar structural levels elsewhere, consistent with deposition in a rift of restricted extent. The Goldenville Formation, as shown on the sections of Faribault (1893–1909; see *Lee* [2005] for complete references) and in measured sections [e.g., *Waldron and Jensen*, 1985; *Horne et al.*, 1997] consists of thick, repeated sandy units (sandstone) separated by much thinner slates or siltstones; it is, in mechanical terms, a multilayer. A second, mechanically significant point is that measurements by several workers show that the Halifax slates have an average density a few percent greater than that of the Goldenville sands [*Lee*, 2005, and references therein]. In structural terms, at the time of folding, the sandy Goldenville would have formed a very thick (kilometer scale), relatively competent multilayer overlain by equally thick, but less competent and denser muds of the Halifax Formation.

[7] The extensive South Mountain Batholith (SMB) and smaller peripheral granites intruded the Meguma Group at circa 380–370 Ma [*Keppie and Krogh*, 1999, and references therein]. Gravity modeling shows that the base of the SMB lies at ~7 km below the present erosion surface [*Benn et al.*, 1999], and mineral assemblages in the contact aureole

indicate that this erosion surface was at a depth of 6–10 km at the time of SMB emplacement [*Raeside and Mahoney*, 1996; R. A. Jamieson, personal communication, 2004]. Rare roof pendants illustrate that the erosion surface is probably close to the roof of the pluton. After emplacement, the SMB and folded Meguma sediments were rapidly denuded such that renewed deposition of sediments directly onto the SMB began by latest Devonian, heralding Devonian–Upper Carboniferous deposition of continental and shallow marine sediments to a total thickness of 5.5 km (Figure 1).

3. Structure and Metamorphism of Eastern Meguma Group

[8] The main period of folding has been attributed to the docking of the Meguma Terrane with the Avalon Terrane [*Keppie and Dallmeyer*, 1987; *Mawer and White*, 1987]. However, if it is correct that the Meguma and Avalon terranes were always together, then the precise tectonic environment in which the folds formed is presently unspecified. Whatever the case, it is generally accepted that much of the fold development predated SMB emplacement and constraints on the age of cleavage associated with the folding must be sought from the numerous published argon cooling ages from the sediments themselves. Of these, the direct dating of cleavage forming micas in low-grade slates and siltstones by *Hicks et al.* [1999] yielded cooling ages of 395–398 Ma. These are probably the most reliable ages because this study was located far from possible effects of SMB emplacement, late activity along CCFS [*Keppie and Dallmeyer*, 1987] or shear zones in southwest Nova Scotia (Figure 1 in the vicinity of Yarmouth [*Keppie and Dallmeyer*, 1995; *Culshaw and Reynolds*, 1997]).

[9] The first studies of the geometry of the eastern Acadian fold belt were the cross sections of Faribault (1893–1909, see *Lee* [2005] for references). These, although outstanding for their time, showed limited extrapolation to depth. Insight into fold mechanisms began with *Keppie* [1976], who suggested that flexural flow was accompanied by tangential longitudinal strain and flattening in the Goldenville folds (Figure 2, NW domain). *Henderson et al.* [1986], in a major contribution [also *Fueten*, 1984], worked with a variety of minor structures along and near the southeast shore (Figure 2, Eastern Shore and East domains), confirmed flexural flow and inferred up to ~40% layer-parallel volume loss in sands of parts of the Goldenville Formation that occurred before or early during the growth of folds by flexural flow. However, this shortening may not have involved volume loss [*Erslev and Ward*, 1994] and there is evidence that in some folds it was restricted to fold hinges [*Young*, 2000].

[10] *Keppie et al.* [2002] concluded that the youngest part of the Acadian folds, the auriferous Goldenville periclinal fold tips, formed between 378 and 366 Ma (post-SMB). This represents a period of lateral fold growth that is much later than most folding, although such lateral fold growth [*Dubey and Cobbold*, 1977] was undoubtedly important at all stages. However, emplacement of auriferous quartz veins was a significant post-SMB structural event. In addition to emplacement in saddle reefs at propagating pericline fold tips [*Keppie et al.*, 2002], vein emplacement was related to shearing that occurred along some fold limbs [*Kontak et al.*, 1990; *Williams and Hy*, 1990]. Hydrothermal muscovite, biotite, and amphibole related to the veins give plateaus at circa 370 ± 8 Ma suggesting rapid cooling through 300°–500°C range of blocking temperatures at time of vein emplacement [*Kontak et al.*, 1990]. The veins are attributed to metamorphic fluids that originated at depth during emplacement of the granites and coeval minor mafic plutons and exerted a fluid pressure that assisted vein emplacement and late deformation. Argon cooling ages within the eastern extremity of the fold belt as young as 360 Ma, constrain deformation that is likely related to late activity on the nearby CCFS [*Keppie and Dallmeyer*, 1987].

[11] High-grade metamorphism of the deep Meguma crust sampled in xenoliths in lamprophyre dikes and inclusions in fault breccia (378 ± 1 Ma [*Greenough et al.*, 1998] and 369 Ma [*Gibbons et al.*, 1996], respectively), is similar in age to granite emplacement. In the upper crust, where the low-P/high-T Barrovian type metamorphism [*Raeside and Jamieson*, 1992] varies from predominant greenschist to upper amphibolite facies close to plutons, isograds transect the folds [*Keppie and Muecke*, 1979], indicating that this is a second metamorphism, posttectonic with respect to the main phase of folding [*Keppie et al.*, 2002] and comparable in age to the deep crustal metamorphism. Also, gneisses in the Liscomb Complex, a plutonic-gneissic assemblage emplaced into the fold belt by unknown means (Figures 1 and 2), may also sample similar crustal levels as the xenoliths and fault fragments and their argon cooling age is consistent with a similar age of metamorphism [*Kontak and Reynolds*, 1994].

[12] Deformation, related to continuing CCFS motion, can locally be traced from the Devonian-Carboniferous, post-SMB cover into the underlying Meguma Group basement [*Horne et al.*, 1999; *Murphy*, 2003] (Figure 1). Carboniferous shear zone-related deformation, possibly related to the latter, also occurs where the Meguma Group is isolated from its post-SMB cover [*Keppie and Dallmeyer*, 1987, 1995; *Culshaw and Liesa*, 1997; *Culshaw and Reynolds*, 1997; *Horne and Culshaw*, 2001].

[13] Whereas much deformation in the fold belt is pre-SMB, in the brittle-ductile CCFS the oldest ductile (mylonitic) fabrics that can be clearly related to the fault affected Late Devonian and Carboniferous rocks [*Eisbacher*, 1970; *Mawer and White*, 1987] suggesting that there is no deformation on the CCFS older than circa 370 Ma (for a contrary view, see *Pe-Piper et al.* [1996]). This is consistent with a Late Devonian–Early Carboniferous palinspastic restoration [*Murphy and Keppie*, 1998] that shows ~150 km of subsequent displacement on the CCFS. Later northwest trending faults that transect the fold belt display left lateral separation (Figure 2). A single local study from a surveyed mine demonstrates oblique slip (east-side down, left lateral) from fold hinge piercing points (R. J. Horne, personal communication, 2004). The age of these brittle-ductile features is controversial and presently is unconstrained within the Carboniferous-Mesozoic range.

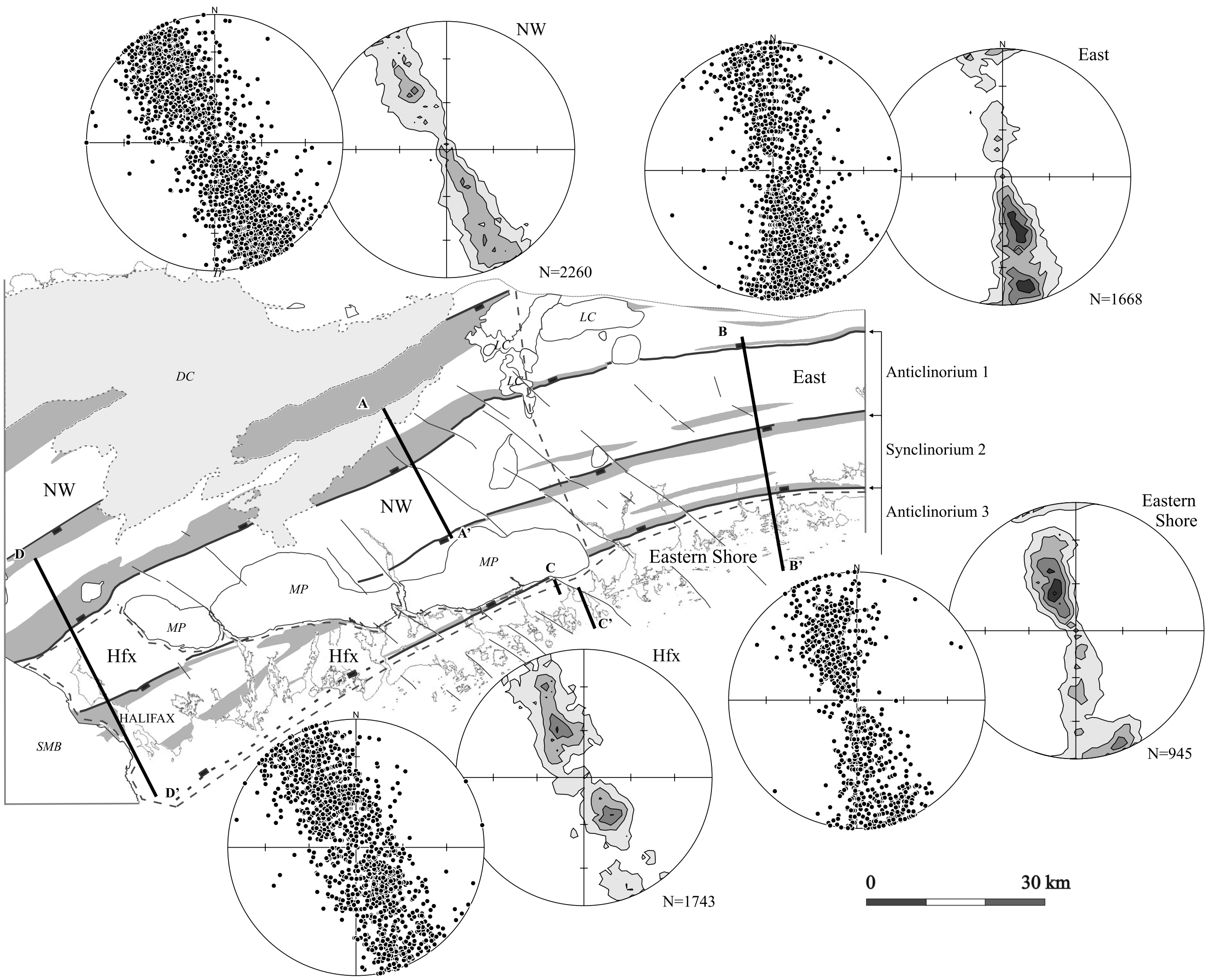
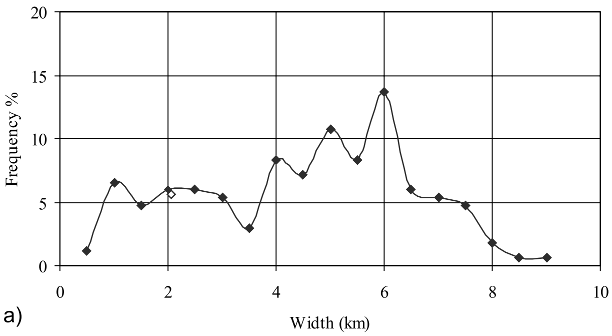


Figure 2. Regional structural geology of part of the eastern Acadian fold belt. Halifax Formation, dark grey; Goldenville Formation, white; Late Devonian–Carboniferous sediments, light grey, DC. Devonian granites and related rocks white, with letter code: SMB, South Mountain Batholith; MP, Musquodoboit Pluton; LC, Liscomb Complex; other smaller plutons, uncoded. Heavy lines indicate the limbs of the largest anticlinoria and synclinoria; the boxes on the lines indicate younging direction of steep limbs; outcrop of Halifax Formation outlines smaller horizontal synclines. The area is divided into domains (boundaries, dashed lines) consisting of the Halifax area between the MP and SMB, along the eastern shore and neighboring islands, the northwest, and east (Hfx, Eastern Shore, NW, and East, respectively). Stereonets for poles to bedding in these areas are shown. The net contour intervals are 2, 4, 6, 8, 10 counts within a counting circle of size 100/N percent of net size (N is number of data). The four cross sections are indicated A-A′, B-B′, C-C′, and D-D′.

[14] Data concerning the crustal-scale structure of the Meguma Terrane is sparse. On seismic reflection lines shot offshore of southeast Nova Scotia, diffuse reflectors at 3–4 s two-way traveltime (twt) lie within transparent crust and could be the base of the Meguma Group (lines 88-2 and 88-4 of *Keen et al.* [1991]). The lowermost transparent zone overlies strong, gently inclined to horizontal lower crustal reflectors extending down to 9–10 s twt. One interpretation of this line shows Avalon crust tapering eastward beneath the Meguma [*Keen et al.*, 1991]. Another line across the Avalon-Meguma boundary at the eastern extremity of Nova Scotia shows a similar geometry, although influenced by Mesozoic extension (line 86-5b of *Marillier et al.* [1989b] [see also *Jackson et al.*, 2000]).

4. Methods

[15] The maps and cross sections (Figures 2 to 5) are derived from a GIS-based compilation of digital geophysical (magnetic grid) and geological vector data. In order to construct cross sections it was necessary to identify marker horizons to supplement the Halifax-Goldenville boundary,



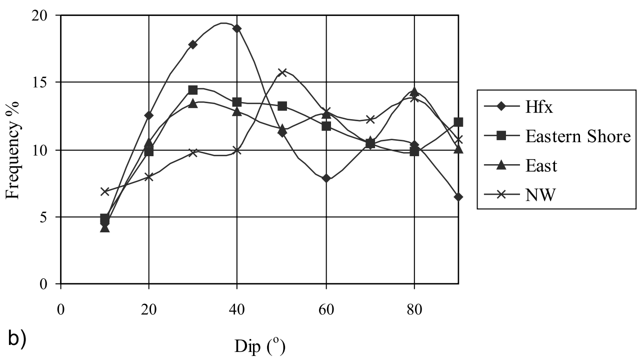


Figure 3. (a) Histogram of map width of anticlines; N = 168. Frequency percent, number of anticlines in each width class intersected along traverses, perpendicular to hinge traces and spaced at 5 km, expressed as a percentage of the total number of anticlines. (b) Histograms of bedding dip for each structural domain (Figure 2). Total number of data in each domain is same (N) as for respective stereonets in Figure 2. Because the folds have horizontal hinges, the frequency of bedding dip is indicative of fold profile shape.

which is the only one showing on maps of the Meguma Group. Two potential markers were identified on cross sections by Faribault where ornamentation suggested similar lithologies at the same level of the upper part of the Goldenville Formation. These units are not shown on maps and no explanatory reference to them can be found in Faribault's map legends or reports [*Lee*, 2005]. There is some evidence from comparison with detailed local studies [e.g., *Waldron and Jensen*, 1985] that the magnetic markers (and therefore the units on Faribault's cross sections) correspond to zones where the number of slate intervals is significantly higher than normal for the Goldenville. The units consistently lie close to spatially continuous magnetic vertical gradient anomalies and thus suggest the possibility of using the anomalies as surrogates for mapped lithological units. To test the consistency of this interpretation, model total field profiles were produced by applying compiled published magnetic data for Meguma slates and metasandstones to geophysical models of Faribault's sections. A model vertical gradient profile, calculated from the model total field profiles, showed magnetic units with the requisite cross-sectional geometry could produce magnetic signatures that match anomalies of the observed vertical gradient map [*Lee*, 2005]. The two anomalies identified as the surrogate units were then mapped throughout the area and used with the Halifax-Goldenville boundary for construction of cross sections using the kink method [*Suppe*, 1985; *Tearpock and Bischke*, 1991], which is appropriate for folds dominated by flexural flow.

5. Results

[16] It is convenient to divide the area into four domains based on fold hinge orientation and location with respect to the two principal granite bodies in the area, the SMB and Musquodoboit pluton (Figure 2). Two groupings of horizontal folds with mean widths of ~2 and 6 km are present throughout the map (Figures 2 and 3a). These folds are mostly cylindrical and upright although in the East and Eastern Shore domains a significant number are overturned (Figure 2, stereonets), and, more locally, folds adjacent to the NW tip of the Musquodoboit pluton are overturned (Figure 4a, location 11). Frequency distribution of bedding dips, indicative of profile shape for upright horizontal folds, shows significant regional variation of moderate dips (coexisting with steep dips) suggesting that more box-like or rounded folds are present in the Halifax area than in the east, where chevrons are more common (Figures 3b and 2). This variation of profile geometry correlates with the change in hinge trend from NE-SW to closer to E-W but may also be related to position relative to granite bodies which may have afforded protection from late deformation (Figure 2). Oblique profiles of rounded and chevron profiles of plunging folds (e.g., Figure 4c, locations 4 and 7) compare with similar variations noted in cross sections by *Horne and Culshaw* [2001] and are a result of progressive development of buckles in certain multilayers [*Fowler and Winsor*, 1996].

[17] The typical aspect ratio for buckles (defined as ratio of length of hinge to half wavelength) has been set at 5:1 to 10:1 [*Sattarzadeh et al.*, 2000]. However, in this study, there are few folds of intermediate widths (6 km mean width) that terminate on the regional map. Those that do are 20–30 km along the axial trace and have aspect ratios of 5:1 and higher (up to ~15:1) (Figure 4c, location 1). Some synclinal traces within Halifax Formation have aspect ratios far in excess of the 'typical' value, continuing without termination for more than 40 to 90 km (Figures 2, 4a (location 2), and 4c (location 2)). Nevertheless, in the west of the area some have much lower aspect ratios. For example, the periclinal Oldham anticline, in the NW domain, has an aspect ratio of <5:1 [*Keppie et al.*, 2002] and that of a dome-like anticline in the SE of the Halifax domain is about 2:1 (Figure 4a, location 3).

Figure 4. (a), (b), and (c) Enlarged maps of parts of the western and eastern areas shown in Figure 2. Synclines, dash-dotted; anticlines, dotted; form lines (constructed from map data), solid thin line; arrows indicate plunge direction; triangles indicate overturning at NW tip of Musquodoboit Pluton. Numbers are locations referred to in text. Unit codes, as in Figure 2. Inset is location map.

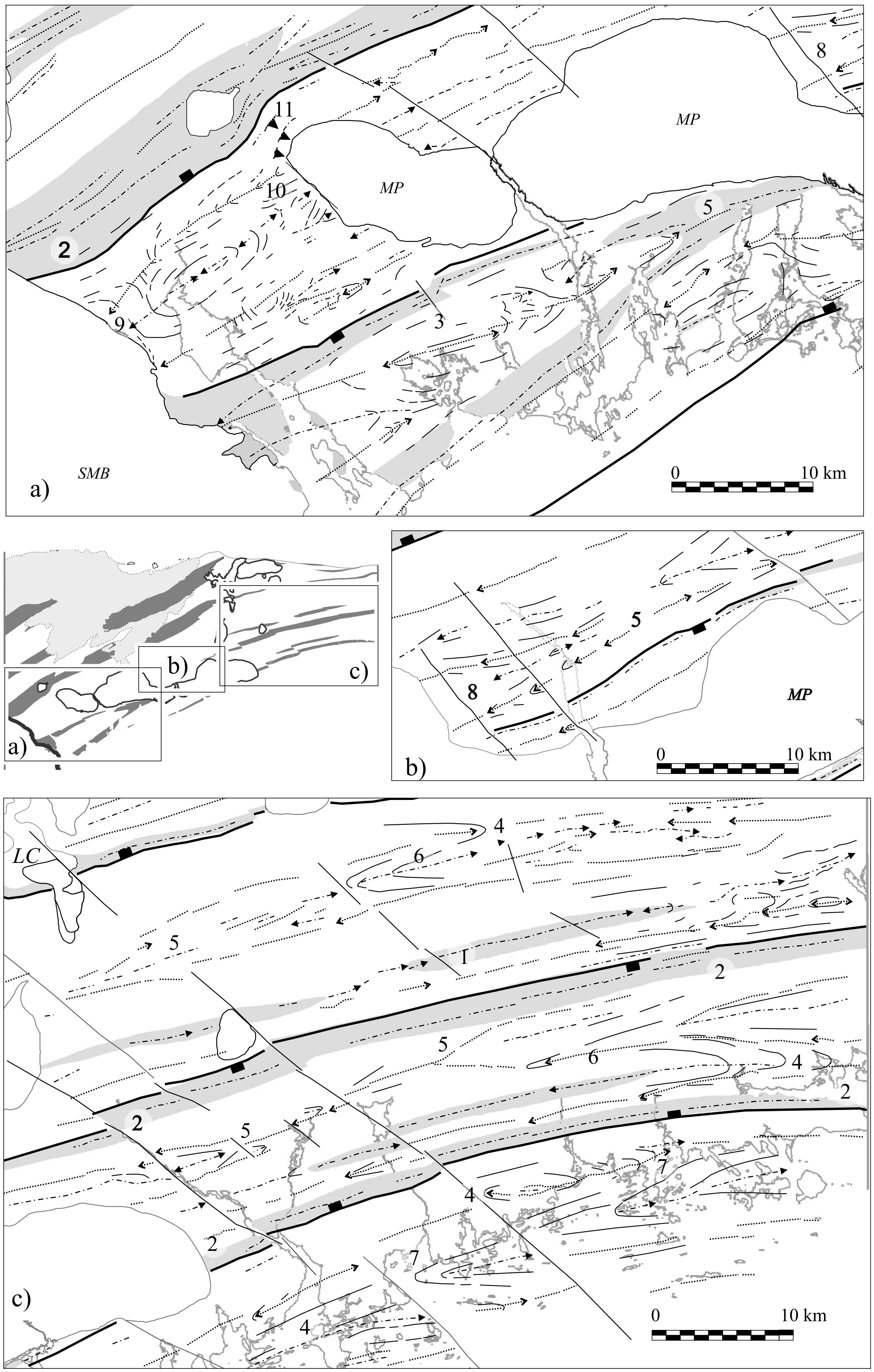


Figure 4

[18] As noted, most folds are horizontal but there are many small changes in plunge (Figure 4) and, some of these, visible in oblique profile expressed by form lines, are located at periclinal fold tips (Figure 4c, location 4). Plunges at periclinal fold tips vary from 1 to 18° but in general are low (12 measured, average 8°). Such periclinal tips are attributed to hinge-parallel propagation of buckles [*Dubey and Cobbold*, 1977]. Wishbone patterns of axial traces, indicative of merging of out-of-phase fold trains of different wavelength [*Dubey and Cobbold*, 1977] are present throughout the area (Figure 4, location 5); the best example is in the south part of the Halifax domain. Linked (en echelon) antiform-synform axial traces have been noted in the east (Figure 4c, location 6 [*Henderson et al.*, 1986]) and are also ascribed to lateral propagation effects [*Dubey and Cobbold*, 1977].

[19] The fold pattern has a different character close to the major plutons. On the NE flank of the second node of the Musquodoboit pluton, wishbone-pattern fold hinges change plunge from NE to SW toward the pluton (Figure 4b, location 8). A comparable change in plunge toward the SMB was documented in the anticlinorium in the north of the Halifax domain (Figure 4a, location 9) [*Culshaw and Bhatnagar*, 2001]. The folds of this anticlinorium also change plunge toward the SW flank of the Musquodoboit pluton (Figure 4a, location 10) with a basin in the crest of the anticlinorium separating the changes in plunge. The dome and basin-like folds situated further east in the Halifax domain (at and close to Figure 4a, location 3) may be less likely to have been formed by pluton emplacement because the plutons are widely separated at this point and a change of plunge toward the SMB is not evident.

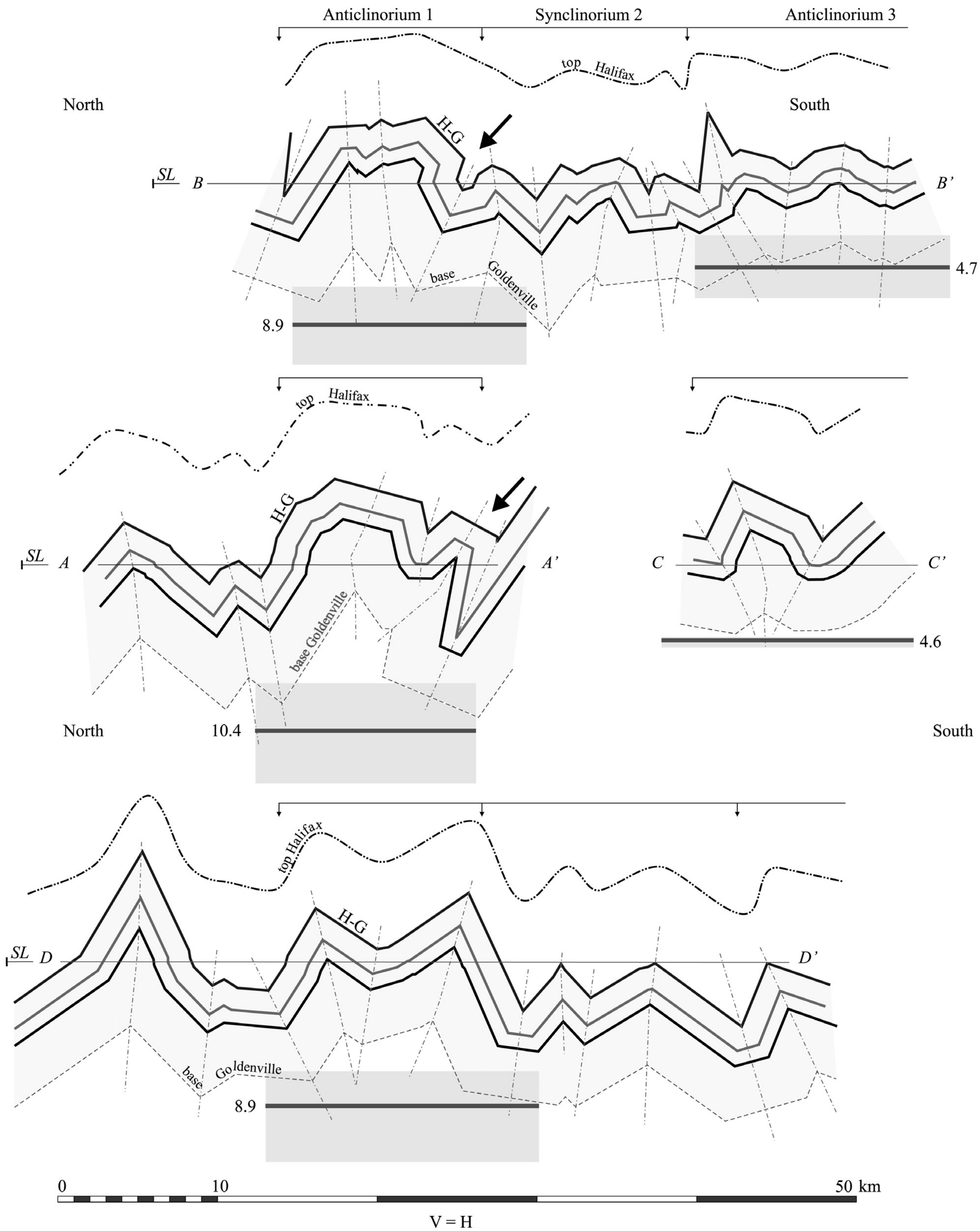
[20] The cross sections are drawn using the contact of the Halifax and Goldenville formations and the two magnetic markers within the Goldenville Formation (Figure 5). The locations of the base of the Goldenville Formation and the top of the Halifax Formation are extrapolated within the range of the thickness estimates given above. The box and chevron fold style, a result of the method used for constructing the sections, imparts an angularity at and within hinge zones not observed in oblique map profiles or on the well-constrained, partial, cross sections of Faribault (1893–1909, see *Lee* [2005] for references). Nonetheless, this style is consistent with the evidence for flexural flow as a predominant folding mechanism in the Acadian fold belt [*Henderson et al.*, 1986; *Horne and Culshaw*, 2001] and the presence of box-like and chevron folds. The sections are very well constrained by the density of the compiled data and the possibility of faulting was only suggested in a couple of places associated with large asymmetric folds (Figure 5). Several processes in addition to flexural flow might have influenced the fold profiles [*Keppie*, 1976; *Fueten*, 1984; *Keppie et al.*, 2002] but are not accounted for by the method used to make the sections. Further, none of the folds are shown as rooting in blind thrusts on the sections because there are no thrusts attributed to the pre-SMB phase of folding recorded at surface within the Acadian fold belt and, under most geothermal gradients, conditions may not have allowed brittle faulting at the depth of the base of the Goldenville Formation (>13 km). The latter consideration implies that blind thrusts may exist as ductile shear zones terminating in the core of the largest folds, and it may be appropriate to show extrapolated markers at depth (e.g., base of the Goldenville Formation) with layer parallel shortening dampening or removing the fold amplitude.

[21] Several large pre-Carboniferous anticlinoria and synclinoria (11–18 km wavelength), which extend along the entire fold belt east of the SMB, are recognized from the cross sections (Figures 2 and 5) and include those identified previously in local studies [e.g., *Keppie*, 1976; *Culshaw and Bhatnagar*, 2001]. The large wavelength folds appear on the section as a result of adherence to the section construction method and are not a result of additional assumptions. The smaller folds (4–6 km wavelength) on the sections are those that are shown on regional maps. The smallest folds inferred from the map data (~2 km width) have very little expression on the sections. The folds are moderately polyclinal, this effect being more strongly developed in the two eastern sections where there is also a tendency for SE overturning in the large northern anticlinorium (Figure 2, anticlinorium 1), although this effect is not as strong as would be expected from the bedding pole data shown on stereonets (Figure 2). The box-to-chevron variation, deduced from the map pattern, is also present.

[22] As a result of the absence of thrusts and the section construction mechanism used, the sections naturally balance and buckle shortening is readily obtained. Comparing matching synclinoria and anticlinoria, shortening in the easternmost section (B-B′) is about 12% greater than for the Halifax section (D-D′) (44% and 32%, respectively), consistent with inferences from limb dip data (Figure 3b). Arc length to thickness ratios may be indicative of the relative amounts of layer parallel shortening and buckling [*Sherwin and Chapple*, 1968; *Abbassi and Mancktelow*, 1990]. For whatever thickness assumed for the active member (up to the estimated thickness of the Goldenville Formation), this ratio is very low, although it is lowest for section B-B′.

[23] Depth to detachment was estimated by calculation based on measurements of bed length and uplifted area of single horizons [*Chamberlin*, 1910] or by the excess area

Figure 5. Cross sections of the Acadian fold belt; locations shown on Figure 2. Thick continuous lines are the Halifax-Goldenville boundary (H-G) and the modeled marker horizons within the Goldenville Formation. The top of the Halifax Formation and base of Goldenville Formation are extrapolated from published thickness estimates. The geometry of the horizons has an angularity inherited from the method of cross section construction and must be regarded as an approximation. Bold arrows show asymmetric folds. The top of the Halifax Formation is shown with a rounded profile and modulated wavelength; the erosion surface at the time of the main phase of folding would have been close to this surface. The upper and lower estimates for depth (in km) to detachment (i.e., depth from present erosion surface is section line, SL, on figure) are shown in shaded boxes; heavy line, mean depth [after *Lee*, 2005].


Anticlinorium 1
Synclinorium 2
Anticlinorium 3
top Halifax
North
South
H-G
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base Goldenville
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8.9
top Halifax
H-G
SL
A
A'
C
C'
base Goldenville
4.6
North
10.4
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Figure 5

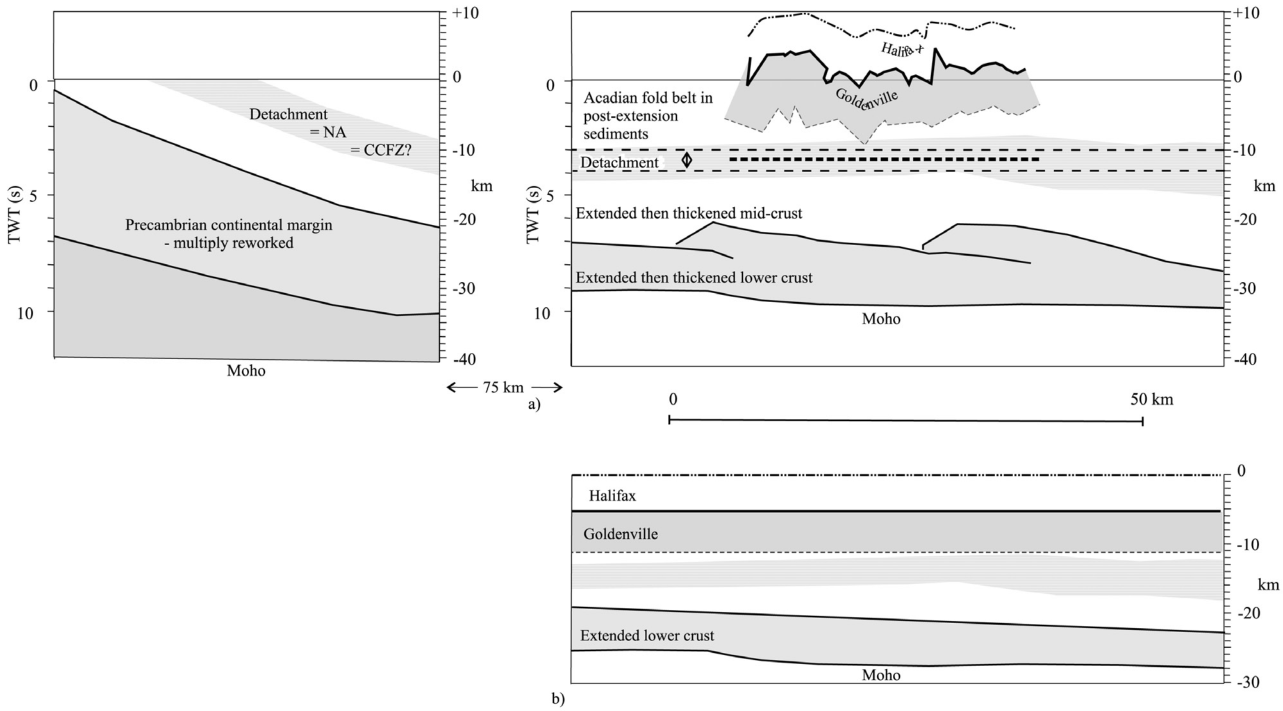


Figure 6. Cross sections superimposed on seismic section line 88-2 (based on Figure 7 of *Keen et al.* [1991]) to show crustal-scale evolution. (a) (left) Schematic adapted from line 88-4 to show crustal ramp at margin of thinned crust. (right) Section B-B′ shown to scale on line 88-2. Line B-B′ is located relative to base of shaded box on Figure 5 at a depth of 11.25 km (deepest detachment estimated for B-B′, heavy short dashes). Range of deep detachments from Figure 5 lies between light dashed lines; these fall within zone of weak reflectors at 3–4 s twt [cf. *Keppie et al.*, 2002] shown as shaded zone. Highly reflective and shallow dipping reflectors in lower crustal appear to be imbricated. Scale is 1 s twt assumed to be ~3 km. (b) Line 88-2 with midcrust and lower crust thinned by restoring the "thrusts" in the lower crust and an equivalent amount of thickening in midcrust; Halifax and Goldenville formations were deposited on this thinned crust.

method [*Epard and Groshong*, 1993], based on multiple horizons within anticlinorial fold trains. A range of values was obtained for different parts of the sections and these are shown on Figure 5 with their arithmetic mean. Points for each horizon plot close to a straight line on excess area-depth plots showing the sections are internally consistent [*Epard and Groshong*, 1993]. The excess area method always produces the deepest estimates (11–13.5 km; base of range in Figure 5), and, because these estimates were based on measurements of fold trains, these are considered the best estimates [*Bulnes and Poblet*, 1999]. Two different apparent depths to detachment are present on two of the sections. The shallower "detachment" lies beneath the Eastern Shore domain, the deeper is beneath the large anticlinoria to the north. The deeper estimate is similar to those obtained by previous workers east of Halifax and in southwest Nova Scotia (Figure 6).

6. Discussion

6.1. Buckle Folding

[24] There are several details that are consistent with the folds being buckles rather than fault-bend or fault-propagation folds (Figures 7a and 7d). The evidence mainly comes from the smaller folds (4–6 km wavelength). The inference that the folds evolved from box-like to chevron compares with analogue models of progressive buckling of multilayers [e.g., *Fowler and Winsor*, 1996; *Ghosh*, 1968]. The analogue models of *Dubey and Cobbold* [1977] show that buckle folds nucleating at isolated irregularities form fold trains that propagate and ultimately merge within the layer to form characteristic axial trace patterns. Several examples of these patterns, including wishbone-shaped patterns of merging hinges of the smaller folds, have been cited in the fold belt (Figure 4) strengthening the conclusion that these folds are simple buckles developed in a multilayer.

6.2. Depth to Detachment

[25] A reliable estimate of the depth to detachment is important for understanding fold mechanisms. A consistent feature of the depth to detachment calculations is the prediction of a shallower detachment in the SE than in the NW of the fold belt. This may be a severe underestimation, possibly an artefact of either the layer parallel shortening demonstrated for the Eastern Shore domain and part of the East domain [*Fueten*, 1984; *Henderson et al.*, 1986]; or, of

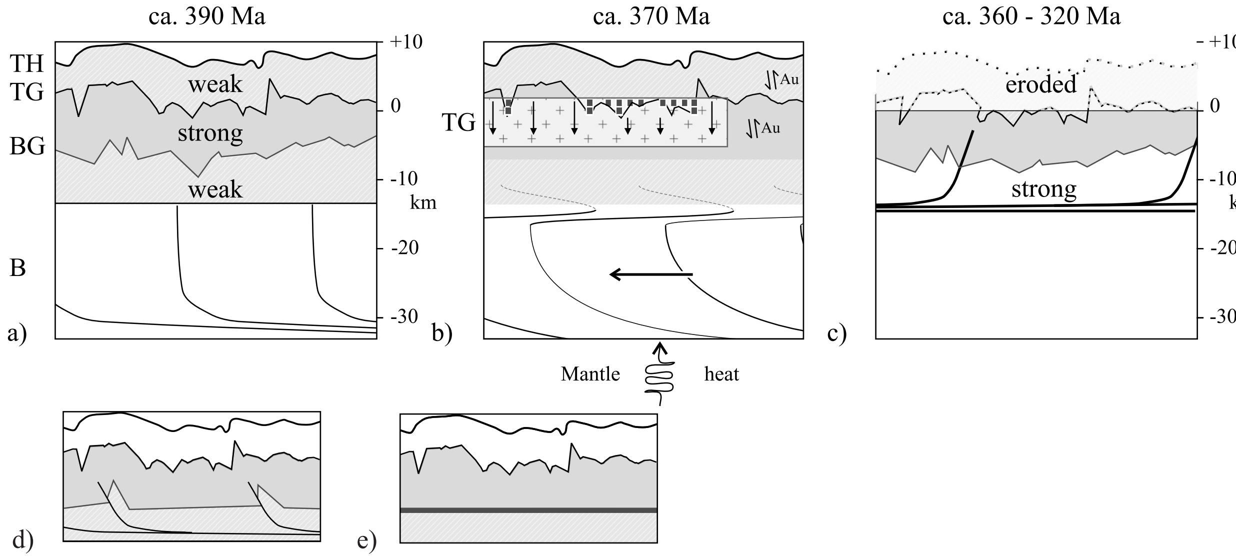


Figure 7. Schematic of crustal-scale cross section showing structural development of the Acadian fold belt. In Figures 7a, 7d, and 7e, from circa 390–370 Ma the Meguma sediments buckle above a thick midcrustal weak detachment zone (at ~8–12 km). (a) The entire crust may be involved in the shortening (vertical lines indicate the possible shortening in midcrust and lower crust), and the Goldenville Formation is a strong, buckled multilayer above the weak detachment zone and below the Halifax Formation; alternately, (d) blind thrusts, rooting in the detachment, core the Goldenville anticlinoria; or (e) lower members of the Goldenville Formation shorten and thicken homogeneously. TH, top Halifax; TG, top Goldenville; BG, bottom Goldenville; B, basement. (b) At circa 380–370 Ma, triggered by delamination-induced mantle heat, the SMB magma is produced and emplaced close to the enveloping surface of the synclinoria (floor down by ductile shear and stoping in Goldenville anticlinoria and Halifax synclinoria, respectively); gold mineralization and local shearing and faulting in the stiff superstructure; ductile flow and high-grade metamorphism in lower crust. (c) Circa 360–320 Ma post-SMB erosion and deposition accompanied by brittle-ductile faulting and asymmetric folding above a detachment cooled and strengthened as a consequence of exhumation.

the incompleteness of the measured fold train in the southern ends of the sections [cf. *Bulnes and Poblet*, 1999]; or, a real effect due to, for example, paleodip of the margin. Because low arc length-to-thickness ratios imply layer parallel shortening may have been present in all sections, including where greater depths to detachment are predicted, we suggest incompleteness of the measured fold train is the major factor in underestimating depth to detachment.

[26] The estimated depth to detachment of ~10–13.5 km compares with that arrived at in the NW domain [*Keppie et al.*, 2002] and in the southwest of the fold belt [*Culshaw and Liesa*, 1997] (Figure 1, Yarmouth area) at about 10 km, and with the depth (3–4 s twt) of diffuse reflectors noted by *Keen et al.* [1991] on line 88-2. As previously noted, the depth to detachment would have been greater at the time of main phase folding by the amount of structural relief of the thickened Halifax Formation, which is 6–10 km (Figures 5 and 7a) and quartz bearing rocks would have been ductile, even more so for micaceous rocks. This effect would enhance the influence of soft rheologies at the base of the Goldenville, and allows for the possibility of a diffuse, thick and soft detachment zone beneath the Goldenville Formation rather than a discrete, thin fault zone. At the time of the main phase folding (pre-SMB), the Goldenville multilayer therefore may have had thick soft zones both below and above (the Halifax Formation in Figure 7a). The potential effects of these are shown by models of buckling of multilayers embedded in ductile half-spaces [e.g., *Ghosh*, 1968] which display profiles resembling those of the fold belt. Other analogue models which lack the soft half-space overlying the multilayer have shown that the presence of a thick and soft detachment suppresses the single sense of vergence found in many fold-and-thrust belts [*Costa and Vendeville*, 2002]. These models, both of which have a thick, soft lower half-space, can produce box-like folds resembling Goldenville profiles. Thus some mix of the ductile half-spaces and thick-soft-detachment models can account for the pre-SMB profiles of the fold belt.

6.3. Large Folds and Crustal Shortening

[27] Large (>10 km) wavelength folds, not readily recognizable from the map, are a major feature of the cross sections (Figures 3 and 5). Whereas the smaller folds, as has been demonstrated, are buckles, the origin of these folds is more problematic: the soft detachment analogue models can produce Meguma-like profiles with or without thrusts. However, the large folds are accompanied on the cross

sections by the shorter-wavelength buckle folds that cannot be separated in time of development, suggesting a common origin for both. Here we outline the case for a buckle origin for the large folds, although the role of detachment-soling blind thrusts in the fold cores remains an open question (Figure 7d). Theoretical studies indicate that for layers or multilayers of kilometer-scale thickness, gravity in addition to thickness and relative competence can act as agent(s) to control buckle wavelength [*Ramberg*, 1964, 1970a, 1970b; *Biot*, 1959, 1961]. In essence, a single very long wavelength will form if the ratio of buckle (layer parallel) to gravitational force is low; a second, shorter wavelength (wavelength governed by relative stiffness and thickness of the layers) will simultaneously develop if this ratio is higher, with layer parallel shortening being important at low compressive stress [*Ramberg*, 1964]. In the limiting case of very high compressive stress, the influence of gravity is nullified, ruling out long-wavelength folds, and the fracture strength may be exceeded, resulting in the formation of thrust faults. For a layer lying beneath a denser layer (e.g., the Goldenville Formation beneath the Halifax Formation), the effect of gravity with respect to compression is enhanced [*Biot*, 1959]. This effect being further enhanced for multilayers such as the Goldenville Formation [*Biot*, 1961].

[28] Given that the sand-dominated Goldenville Formation was a stiff multilayer of several kilometers thickness that lay beneath the soft (muddy), denser Halifax Formation during the main phase folding event, the potential role of gravity in shaping the large wavelength Meguma folds becomes clear whereas he wavelengths of the 5–6 km folds were likely controlled by material properties of the Goldenville multilayer. The spaced cleavage in the Goldenville Formation of the Eastern Shore domain and the southern part of the East domain [*Henderson et al.*, 1986] may be attributed to layer parallel shortening in a gravity-affected system at low compressive stress [*Ramberg*, 1964]. In this view it is clear why there are no main phase thrusts mapped in the fold belt; the rate of compression was too low. The reason for this may be that during the pre-SMB phase of folding highly oblique convergence was partitioned into a high strain rate, lateral displacement along a fault and a lower strain rate, orthogonal compression in the fold belt.

6.4. Along-Strike Length of Largest Folds: Basement Faulting and Cover Buckling?

[29] An additional, related, feature of the map view is the continuity, over tens of kilometers, of the long-wavelength and some shorter-wavelength folds (Figure 2). The theory of buckling affected by gravity does not address the hinge geometry of such folds. Buckles are expected to propagate along their hinges forming a pattern of discontinuous hinges [*Dubey and Cobbold*, 1977], but both the very wide anticlinoria and synclinoria and the extremely long, continuous synclines are difficult to explain as short folds amalgamated by lateral propagation.

[30] Control of high aspect ratio folds in the Zagros fold belt has been attributed to the influence of basement faults [*Sattarzadeh et al.*, 2000]. The possibility that basement faults were active during development of the Acadian fold belt is suggested by the likely nature of the sub-Meguma crust as it was prior to folding of the Meguma. Whatever crust the Meguma Group was deposited on or transported onto (Gondwanan or Avalonian passive margin or Avalon-Africa back-arc crust) it would likely have been tectonically thinned earlier. Such crust could have shortened by inversion of extensional faults as the overlying Meguma Group sediments folded (Figure 7a). This would explain the apparent imbrication of the strongly reflective, sub-Meguma lower crust on line 88-2 [*Keen et al.*, 1991] (Figure 6a). Analogous inversion of a margin thinned in the late Precambrian has been suggested to explain seismic patterns in Grenville basement beneath the western parts of the Appalachians in Atlantic Canada [*Marillier et al.*, 1989a; *Stockmal et al.*, 1987]. Inversion of crust locally further thinned in the Ordovician, or even throughout Meguma deposition [*White and Barr*, 2004], may also be implied by deformation of the extension-related White Rock through Torbrook formations [*Culshaw and Liesa*, 1997].

[31] However, even though there is independent support for the existence and inversion of basement faults, it is unlikely that they can be used to explain the lateral extent of the Meguma fold hinges during pre-SMB folding. One reason for questioning fault control for the pre-SMB stages of the largest folds is that they appear to be periodic, as is appropriate for buckle folds (Figures 2 and 5, B-B′). In any event, there is no reason why basement fault inversion should not have accompanied Meguma buckling, as it did where Variscan basement inversion accompanied thrust-free buckling of sedimentary cover in the Anti-Atlas of Morocco [*Helg et al.*, 2004], a persuasive comparison because the Anti-Atlas is a candidate African lateral equivalent to the Meguma Group [*Schenk*, 1971].

6.5. SMB Emplacement and Fold Belt Development

[32] The Devonian plutons, emplaced after significant fold growth, interacted with the fold belt in several ways. The Halifax domain lay in the strain shadow between the SMB and Musquodoboit pluton, and was sheltered from Late Devonian–Carboniferous strain, therefore, preserving elements of pre-SMB fold patterns. The evidence for this includes the inferred more rounded or box-like profiles of the folds, the lower buckle shortening measured on the cross section, the wishbone hinge pattern with a wide opening angle (compared with similar patterns outside this domain) and, possibly, the low aspect ratio fold in the southeast of the domain. The overturned folds at the northwest tip of the Musquodoboit pluton (Figure 4a, location 11) may be an indication of the buttressing effect of the pluton against regional deformation at the edge of the strain shadow. The strain shadow effect cannot have been absolute because auriferous quartz veins, most likely syn- or post-SMB, occur in the domain.

[33] The second mode of pluton fold belt interaction is the alteration of fold orientations in the Goldenville anticlinoria during emplacement of the SMB to the east and west of the southeastern part of the SMB such that they plunge toward the pluton margin accompanied by formation of steeply lineated high strain rocks at the immediate pluton

margin [*Culshaw and Bhatnagar*, 2001]. This effect was ascribed to either depression of the floor of the pluton (paired with stoping in Halifax synclinoria) or late amplification of anticlinoria during emplacement (Figure 7b). The evidence that these effects are widespread where the SMB and Musquodoboit pluton crosscut the regional fold trend includes several instances of plutonward plunges (Figure 4). The discrepancy between the model thickness of the SMB (~7 km from *Benn et al.* [1999]) and the estimated depth to detachment (~10 km) may possibly be linked to floor depression at the contacts with the anticlinoria. Thus the level of emplacement of the SMB, and related plutons, may not have been controlled by the anisotropy of the detachment, but by mechanical properties of members of the folded sequence. We suggest that the strengthening within the thermal aureole of the Halifax Formation by development of hornfels provided a stiff lid in which stoping was the predominant emplacement mechanism (Figure 7b). The weakness in the lower part of the quartz-rich Goldenville, relative to the Halifax hornfelses, allowed for downward displacement of the Goldenville floor into soft material below i.e., the emplacement level may have been at the base of a stiff lid rather than at the interface with a stiff basement. We have already argued for a thick, soft detachment zone and so, below we suggest that events surrounding pluton emplacement may have enhanced the weak zone.

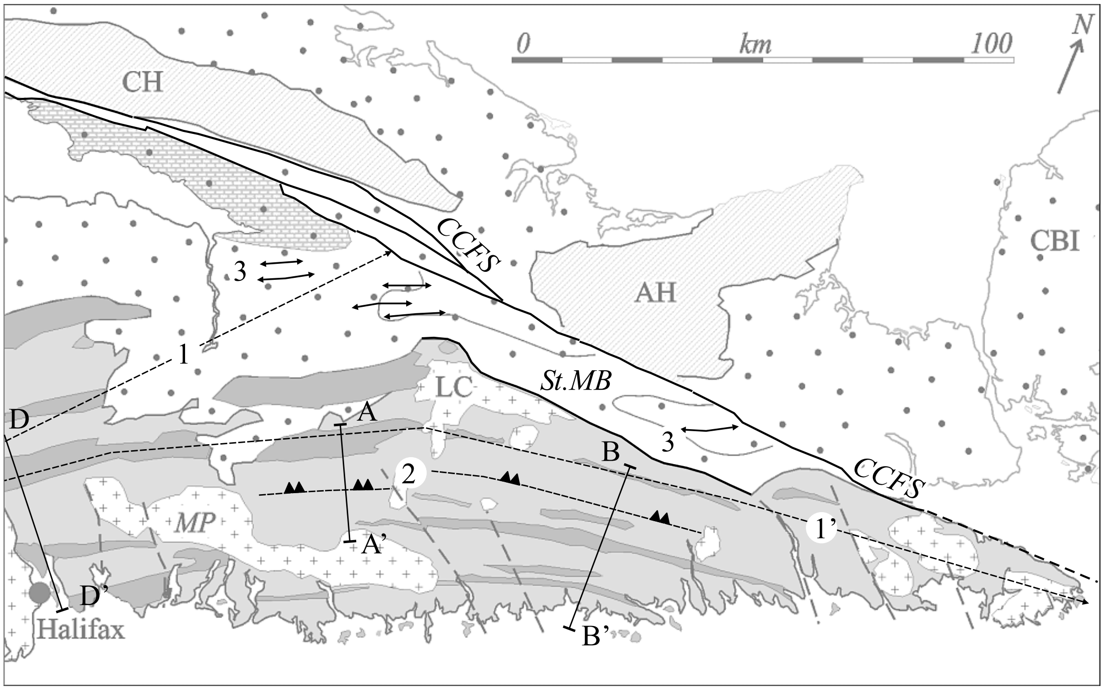
6.6. Fold Belt: A Superstructure During Syn-SMB Lower Crustal Deformation?

[34] Consideration of crustal structure constrained by fold geometry is relevant to the problematic source of heat necessary to form the voluminous late Devonian granites and to generate the late high-grade metamorphism evident in the deep crustal samples. It has been linked to mantle heat accompanying minor mafic plutonism [*Tate and Clarke*, 1995] with some authors invoking a plume source [*Murphy et al.*, 1999] or asthenospheric influx following delamination of the mantle lithosphere and part of the orogenically thickened crust [*Keppie and Dallmeyer*, 1995]. Delamination or thinning of the mantle lithosphere at a late stage of evolution of an active margin or collisional zone is the simplest solution and has been suggested to explain late tectonic magmatism (often bimodal, as in the Meguma Terrane) present on the ancestral Laurentian margin from the Paleoproterozoic onward [e.g., *Kerr*, 1997; *Ketchum et al.*, 2002] and in other convergent environments [e.g., *Chung et al.*, 2003; *Aldanmaz et al.*, 2000]. In the case of the Meguma Terrane, delamination may have affected a lithosphere with a relatively thin orogenic crust (Figures 7a and 7b): deformation of a ~25 km thick crust (Figure 6b, thinned lower crust plus Meguma Group) by a vertical pure shear equivalent to the buckle shortening measured from the cross sections would produce a pre-SMB crust ~45 km thick (Figure 6a, matching present thickness plus eroded Halifax Formation). This modest thickening, which ignores estimates of layer parallel shortening, alleviates the need to get rid of up to half of a crust thickened to Tibetan dimensions, in addition to lithospheric mantle, during syn-SMB delamination [*Keppie and Dallmeyer*, 1995].

[35] If the estimates for position of Meguma toward the end of the Devonian are correct [*Murphy and Keppie*, 1998], then the Meguma Terrane lay significantly outboard of its present position during delamination. As pointed out by *Murphy and Keppie* [1998], this position would have aligned the Meguma Terrane and its Devonian plutons, along a line of Devonian plutons that includes those in western Cape Breton Island and parts of Newfoundland. All plutons may have been produced in the same delamination event.

[36] With regards to why such modification of the lithosphere should take place deep within an almost assembled supercontinent, we suggest that a good analogue for the northern Appalachians in the late Devonian is the Mediterranean basin and its surrounding mountain belts. The analogy is appropriate insofar as it involves terminal assembly of a large continental mass during which several small ocean basins are trapped (or have already just been consumed), essentially landlocked within converging continental landmasses [*Le Pichon*, 1982; *Wortel and Spakman*, 2000]. The peri-Mediterranean consumption of Tethyan remnants may therefore compare with the late stages of assembly of Pangea as the last terrane (Meguma) was accreted and Gondwana approached closely to Laurentia. In the Mediterranean case, consequences of the disposal of such scraps of oceanic lithosphere in a low convergence rate environment can include, for example, delamination of the mantle lithosphere, as in the Alboran Sea [e.g., *Seber et al.*, 1996] and mantle and crust-generated magmatism, exhumation and basin formation affecting the continental crust left behind at the surface (see *Girbacea and Frisch* [1998], *Pearce et al.* [1990], and *Aldanmaz et al.* [2000] for examples within the Carpathians, eastern, and western Anatolia, respectively).

[37] Clearly, the thermal input generated by such a synconvergence lithospheric event, in addition to generating the Devonian granitoids and Late Devonian Mafic Intrusives, lead to rapid exhumation and ultimately aided in Devonian-Carboniferous basin formation. We further speculate that during continued convergence the mantle-generated and related magmatic heat would have allowed the flow of the thermally softened midcrust and lower crust detached from an upper crustal superstructure in which early (pre-SMB) structures were preserved [*Beaumont et al.*, 2004; *Culshaw et al.*, 2004]. The hypothesis of lower crustal flow beneath a stiff upper crustal lid offers an explanation for several features (Figure 7b). Most notably, the occurrence of several samples of high-grade lower crustal tectonites (xenoliths, fault-breccia inclusions) with metamorphic ages similar to pluton ages is reconciled with upper crustal posttectonic isograds. Secondly, the lower crustal flow may have been intimately related to superstructure gold mineralization, as in the Archean Superior Province where young, lower crustal flow accompanied gold mineralization in shear zones formed within old, upper crustal structures [*Krogh*, 1993]. A further interesting corollary of the lower crustal flow hypothesis for syn- to post-SMB development is an explanation for the emplacement of the Liscomb Complex as a type of core complex forming



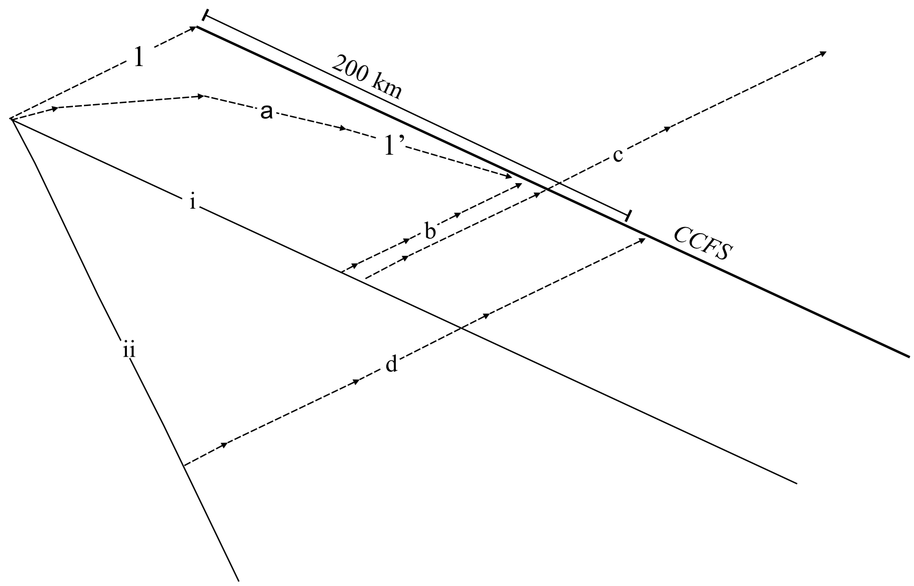


Figure 8. Real and postulated Carboniferous structures in and adjacent to the east end of the fold belt. (top) The label 1, orientation of fold axial trace from south west of Halifax (unaffected by bending adjacent to CCFS) projected to CCFS; 1′, deformed axial trace of same fold as in 1 (now affected by bending adjacent to CCFS) followed to CCFS; 2, axial traces of overturned first order anticlinoria seen on sections A-A′ and B-B′ (Figure 5), same anticlinorium on D-D′ is upright; 3, fold hinges in Late Devonian–Carboniferous strata of Saint Marys Basin [from *Murphy*, 2003]. Unit codes are as in Figure 1. (bottom) Some possible deformation paths for developing the bend in the fold axial traces (1′ in Figure 8 (top), a in Figure 8 (bottom)). The axial traces are shown in several starting locations (b, c, and d) dictated by amount of inferred Late Devonian Carboniferous displacement along CCFS and end-member displacement trajectories (i, pure strike slip, and ii, transpressive, perpendicular to assumed original fold hinge trend).

when, under certain conditions of surficial erosion, the lower crustal flow penetrates into a locally attenuated superstructure [*Beaumont et al.*, 2001]. Finally, the idea of a stiff superstructure overlying a soft infrastructure is consistent with the suggestion that the SMB (and other Devonian plutons, as suggested by this study) was emplaced along the interface of a stiff lid allowing it to push down into a soft substrate. This hypothesis, based on geodynamic models, supports the linkage between all circa 370 Ma events suggested by earlier workers [e.g., *Kontak et al.*, 1990].

6.7. Postexhumation Carboniferous Modification of the Fold Belt?

[38] We argued above against the influence of faults (rooting within the basement or at the detachment) in the pre-SMB formation of the largest folds, however faulting at the detachment and penetrating into the Meguma sediments may have become important after exhumation of the fold belt (post-SMB; Figure 7c). Some of the largest folds have an asymmetry (Figure 5, arrows; Figure 2, stereonet for East domain) comparable to that imposed on Acadian folds by Carboniferous reworking in the White Rock Formation and Meguma Group in southwest Nova Scotia (Figure 1, Yarmouth area) which has been interpreted as related to faulting soling in the detachment [*Culshaw and Liesa*, 1997]. Development of structures with constant asymmetry (vergence) may be related to the presence of a strong detachment [*Costa and Vendeville*, 2002]. In the case of the Meguma Terrane, we suggest that the detachment became relative strong due to cooling that accompanied post-SMB unroofing. In fact, a weak and strong detachment related to relative depth of burial before and after exhumation would nicely explain the contrast between the pre-unroofing (pre-SMB) more polyclinal fold style and the later locally monoclinal asymmetry, respectively, imposed on the preexisting folds in southwest and eastern Nova Scotia (Figure 8). The additional buckle shortening measured on the eastern sections may be another result of this postexhumation phase.

[39] An additional line of investigation follows from the association of the asymmetric structures with the progressive map plane deflection of NE-SW trending fold hinges toward the CCFS. Figure 8 shows the asymmetric structures in the context of the bend in Meguma fold hinges close to the CCFS: the asymmetric anticlinoria of sections A-A′ and B-B′, which record pre-SMB and Carboniferous deformation, lie on the bend, whereas folds in the Saint Marys Basin, which record only Carboniferous deformation have a much higher angle to the CCFS than the rotated basement folds. This is consistent with the previously noted fact that the ductile strain on the CCFS is no older than late Devonian plutons along the fault and displacement along the CCFS continued in the Late Devonian–Carboniferous. Additional support to the idea that the bending is primarily a Carboniferous effect follows from the amount of dextral displacement (150–200 km) implied by the bending, which is comparable to that given by the Carboniferous restoration of *Murphy and Keppie* [1998] (Figure 8). We interpret the bending to be mostly a Late Devonian–Carboniferous map plane effect of the postulated cold Carboniferous detachment.

[40] Because the amount of Late Devonian–Carboniferous displacement implies the fold belt was further east in its pre-SMB stage, the mode of origin of the bend in the fold traces has potential relevance for the early history of the fold belt. Figure 8 (bottom) shows three end-member deformation schemes accounting for curvature of the fold axial traces. In strike-slip deformation path b-a, axial traces are stretched by heterogeneous simple shear parallel to CCFS creating high levels of hinge parallel stretching, for which there is at present no evidence. In a second strike-slip path, c-a, axial traces initially project beyond the CCFS and must be bent along the fault by strike-slip displacement parallel to CCFS (trajectory i). If bending had been accomplished by layer-parallel simple shear analogous to flexural flow, maximum strains would have been low. This path implies that some Meguma folds lay to the north side of the CCFS earlier in their history. In path d-a, axial traces are displaced perpendicular to assumed original axial trend (trajectory ii). This transpression has approximately equal amounts of pure and simple shear. The high component of pure shear would imply that fold hinges in syntectonic sediments would be at a relatively low angle to the CCFS, about 10°, which is considerably less than the average orientation of hinges in the Saint Marys Basin (data from *Murphy* [2003], mean of 30°, range of 14°–46°).

[41] Given that the Saint Marys Basin fold hinge orientations are inappropriate for transpressive deformation path d-a but that Carboniferous mylonites fabric orientations in the Cobequid Highlands (CH, Figure 8) are consistent with some oblique displacement [*Eisbacher*, 1970], we suggest some path between this and c-a (a path between trajectories i and ii in Figure 8) for Devonian-Carboniferous displacement. This implies that during the Devonian (pre-SMB) development of the fold belt it would have impinged on the Avalon to the north of the CCFS which was itself draped around a promontory on the Laurentian margin that had already influenced the style of terrane accretion [*Lin et al.*, 1994]. A test for this model would be the discovery of Meguma Group rocks to the north of the CCFS.

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