

SIGNIFICANCE OF TRANSCURRENT FAULTING IN EASTERN MAINE AND LOCATION OF THE SUTURE BETWEEN AVALONIA AND NORTH AMERICA

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ABSTRACT. Paleomagnetic data have recently been interpreted to indicate that a northeast-trending transcurrent fault with up to 1500 km of sinistral Carboniferous offset separates the North American craton from rocks of southeastern Maine (Kent and Opdyke, 1978). Five lithotectonic belts in eastern Maine are fragmented and separated by northeast-trending faults, some of which have histories of strike-slip displacement and belong to the regional Norumbega Fault Zone. The stratigraphic, structural, plutonic, and metamorphic histories of the five belts are compared to determine whether these faults are part of the postulated suture zone.

Stratigraphic reconstruction indicates facies changes but general lateral continuity throughout the region. Remnants of a possible pre-Silurian island arc (Miramichi Anticlinorium) and back-arc basin (Calais Cambro-Ordovician Belt) suggest eastward subduction during the Ordovician. Silurian, and Devonian shallow water volcanic rocks (Coastal Volcanic Belt) and deeper water turbidite basins (Fredericton Trough; Chaleur Bay Synclinorium) developed on the Ordovician convergent boundary. Correlation of structural elements also indicates Early to Mid-Paleozoic continuity of the five belts. All experienced Early to Early Middle Devonian Acadian folding, closely followed by regional plutonism at about 400 m.y. Late and post-Acadian faults affected both meta-sedimentary and plutonic rocks, but none significantly displace the contacts between Devonian plutons and their host rocks. Some of the faults have a dextral strike-slip history, but most have been sporadically reactivated and have complex displacements. None appear to have had large-scale sinistral offset.

The boundaries between lithotectonic belts formed no later than Early Devonian, well before the postulated onset of sinistral transcurrent faulting. Eastern Maine, from Eastport to Houlton, has acted as a single tectonic entity and is not the site of a major transcurrent fault boundary between the North American craton and a second continental plate. Any transcurrent fault suture of the type suggested by Kent and Opdyke (1978) must lie northwest of the Chaleur Bay Synclinorium.

INTRODUCTION

Eastern and southeastern Maine are underlain by five lithotectonic belts of pre-Silurian, Silurian, and Silurian/Devonian age that define a deceptively simple structural and stratigraphic framework (fig. 1). Plate-tectonic models for Northern Appalachian orogenesis have located one or more suture zones within this region, using lithofacies from the five belts to reconstruct Early Paleozoic paleogeography (Bird and Dewey, 1970; Poole, 1976; Ruitenberg and others, 1977; Osberg, 1978). These models assume that the present positions of the lithotectonic belts were attained by the telescoping and subduction of a single ocean basin or of a series of oceans and marginal seas separated by small microcontinental blocks.

Recent studies suggest, however, that extensive lateral transport along strike-slip faults may have played a major role in establishing the present configuration. Stewart and Wones (1974) and Wones (1978) have mapped a major zone of northeast-trending right-lateral transport in coastal and eastern Maine (the Norumbega Fault Zone). Right lateral offset of about 30 km is possible within this zone (Wones, personal com-

mun., 1979). Paleomagnetic studies have been interpreted to indicate as much as 1500 km of *left-lateral* Upper Devonian and Carboniferous movement of the Eastport, Maine area relative to the Catskill region of New York (Kent and Opdyke, 1978; Irving, 1979; Brown, 1979). This transport is thought to have brought rocks of the Coastal Volcanic Belt and parts of New Brunswick, Nova Scotia, and Newfoundland from the southern hemisphere to join the rest of North America in the northern hemisphere. The precise location of the suture, or sutures, between cratonic North America and the Coastal Volcanic Belt is unknown.

If either megascopic or mesoscopic lateral movement is responsible for the juxtaposition of otherwise unrelated rocks, the local lithofacies and structural relationships used in constructing the plate tectonic models would be invalid. Enough data now exist from eastern Maine to permit comparison of the histories of the five lithotectonic belts. The purposes of this paper are (1) to compare the stratigraphic, structural, plutonic, and metamorphic histories of the five belts; (2) to determine when the belts arrived at their present configuration; (3) to evaluate the effects of transcurrent faulting in the region and the possibility that there might be a suture between two continental plates.

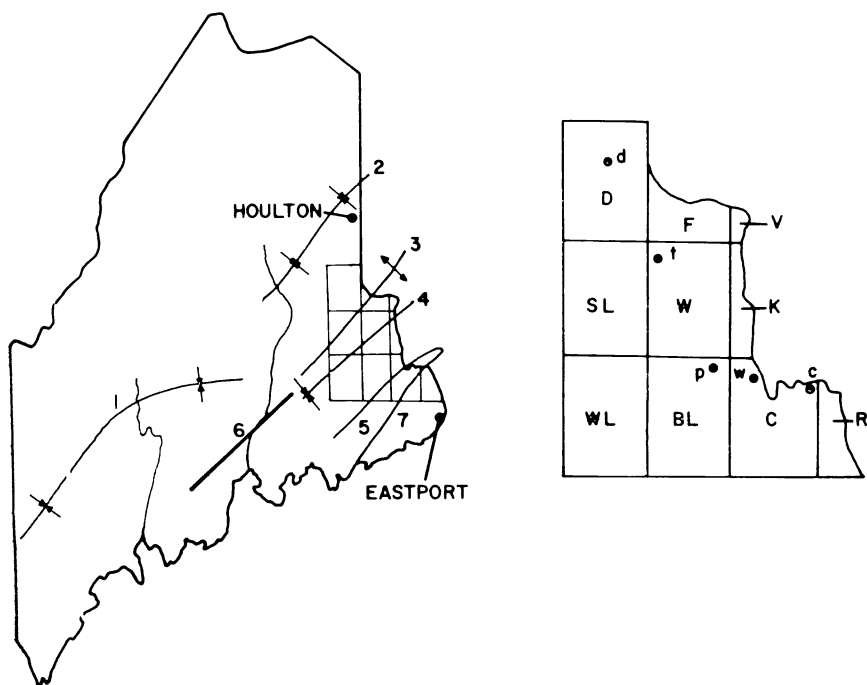


Fig. 1. Geographic and tectonic setting. (1) Merrimack Synclinorium; (2) Chaleur Bay Synclinorium; (3) Miramichi Anticlinorium; (4) Fredericton Trough; (5) Calais Cambro-Ordovician Belt; (6) Norumbega Fault Zone; (7) Coastal Volcanic Belt.

Quadrangles: (D) Danforth; (F) Forest; (V) Vanceboro; (SL) Scraggly Lake; (W) Waite; (K) Kellyland; (WL) Wabassus Lake; (BL) Big Lake; (C) Calais; (R) Robbinston.

Towns: (d) Danforth; (t) Topsfield; (p) Princeton; (w) Woodland; (c) Calais.

STRATIGRAPHY

The area investigated comprises most of the United States portion of the Fredericton 2° sheet and is situated between the towns of Calais and Danforth in eastern Maine (figs. 1, 2). The five northeast-trending lithotectonic belts of eastern and southeastern Maine preserve a record of Early and Middle Paleozoic sedimentation, volcanism, deformation, plutonism, and metamorphism. The present geographic distribution of the stratified and plutonic rocks is shown in figure 2, and the inferred age relationships are summarized in table 1. Boundaries between the five belts are for the most part tectonic, including strike-slip and thrust faults of as yet undetermined amount of offset (Ludman, 1977, 1978a and b).

The dominant tectonic feature of central and western Maine, the Merrimack Synclinorium, can be traced into the Chaleur Bay Synclinorium in the study area. The Chaleur Bay rocks are separated from correlative units in the Fredericton Trough by the pre-Silurian rocks of the Miramichi Anticlinorium, a major structure that appears to plunge southwestward but may connect with the Liberty-Orrington Anticline to the southwest. Other pre-Silurian rocks near Calais separate the Fredericton Trough from the Silurian-Devonian Coastal Volcanic Belt. The pre-Silurian rocks belong to two different zones in Williams' (1979) five-fold subdivision of the Appalachian Orogen. The Miramichi Anticlinorium lies within his Gander Zone, while the Calais Cambro-Ordovician Belt is part of his Avalon Zone. The boundary between these zones is masked by the younger cover rocks of the Fredericton Trough.

Chaleur Bay Synclinorium

Rocks of the Chaleur Bay Synclinorium sequence underlie a large area of Maine and New Brunswick to the north and northwest of that shown in figure 2. Only a small area of figure 2 is underlain by Chaleur Bay rocks, but the boundary between this belt and the Miramichi Anticlinorium lies in the western part of the Danforth quadrangle. Pavlides (1974) has divided the Chaleur Bay stratigraphy near Houlton, Maine (about 55 km north of Danforth) into the Middle Ordovician to Early Silurian Carys Mills Formation (calcareous flysch) and the conformably overlying Silurian Smyrna Mills Formation (less calcareous graywacke, siltstone, and slate).

Argillaceous micritic limestone (SOs) exposed in the northwest corner of the Danforth quadrangle is similar to the ribbon limestones of the Carys Mills Formation, and variably calcareous siltstones and sandstones (also SOs on fig. 2) in the southwestern part of the same quadrangle are probably correlative with the Smyrna Mills Formation. Both rock types are markedly different from the largely non-calcareous sedimentary and volcanic rocks of the Miramichi Anticlinorium sequence to the southeast.

Miramichi Anticlinorium

The Miramichi Anticlinorium is a major structural feature of north-central New Brunswick, but it narrows rapidly toward the southwest,

TABLE 1
Correlation of stratigraphic units

Age	Chaleur Bay Synclinorium	Miramichi Anticlinorium	Fredericton Trough	Calais Cambro- Ordovician Belt	Coastal Volcanic Belt	
					Distal	Proximal
Carboni- ferous			Unnamed redbeds (Cs)			
Devonian	Mapleton Sandstone					Perry Fm.
Silurian	Smyrna Mills Fm. (SOs)		Flume Ridge Fm. (SDs)		Waweig Fm. (SDv)	Eastport Fm.
			Digdeguash Fm. (SDs)		Oak Bay Fm. (SDv)	Hersey Fm.
						Leighton Fm.
						Edmunds Fm.
						Dennys Fm.
Ordovician	Carys Mills Fm. (SOs)	SOv				Quoddy Fm.
		Os				
		OSs				
		EOu		Cookson Fm. (EOu)		
Cambrian						

- - - - : Unconformity

where it plunges beneath or is truncated by younger rocks in Maine. Four unnamed stratigraphic units are recognized in the Miramichi Anticlinorium in the study area and are designated as ϵ Ou, OSs, Os, and SOv.

The oldest unit (ϵ Ou) was originally described by Larrabee, Spencer, and Swift (1965) as interbedded maroon and green slate and was tentatively assigned a Cambro-Ordovician age. The formation crops out in three belts separated by younger rocks, but only in the easternmost belt is a relatively complete section through the unit visible. Faulting in the other two belts has apparently thinned the section considerably, and the following description is based mostly on rocks of the easternmost belt.

Recent mapping has revealed that the major part of this formation consists of light gray to white weathering, green, chlorite-rich feldspathic wacke that occurs in well-graded beds with very subordinate amounts of green slate (Ludman, 1978b). Wacke:slate proportions are typically 5:1 or greater. Beds of hematite-rich and hematite-poor laminated siltstone and mudstone are associated with the thickest-bedded wackes and in some instances form intraclasts up to 20 cm by 1 m that are incorporated near the bases of the graded beds.

The maroon and green rocks described by Larrabee, Spencer, and Swift (1965) flank the wacke on both the northwest and southeast sides of the easternmost outcrop belt and seem to lie higher in the formation than the wacke. Zones up to 30 m thick of thinly interbedded red hematite-rich sandstone, siltstone, and slate alternate with zones composed of green, hematite-free varieties of the same rocks. Pelitic beds are much more abundant than in the lower part of the formation, and some exposures are composed entirely of green or red slate.

The inferred Cambro-Ordovician age for this unit is based on the presence of early isoclinal folds in this formation that have not been found in nearby rocks of known Middle Ordovician (Caradoc) age. Fossils have not been found in ϵ Ou, however, and this age must be considered tentative. Red and green sandstones and slates similar to those of ϵ Ou have been described by Neuman (1967) in the Shin Pond area to the northwest. These rocks, named the Grand Pitch Formation, are also assigned a Cambro-Ordovician age by Neuman based on structural evidence and the presence of the trace fossil *Oldhamia*.

Rocks of Ordovician, Ordovician(?), and Silurian(?) age flank the Cambro-Ordovician rocks on both sides of the main (eastern) outcrop belt and are divided into three units. Gray turbiditic sedimentary rocks (OSs) are immediately adjacent to ϵ Ou in all three belts. Contacts with ϵ Ou in the three belts on the northwest flank of the Miramichi Anticlinorium are apparently conformable, but the contact on the east flank is modified by faulting. On the northwest flank, rocks of OSs are generally graywacke and slate in thick (15 cm-1 m), well graded beds. These thick-bedded rocks are intercalated with zones of thinner bedded, finer grained siltstones interlayered with slate. Graywacke is dominant in the thick-bedded zones, slate in the thin-bedded exposures. On the southeast flank of the anticlinorium, the thinner bedded rocks are dominant. There, gray

slate and lighter gray graywacke are interbedded on a scale of 1 to 10 cm and occur in thin graded beds. Cordierite porphyroblasts are prominently developed in the pelitic parts of the graded beds on both flanks of the anticlinorium.

A distinctive unit (Os) composed almost entirely of rusty-weathering sandstone, siltstone, and carbonaceous pelite forms narrow outcrop bands adjacent to OSs on the northwest flank of the anticlinorium but has been faulted out on the southeast with the exception of a single sliver that could not be shown at the scale of figure 2. Graptolites from Os pelites in the Danforth quadrangle (Larrabee and Spencer, 1963) date the formation as Middle Ordovician (Caradocian; Neuman, personal commun., 1978). Larrabee, Spencer, and Swift (1965) suggested a Silurian age for the turbiditic rocks mapped as OSs, but an Ordovician age is postulated here because of their position between rocks of Cambro-Ordovician(?) and Middle Ordovician age.

Dominantly volcanic rocks (SOv) are in seemingly conformable contact with Os on the northwest but in fault contact with OSs to the southeast. Chalky white-weathering, partly silicified felsic tuffs and flows form distinct ridges on the west flank and are interlayered with volcanoclastic sedimentary rocks, minor tuffaceous agglomerates, and sparse mafic tuffs. The volcanic rocks on the southeast flank of the anticlinorium are strongly sheared but are identifiable as mafic tuffs and flows.

Fredericton Trough

Silurian(?) and Silurian and Devonian(?) rocks of the Fredericton Trough, designated as SDs in figure 2, are in fault contact with rocks of the Miramichi Anticlinorium to the northwest and Cambro-Ordovician rocks to the southeast. Two formations are recognized but not separated on the map. The oldest rocks are the non-calcareous turbidites of the Digdeguash Formation (Ruitenbergh, 1967; Ruitenbergh and Ludman, 1978). The Digdeguash consists of variably but generally very well graded beds of graywacke and polymictic granule conglomerate with variable amounts of dark gray slate. Beds range from a few centimeters to over 1.5 m in thickness, and the graywacke:slate ratio from 10:1 to 1:2. A few tuffaceous interbeds and one calcareous layer have been observed, but these amount to far less than 1 percent of the formation. Clasts in the coarser Digdeguash rocks include felsic volcanic fragments, chert, quartzite, and rare schist fragments in addition to monomineralic clasts.

The Digdeguash is overlain conformably by the generally calcareous turbidites of the Flume Ridge Formation. Some zones in the Flume Ridge consist of massive calcareous and non-calcareous sandstones, but others are well-graded calcareous sandstone, siltstone, and slate. Chlorite-grade exposures commonly contain ferroan carbonate in both sandstone and pelite in addition to calcite.

Ruitenbergh (1967) assigned a Silurian age to the Digdeguash and an Early Devonian age to the Flume Ridge based on mapped relationships with fossiliferous rocks of the Coastal Volcanic Belt in New Brunswick,

but fossils have not yet been found in Fredericton Trough rocks and their age is uncertain. The Flume Ridge is very similar to, and probably correlative with, the Bucksport Formation of the Penobscot Bay area to the southwest (Stewart and Wones, 1974), but no Digdeguash equivalent has been recognized there.

The rocks of the Fredericton Trough indicate filling of an originally deep basin, with the change from non-calcareous Digdeguash sedimentation to calcareous Flume Ridge deposition suggesting a shallowing of the water. Much of the felsic volcanic debris in the Digdeguash may have been derived from an eroded island arc, but quartz and schist fragments indicate a continental source as well.

Calais Cambro-Ordovician Belt

Cambrian(?) and Ordovician rocks mapped as the Cookson Formation (Ruitenbergh, 1967; Ruitenbergh and Ludman, 1978) form an outcrop belt in the Calais and Big Lake quadrangles (EOu in fig. 2) that can be traced along strike to both northeast and southwest. The Cookson contains a variety of rock types, all pyritiferous and hence rusty weathering. Lithologies present include: quartzite, black carbonaceous pelite, thick and thin-bedded graywacke and slate, massive graywacke, pillowed and massive basalt with black carbonaceous slate and chert interbeds, tuffaceous basalt, and sparse calcareous sandstones. Intense folding, faulting, and plutonism obscure internal contacts within the Cookson, but quartzites are thought to be the oldest part of the formation. Pillow basalts with their associated sedimentary rocks probably belong near the top.

Graptolites from the type locality on Cookson Island in Oak Bay, New Brunswick, indicate an Early Ordovician (Tremadocian) age for a black shale thought to lie near the top of the formation (see Ruitenbergh and Ludman, 1978). Much of the Cookson is older and probably of Cambrian age. Some, including the volcanic section, is younger. The Cookson lithologic suite indicates a deep-water restricted (euxinic) basin that periodically received large amounts of material by turbidity current deposition and underwent volcanism in its later stages.

Coastal Volcanic Belt

The stratigraphy of the Coastal Volcanic Belt has been studied in detail by Gates (1975, 1978), who described a sequence of Silurian through Early Devonian felsic and mafic volcanic rocks interbedded with variably fossiliferous sedimentary rocks in quadrangles south of the study area (see table 1). A distal facies of the Coastal Volcanic Belt (SDv) crops out along the United States-Canada border in the Calais and Robbinston quadrangles as small outliers and more extensively along strike in adjacent New Brunswick. More typical proximal volcanic rocks crop out in the southeast corner of the Calais quadrangle.

The distal facies consists of the Oak Bay and Waweig formations (Ruitenbergh, 1967). Polymictic conglomerate of the Oak Bay Formation exposed in the St. Croix River near Calais contains well rounded but

tectonically flattened cobbles of tonalite, granite, volcanic rocks, quartzite, and limestone. Cumming (1967) reported a Silurian (Llandoveryian) pentamerid brachiopod from one limestone clast in the Oak Bay at the type locality in New Brunswick. The formation rests unconformably on the fossiliferous Tremadocian black shale of the Cookson Formation at Cookson Island a few kilometers northeast of Calais but is in fault contact with a different Cookson lithology at Calais.

The Oak Bay grades rapidly upward into the Waweig Formation, a sequence of fine-grained calcareous and non-calcareous sandstones, siltstones, and mudstones with a few thin shell-hash beds. Tuffaceous interbeds become abundant in the Waweig toward the east, demonstrating its affinity to the Coastal Volcanic Belt. Pickerill (1976) identified a shallow water *Salopina* fauna in the Waweig that indicates a latest Silurian (Pridoli) age for at least part of the formation and demonstrates its equivalence to the Leighton Formation of the Coastal Volcanic Belt proximal facies. The Oak Bay is essentially a basal conglomerate of the Waweig. Its precise age is not known, but it must be older than Pridoli (the age of the Waweig fossils) and younger than the Llandoveryian age of the fossils found in its clasts.

Gates (1975) has shown that the Coastal Volcanic Belt sequence was formed around a series of volcanic islands separated by shallow water, but there is some dispute about the tectonic setting of this environment. Gates (1978) cites steep syndepositional normal faults and the bimodal nature of the volcanic rocks as evidence for a rifting environment during Silurian and Early Devonian times. Others, however, have suggested that the suite represents an ensialic island arc associated with Silurian and Devonian subduction (Osberg, 1978; Rast and Stringer, 1975; Ruitenberg and others, 1977). The rocks in the United States portion of the Fredericton 2° sheet provide little insight into this problem.

Carboniferous(?) Rocks

All the stratified rocks described above have been strongly deformed and variably metamorphosed. Unmetamorphosed, only slightly deformed redbeds are exposed in narrow fault blocks within the Fredericton Trough near its boundary with the Miramichi Anticlinorium (fig. 2). These rocks include: (1) polymictic boulder and cobble conglomerates containing well rounded clasts of metamorphosed rock types from the Miramichi COu unit, unmetamorphosed red and gray sandstones, and sparse granite fragments; (2) fluvial deposits consisting of cross-bedded channel sandstones with lag gravel deposits, fine grained sandstones, and dark red mudstones; (3) debris flows consisting of a dark red, hematite-rich matrix mudstone supporting cobbles of metamorphosed and unmetamorphosed sedimentary rocks.

The redbeds are younger than the last major folding and igneous intrusion in the study area and are very similar to rocks of known Carboniferous age in adjacent New Brunswick. A Carboniferous age is likely,

but since the last major folding in the region appears to have been Early Devonian (see below), a Middle or Late Devonian age is also possible.

DEFORMATION

Each of the lithotectonic belts contains a complex record of folding, faulting, and plutonism. Only the Carboniferous(?) rocks, deposited after most of this deformation, have escaped lightly, and even they are tilted, dipping at 60° to 80°. Structural elements and relationships within the Miramichi Anticlinorium, Fredericton Trough, and Calais Cambro-Ordovician Belt are discussed below. They are compared with data from the other two belts compiled by Pavlides (1974) and Gates (1975, 1978) in figure 3. In each of the belts discussed here, episodes of ductile deformation were followed by a series of brittle events.

Miramichi Anticlinorium

The unnamed Cambro-Ordovician(?) rocks in the core of the Miramichi Anticlinorium have undergone two periods of intense isoclinal folding, whereas only the second of these events has affected the younger units in the map area. The early event strongly deformed the massive graywackes as well as the red and green slates and produced a strongly penetrative cleavage. The later episode resulted in north- and northeast-trending upright isoclinal folds and is responsible for most of the observed map pattern. This second event refolded the early isoclinal folds. Early closures cut by a second cleavage, refolded folds, and inverted folds have been observed in a few large exposures of ϵ Ou.

Three episodes of brittle deformation followed. Northeast-trending shear zones cut most rocks of the anticlinorium, and zones of mylonite separate some of the units. One such fault forms the boundary with the Fredericton Trough. Slickensides and drag folds indicate a complex displacement history, involving sporadic strike-slip and dip-slip movement. The early motion appears to have been right-lateral. These faults are offset by steeply dipping, north-trending dip-slip faults, which are locally accompanied by gently plunging north-trending open folds and a weakly penetrative cleavage. A third stage of faulting occurred along northwest-

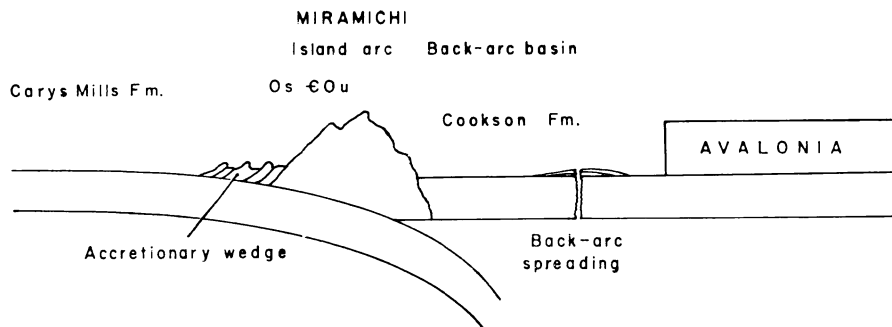


Fig. 3. Tectonic setting during Early to Middle Ordovician times.

to west-trending zones that offset all earlier features with primarily left-lateral displacement.

Fredericton Trough

One set of northeast-trending, upright, tight to isoclinal folds affects both the Flume Ridge and Digdeguash formations throughout the Fredericton Trough. In adjacent New Brunswick, a later episode of recumbent folding is also recorded near the contact with the Cookson Formation (Ruitenbergh, 1967). Ruitenbergh suggested that this folding was associated with a southeast-dipping fault on which the Cookson was thrust westward over the Fredericton Trough rocks. Neither recumbent folds nor gently dipping cleavage has been found in the Fredericton Trough in the map area, although both have been observed in the Cookson. Later faults mapped at the boundary between the Cookson and Fredericton Trough rocks have probably removed the structural zone in which the evidence would have been preserved.

A sequence of brittle events similar to that of the Miramichi Anticlinorium followed the isoclinal folding. Steeply dipping northeast-trending faults with histories of strike-slip, dip-slip, and oblique-slip separation cut the isoclinal folds and axial plane cleavage. Gently plunging, north-trending open folds deform earlier structures and are associated with a second stage of north-trending high-angle faults. Northwest- and west-trending faults cut all earlier structural elements.

The Carboniferous(?) rocks have been tilted to steep dips in fault blocks that formed during late dip-slip reactivation of the earliest northeast-trending faults. This reactivation appears to have been the last significant deformation of the Fredericton Trough.

Calais Cambro-Ordovician Belt

Most of the events recorded in the Fredericton Trough are also observed in the Cookson Formation, including a period of intense isoclinal folding with nearly vertical, northeast-trending axial planes, and a later history of northeast-, north-, and west-northwest trending faulting. The Cookson rocks, however, also record an episode of recumbent folding that occurred between the isoclinal folding and early stages of northeast-trending faulting. Small-scale recumbent folds with weakly developed cleavage deform early cleavage and are associated in some instances with small east-over-west thrusts with separations up to a few meters. These thrusts are concentrated near the boundary with the Fredericton Trough and represent the episode of thrusting described by Ruitenbergh (1967). At one time, the thrust faults probably formed the contact between the two belts, but later northeast- and north-trending faults now separate them.

The Outer Belts

Deformation in the Chaleur Bay Synclinorium and Coastal Volcanic Belt has been summarized by Pavlides (1974) and Gates (1975, 1978), respectively. Their histories are very similar. In the Chaleur Bay Synclinorium, an early period of upwarping indicated by local unconformi-

ties was followed by sedimentation and then a climactic episode of folding. Upright, tight to isoclinal folds were produced whose axial surfaces parallel those formed during the second episode of folding in the Miramichi rocks. In the Coastal Volcanic Belt, an early syndepositional period of extension was followed by extensive volcanism and then a climactic period of folding. The folds trend northeast, parallel to those in the adjacent Cookson Formation. They are relatively open structures but become tighter and almost isoclinal to the northwest near the contact with the Calais Cambro-Ordovician Belt.

PLUTONISM

Intrusive igneous activity followed folding in all five belts and was widespread throughout the map area. To the north, felsic plutons in the Forest and Danforth quadrangles (Pokiok Batholith) and the Scraggly Lake and Waite quadrangles (Bottle Lake Pluton) cut isoclinal folds in the Chaleur Bay Synclinorium and both generations of folds in the Miramichi Anticlinorium. To the south, large volumes of mafic rocks are also present. Mafic plutonism preceded felsic activity in all instances, and mafic rocks intrude folded strata in the three southernmost lithotectonic belts. Most of the mafic rock is found in a few large layered bodies such as the Pocomoonshine Gabbro-Diorite in the Big Lake quadrangle (Westerman, 1973) and the St. Stephen Gabbro at the Maine-New Brunswick border in Calais, but there are also several smaller bodies scattered through the Calais Cambro-Ordovician Belt. Some of the smaller bodies are as well layered as the larger ones. Closely spaced episodes of felsic plutonism followed mafic activity and resulted in numerous plutons whose temporal relationships have been detailed by Amos (1963) and Abbott (1978).

Relationships between plutonism and folding are clear, so that radiometric dating of the igneous rocks provides minimum ages for the ductile deformation (see below). Relationships between faulting and plutonism, however, are less well understood; in many areas the two appear to have been contemporaneous. In a few instances, bracketed relationships permit dating of the brittle deformation by dating the plutons (Ludman and Brueckner, in preparation).

METAMORPHISM

Low grade regional metamorphism accompanied tight and isoclinal folding in all belts and has affected all stratified rocks in the study area except the Carboniferous(?) redbeds. North- to northeast-trending foliations defined by muscovite and chlorite flakes are axial planar to the major folds in all five belts. Regional metamorphic grade is uniformly of the lower greenschist facies throughout the region, and in most exposures bedding and other primary features such as cross-laminations, graded bedding, and scour-and-fill structures are preserved.

The multiply folded COu rocks in the Miramichi Anticlinorium have been metamorphosed twice. Their dominant foliation parallels that

found in the younger rocks that flank ϵ Ou and is axial planar to the second set of isoclinal folds. An older, much more weakly defined parallelism of chlorite and muscovite flakes parallels axial planes of the earlier folds. The early foliation shows no sign of retrograde metamorphism, suggesting that the first metamorphism was also of low intensity.

Broad contact metamorphic aureoles surrounding the plutonic rocks are superimposed on the low-grade regionally metamorphosed terrane. The most intense recrystallization is found in the inner parts of aureoles around the mafic plutons, and in some areas the host rock was partially melted. Thus, gneissic rocks in the Calais and Big Lake quadrangles are the result of contact metamorphic anatexis of Cookson and Digdeguash wackes and do not represent high grade regional metamorphism (Ludman, 1978c).

DISCUSSION

Northeast-trending shear zones and faults shown in figure 2 define a broad zone of cataclasis that extends for at least 45 km across strike between Calais and Topsfield. It is through this zone that Kent and Opdyke (1978) drew their major transcurrent fault. Although they call upon sinistral separation, mapping has shown dominantly dextral separation in early stages of faulting, followed by dip-slip activity. Interpretation of the complete displacement history in the zone of cataclasis is difficult because of the reactivation of many of the faults, however, and two lines of evidence were used to evaluate the possibility that this zone might represent a suture between cratonic North America and an Avalonian microcontinent as postulated by Kent and Opdyke (1978) and Irving (1979): (1) the degree of continuity of stratigraphic, structural, and metamorphic features across the proposed suture was analyzed, and (2) the ages of the boundaries between lithotectonic blocks were used to determine how long the presently juxtaposed rocks have been in contact with one another.

Continuity across the Cataclastic Zone

Juxtaposition of exotic lithofacies or metamorphic terranes and abrupt discontinuity of structural elements across the proposed suture would argue strongly for a major tectonic break in the region. Analysis of stratigraphic, structural, and metamorphic features, however, suggest little, if any, large scale discontinuity.

Stratigraphic correlation.—Regional correlations shown in table 1 have been used to reconstruct paleogeographic relationships for pre-Silurian and Silurian/Devonian times, and these fit well with the recent plate tectonic models (fig. 3). The Miramichi Anticlinorium section represents the foundation of an Ordovician island arc system in which subduction was directed toward the southeast, presumably beneath the Precambrian rocks now exposed near St. John, New Brunswick (Osberg, 1978; Ruitenberg and others, 1977; Rast and Stringer, 1975). The Cookson Formation represents partial filling of a marginal sea in which back-arc spreading provided access for the late Cookson basaltic volcanism. Ex-

tension during back-arc spreading may have thinned the crust beneath the Cookson to the extent that it became the locus of mafic plutonism during later deformation. There is no indication that the Cookson marginal basin closed during the Ordovician. Thus, the earliest Silurian sedimentation in the Fredericton Trough (Digdeguash Formation) may have been a continued filling of this basin with materials eroded from the Miramichi arc to the west and Avalonia to the east. This would account for the mixture of volcanic and continental debris in the Digdeguash.

The Coastal Volcanic Belt is the key to understanding the Silurian and Early Devonian paleogeography of the region. If it was an island arc, it and the Fredericton Trough could represent a Silurian-Devonian island arc back-arc-basin pair comparable to the Ordovician Miramichi arc/Cookson basin. The direction of subduction, however, would have reversed and become northwestward, presumably beneath the Miramichi region. This subduction would have closed the remains of the Cookson marginal sea and brought Avalonia into contact with the basement in the Miramichi arc. If, however, the Coastal Volcanic Belt represents an extensional rather than a compressional environment as argued by Gates (1978), it and the Fredericton Trough could simply have formed as rift basins. During this time span, the Chaleur Bay sequence resulted from filling of a small basin to the west of the eroded Miramichi arc.

In either instance, there do not appear to be readily recognizable exotic terranes in the region. Lithofacies distribution patterns can be explained by positions relative to convergent plate boundaries for the Ordovician and to either compressional or extensional environments during the Silurian and Early Devonian.

A similar argument for the absence of exotic materials can be made from the nearly identical regional metamorphic histories of the five lithotectonic belts. There are no abrupt discontinuities in metamorphic zonation across any of the fault or shear zones. These are basically negative arguments and do not disprove the transcurrent suture hypothesis but show that there is no support for it in the stratigraphic and metamorphic record in the area. A more positive argument for lateral continuity across the cataclastic zone can be made from structural data.

Dating and correlation of structural elements.—Precise dating of the deformations described above is difficult because of the scarcity of fossils throughout most of the region and because of the dangers inherent in correlating across boundaries between different belts. Conclusions can be drawn, however, by combining radiometric ages of post-kinematic plutons with the few available fossil-based ages. The results are shown in figure 4, and a synopsis of events indicating the control of estimated ages follows.

Early isoclinal folding in the Miramichi Anticlinorium was apparently the oldest deformation event in the region. It affects only the ϵ Ou unit and is not recorded in the adjacent rocks of known Middle Ordovician age (Os). It is clearly pre-Middle Ordovician but can not be more precisely dated in the study area without faunal evidence for the ages of ϵ Ou and Os. A Taconian affinity is possible but unlikely, since Pavlides

(1974) has demonstrated a Late Ordovician age for that event in northern Maine. Neuman (1967) proposed the name Penobscot Orogeny for a Late Cambrian(?) to Early Ordovician(?) deformation that affected the Grand Pitch Formation in the Shin Pond area, and the early isoclinal folding of ϵ Ou is tentatively correlated with that event.

This Penobscot(?) folding is not recognized in Cambro-Ordovician rock in the Calais area, although part of the unconformity at Cookson Island might conceivably represent contemporaneous uplift. If a major suture separates Calais from Danforth, this would be expected, but less dramatic explanations are equally plausible: (A) compressional deformation in an accretionary wedge on one side of an island arc would not be expected to occur in the extensional back-arc environment; (B) the Calais Cambro-Ordovician rocks were deposited after this folding, suggesting a very old age for the event.

Each of the five lithotectonic belts was affected by a period of intense folding during the Early to Middle Devonian (fig. 4). Attitudes of hinge surfaces and hinge lines remain relatively constant from the Coastal Volcanic Belt to the Chaleur Bay Synclinorium, although the deformation in the east is more open than in the west. This may merely reflect the competence of the thick pile of volcanic rocks in the Coastal Belt. Whether this folding is indeed a single event as suggested by the uniform hinge surface attitudes or rather a fortuitous grouping of different events is the most important problem in regional structural analysis. The precision of dating the (se) event(s) varies from belt to belt, but general conclusions can be reached.

In the Chaleur Bay Synclinorium, where intensely deformed Lower Devonian volcanic rocks are unconformably overlain by relatively undeformed Middle Devonian molasse (Mapleton Sandstone), the age of de-

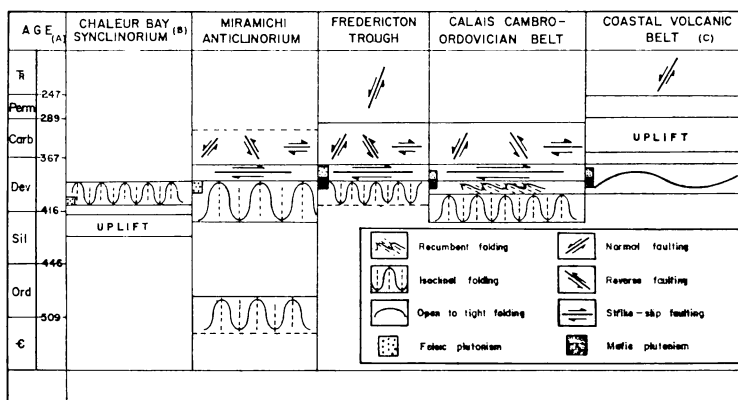


Fig. 4. Correlation of deformational episodes. (A) Dates after Armstrong (1978); (B) after Pavlides, 1974; (C) after Gates, 1975.

formation is narrowly bracketed (Pavlides, 1974). A similar age is indicated in the Coastal Volcanic Belt where deformed Lower Devonian rocks of the Eastport Formation are intruded by the Early Middle Devonian post-kinematic Red Beach Granite (400 m.y.; Spooner and Fairbairn, 1970), and both are unconformably overlain by the Upper Devonian molasse of the Perry Formation (393 ± 6 m.y.; Spooner and Fairbairn, 1970). The styles of deformation were somewhat different, but the timing was nearly identical.

A minimum age of 372 (K/Ar) to 400 (Pb-alpha) m.y. has been determined for northeast-trending upright isoclinal folding in both the Miramichi Anticlinorium and the Fredericton Trough. These ages were determined by Faul and others (1963) for the pink granite facies of the Bottle Lake Pluton, where it intrudes folded rocks of both belts in the vicinity of Topsfield. In the Calais Cambro-Ordovician Belt, a minimum age of approx 400 m.y. is given by the post-kinematic Charlotte and Meddybemps granites (Faul and others, 1963; Spooner and Fairbairn, 1970). The minimum age in all belts is thus approx 400 m.y.

Maximum ages are more difficult to determine in the generally unfossiliferous rocks of the three internal belts. Caradocian (Os) and younger (SOv) rocks are affected in the Miramichi Anticlinorium, indicating a broad possible range of post-Middle Ordovician to pre-400 m.y. In the Fredericton Trough, the age of deformation must be younger than the Flume Ridge Formation (Early Devonian) but older than the post-kinematic Pocomoonshine Gabbro-Diorite (408-423 m.y.; Westerman, 1973). If both the inferred stratigraphic age and the radiometric data are correct, folding and plutonism followed closely on deposition of the Flume Ridge. At the boundary between the Coastal Volcanic Belt and the Calais Cambro-Ordovician Belt on Cookson Island, axial plane cleavage can be traced upward from the Cookson Formation into the overlying Oak Bay and Waweig formations (Stringer, personal commun., 1978), indicating that the folding in the Calais area began no earlier than post-Pridoli.

It is apparent that all five belts experienced a major episode of folding at approximately the same time — Early to Early Middle Devonian. This event is attributed to the Acadian Orogeny and was roughly contemporaneous throughout the region.

Recumbent folding and thrusting of the Cookson Formation over the Digdeguash and Flume Ridge formations followed the early Acadian upright isoclinal folding but preceded the emplacement of gabbros and granites near Woodland, Maine. This deformation is considered to be a later phase of the Acadian Orogeny that was centered on the Cookson Formation because of the incompetence of the sequences of carbonaceous pelite found throughout that formation.

Late brittle deformation followed ductile deformation in all five belts, with trends for the high-angle faults falling into three general groups: northeast, north, and west-northwest. The timing of initial displacement is unclear because faults of all three sets were sporadically reactivated and can now be observed to cut one another. There is the

possibility that the three are actually conjugate (Ludman, 1979), but the most commonly observed sequence is that in which they were listed above.

The age of the northeast-trending faults is of greatest interest since they define the cataclastic zone. Four of the larger faults of this set have been traced to the Penobscot Bay area by Wones (1978) as part of the Norumbega Fault Zone, and one can be traced to the northeast into the Fredericton Fault in New Brunswick. Drag folds indicate that the earliest offset on these faults was right-lateral. All stratified rocks and both the mafic and felsic plutons were affected, but pluton/host rock contacts are offset very little. This, coupled with the fact that small felsic plutons in the Big Lake quadrangle appear to have been emplaced along the trace of one of the northeast-trending faults, suggests that faulting began shortly before and continued through emplacement of the plutons. The latest displacement was of dip-slip nature and resulted in block faulting that preserved the Carboniferous(?) rocks along fault traces in the Waite and Kellyland quadrangles. Similar displacement of known Carboniferous rocks along strike in New Brunswick indicates late or post-Carboniferous movement, perhaps associated with Triassic faulting in the region.

Left-lateral strike-slip faults do exist in the region, but they are the northwest-trending set. Those in the Danforth quadrangle that clearly truncate and offset the northeast-trending faults are cut themselves by the Bottle Lake Pluton at Topsfield or fracture it without offset. It thus appears that the strike-slip displacement along the northeast-trending faults was not only of the wrong sense for the proposed suture, but that it had largely ended by the time that the Bottle Lake Pluton was emplaced.

The deformation histories of the five belts are remarkably similar, particularly with regard to the timing and style of the Acadian Orogeny. Donohoe and Pajari (1973) have demonstrated that the age of this orogeny decreases systematically from southeast to northwest across New Brunswick and Maine, but in the two outer belts where fossil control permits the most precise dating, the ages of deformation are nearly identical. The attitudes of both early Acadian folds and late Acadian faults are also nearly identical throughout the entire map area. These similarities would hardly be expected if there were a suture zone in the midst of the area that separated blocks that had originally been 1500 km apart.

Ages of Boundaries between Lithotectonic Belts

Kent and Opdyke (1978) indicate that the transcurrent fault separating the Coastal Volcanic Belt from cratonic North America was active in very Late Devonian through Carboniferous times. If it can be demonstrated that the five lithotectonic belts had attained their present relationships before that time, the postulated suture would be ruled out within the map area. Enough radiometric and fossil data have now been obtained to date most of these boundaries (table 2). In all instances, the boundaries formed before the Middle Devonian.

TABLE 2
Age control on boundaries between lithotectonic belts

Boundary	Type	Age Control	
		Maximum	Minimum
Coastal Volcanic Belt/	Unconformity (at Oak Bay)	Post-Llandovery	Pridoli (Pre-Waweig)
Calais Cambro-Ordovician Belt	High-angle fault in Calais quadrangle	Siluro-Devonian (after unnamed volcanic rocks)	Early Devonian (404 m.y.) (before Meddybemps Granite)
Calais Cambro-Ordovician Belt/	SE-over-NW thrust fault	Early Devonian(?) (after Flume Ridge Fm.)	Early Devonian(?) (before unnamed gabbros)
Fredericton Trough	North-trending high-angle fault	Early Devonian (after Pocomoonshine Gabbro-Diorite)	Early Devonian(?) (before unnamed felsic plutons)
Fredericton Trough/ Miramichi Anticlinorium	High-angle northeast-trending fault	Early Devonian(?) (after Flume Ridge Fm.)	370-380 m.y. (before pink granite at Topsfield)
Miramichi Anticlinorium/ Chaleur Bay Synclinorium	Northeast-trending fault	Silurian (after Smyrna Mills Formation)	370 m.y. (before Pokiok Batholith)

The only non-tectonic contact is between the Coastal Volcanic Belt and the Calais Cambro-Ordovician Belt at Cookson Island, where there is an unconformity that formed during Middle to Late Silurian time. The contact between the Calais Cambro-Ordovician Belt and the Fredericton Trough is everywhere a fault — a thrust in New Brunswick and the eastern part of the Calais quadrangle and a later high-angle fault to the west and southwest. In both instances the contact formed before emplacement of the Early Devonian gabbros. The Fredericton Trough and Miramichi Anticlinorium are separated by one of the major northeast-trending faults, but that fault is intruded by the Bottle Lake Pluton at Topsfield, indicating that this contact too had formed by at least the Early Devonian. The boundary between the Miramichi Anticlinorium and Chaleur Bay Synclinorium is masked in most places by thick glacial cover, but intense cataclasis and local minor folding indicate that it is also a fault. The Pokiok Batholith intrudes this contact northeast of Danforth, once again demonstrating a pre-Early Devonian joining of the belts.

The five lithotectonic belts have apparently had their present positions relative to one another since at least Early Devonian time, and in one instance, since the Silurian. They have acted as a structural entity since the Early Devonian, and none has since been juxtaposed by transcurrent faults of the age required for the postulated suture.

CONCLUSIONS

All lines of evidence discussed above point toward lateral continuity within the map area, rather than the discontinuity required by a transcurrent fault suture. Thus, there is no evidence for stratigraphic, metamorphic, or structural discontinuity on opposite sides of the cataclastic zone (negative evidence), and there is strong evidence from structural and radiometric age data of continuity across the entire region (positive evidence). Relationships in the map area were inherited from pre-Silurian plate convergence, modified strongly by compression during the Acadian Orogeny, and only slightly affected by post-Acadian events. The five lithotectonic belts in eastern Maine have been a structural unit since Early Devonian times and are not broken anywhere by northeast-trending sinistral strike-slip faults. Lithofacies distribution patterns in the region may thus be used in paleogeographic and tectonic reconstructions.

A northeast-trending cataclastic zone containing several strike-slip faults does exist between Calais and Topsfield, but its activity ended before that of the postulated suture would have begun, and it was of the opposite sense of offset. Left-lateral faults in the region trend west-northwest. They and the northeast-trending right-lateral faults probably formed as a conjugate set associated with strong east-west compression in the later stages of the Acadian Orogeny.

Attempts to locate a suture between the Eastport area and the North American craton must focus farther to the north and northwest. If the Coastal Volcanic Belt has undergone 1500 km of lateral displacement, the other belts as far northwest as the Chaleur Bay Synclinorium must have been displaced by the same amount. The suture must lie to the northwest of the study area.

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