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SUBSIDENCE IN LATE PALEOZOIC BASINS IN THE NORTHERN APPALACHIANS

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Abstract. During the interval between continental collision in the Devonian and continental breakup in the Triassic the northern Appalachians became the site of a wide plate boundary zone of dominantly right-lateral strike slip. As is typical of intracontinental transforms, tectonism was both diachronous and rapidly variable along strike through regimes of 'pure' strike slip, transpressional deformation, and rapid subsidence of extensional basins. Up to 9 km of mainly nonmarine, clastic sediments accumulated in these local depocenters, which subsided episodically in two stages: (1) an initial phase of stretching and thinning of the lithosphere, when subsidence was rapid, fault controlled, and often accompanied by volcanism and (2) a subsequent phase of gradual thermal subsidence, during which the depositional basins expanded to bury the earlier border faults and progressively younger sedimentary units onlapped basement. The largest depocenter, the Magdalen Basin, opened as a pull-apart between strike slip faults in Newfoundland and New Brunswick from late Devonian to early Carboniferous. Subsequent thermal subsidence affected a large area during medial and late Carboniferous, a phenomenon that is well recorded to the north and west, where no later tectonism occurred. In areas to the south and east of the basin, strike slip on other faults continued into the time of thermal subsidence, introducing complications such as localized transpressional deformation and rapid subsidence in smaller pull-aparts.

INTRODUCTION

McKenzie [1978] has shown that the subsidence history of many sedimentary basins can be modelled in terms of an initial phase of stretching of the lithosphere (rift phase), followed by an episode of exponentially declining thermal subsidence (cooling phase) (Figure 1). This two-stage evolution is particularly well illustrated by the cross-sectional 'steer's head' configuration that typifies many undeformed basins straddling rifts such as the North Sea and Michigan basins [McKenzie, 1978; Dewey and Pitman, 1982]. Similarly, Atlantic-type continental margins, which can be considered halves of rifts, subside owing to thermal decay following an initial episode of extension [Pitman, 1978]. Stretching of the lithosphere is ordinarily expressed at the surface by the formation and sinking of grabens that fill rapidly with such rift facies as growth-fault fanglomerates and more distal fluviolacustrine or marine sediments. Stretching is accompanied by increased heat flow and, in many cases, by alkaline to tholeiitic volcanism. Following the rift phase, dropping of isotherms causes the subsidence of an enlarged sedimentary basin that buries the initial rift beneath a

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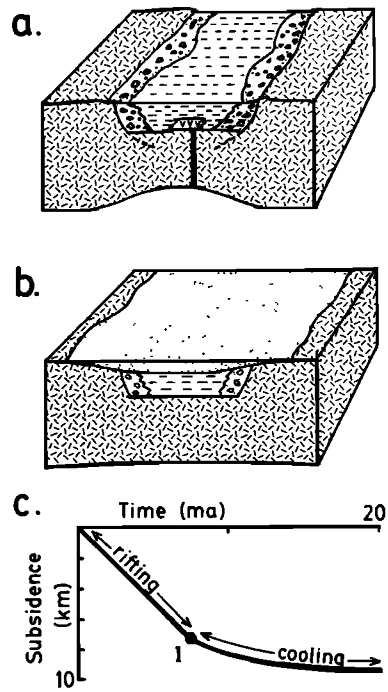

Fig. 1. (a) Block diagram illustrating the initial stretching phase in an idealized rift. Growth faults control thickness and facies of rapidly deposited, immature clastics shed from local source areas. (b) Subsequent phase of thermal subsidence, which affects a wider area but proceeds at a slower rate. Mature clastics are deposited farther from source areas. (c) Idealized subsidence curve of a basin formed as a result of stretching of the lithosphere by a factor of about $\beta = 2$. The inflection point of the curve, I, is the initial subsidence.

blanket of more mature clastic sediments deposited more slowly. Recent subsidence studies have dealt mainly with presently subsiding, undeformed rifts and passive margins [Royden and Keen, 1980; Royden et al., 1980; Sclater et al., 1980; LePichon and Sibuet, 1981]. Sclater et al. [1980] have extended the application of the McKenzie [1978] model to the subsidence of pull-aparts in the Carpathian region. Although many older basins have suffered deformation and do not contribute accurate stratigraphic data to these quantitative discussions, they too exhibit the familiar two-stage evolution qualitatively. Here I apply McKenzie's [1978] model to the deformed upper Paleozoic rocks of the northern Appalachians.

During the interval between continental collision in the Devonian and continental breakup in the Triassic, up to 9 km of mainly nonmarine, clastic sediments were deposited in a number of interconnected basins, which subsided within a wide intracontinental transform fault zone [Webb, 1969; Belt, 1968; Bradley, 1981]. Early workers in the Canadian Maritimes recognized that sedimentation during early and medial Carboniferous was largely controlled by high-angle faults that divided the composite Fundy Basin (Figure 2) into series of subbasins and intervening basement massifs [Bell, 1929]. Some of these basins have now been recognized as pull-aparts [Fralick and Schenk, 1980; McMaster et al., 1980; McCabe

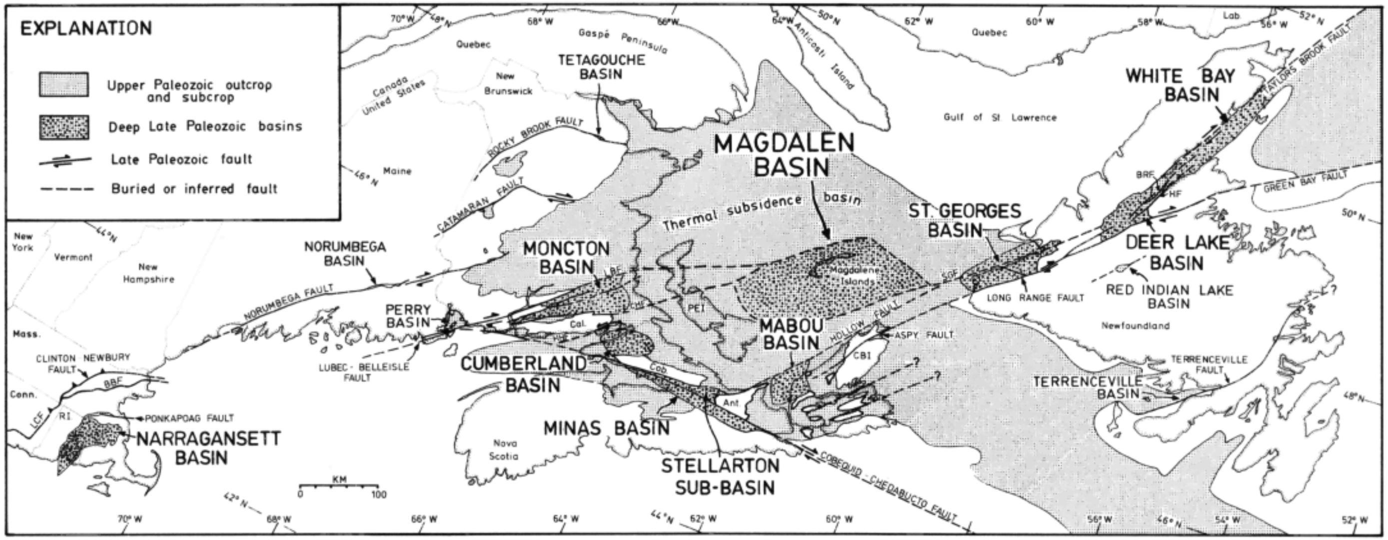

Fig. 2. Late Paleozoic basins and faults in the northern Appalachians. Abbreviations used are as follows: CBI, Cape Breton Island; PEI, Prince Edward Island; RI, Rhode Island; Cal, Caledonia Massif; Cob, Cobequid Massif; Ant, Antigonish Massif; HF, Hampden fault; BRF, Birchy Ridge fault; HHF, Harvey-Hopewell fault; CHF, Clover Hill-Pollet River fault; PBF, Petitcodiac-Berry's Mills fault; LBF, Lubec-Belleisle fault; BBF, Bloody Bluff fault; LCF, Lake Char fault. Many other faults are not shown. Composite Fundy Basin refers to the area of contiguous upper Paleozoic strata in New Brunswick, Nova Scotia, Prince Edward Island, southwestern Newfoundland, and the Gulf of St. Lawrence.

et al., 1980; Hyde and Ware, 1981]. Fault control of sedimentation died out during late Carboniferous, and the Fundy Basin simultaneously expanded beyond its former limits onto pre-Carboniferous basement. Thus, on a regional scale, the late Paleozoic basins of the northern Appalachians evolved through the two stages for which McKenzie's [1978] model accounts. However, the overlapping effects of local extension, local transpressional deformation, and regional thermal subsidence introduce complexities not encountered in relatively simple rifts. The present paper is an attempt to rationalize some of these complexities and to explain the broader-scale aspects of the upper Paleozoic of the northern Appalachians in terms of the diachronous two-stage subsidence of extensional basins within an intracontinental transform fault zone.

GEOLOGIC SETTING AND EVIDENCE FOR STRIKE SLIP

Medial and Late Devonian

Upper Paleozoic strata in the northern Appalachians lie unconformably on rocks that were deformed, metamorphosed, and intruded as a result of continental collision during the medial Devonian Acadian orogeny [Rodgers, 1970; Bird and Dewey, 1970; McKerrow and Ziegler, 1972]. Because of a scarcity of sedimentary rocks of appropriate age, the detailed late Acadian paleogeography cannot be known. Acadian convergence was sufficient to create a range of mountains, documented by facies, paleocurrents, and thickness of molasse (nonmarine fluvial facies) in the foreland basins of the Gaspe Peninsula [Beland, 1969], and the Catskill 'delta' in New York [Allen and Friend, 1968], which indicate source areas within the orogen. Coexisting aluminosilicates indicate that rocks now at the surface in central New England were metamorphosed at depths of about 15 km [Thompson and Norton, 1968]. The height of Acadian mountains in New England can be estimated at 4 km by adding this now eroded column of rock to the present crustal thickness of 40 km [Taylor et al., 1980], assuming an Airy model of isostatic compensation, a mantle density of 3.3, and a crustal density of 2.7. Late Devonian was a time dominated by the intrusion of postkinematic, high-potash minimum melting granites [Loiselle and Ayuso, 1979] that indicate partial melting of abnormally thickened continental crust [Dewey and Burke, 1973; Dewey and Kidd, 1974]. Middle and Upper Devonian strata are preserved today within the orogen in only a few isolated fault-bounded basins [Donohoe and Pajari, 1973; Donohoe, 1979; Donohoe and Fralick, 1980] and consist of volcanics and nonmarine clastics derived from nearby, elevated source terranes. The late Devonian paleogeographic picture that emerges is of a region of lofty mountains containing a few fault-bounded intermontane basins. Whether or not these basins subsided within the strike slip regime that came to dominate during the Carboniferous is not known.

Latest Devonian through Early Permian

From the end of the Devonian to early Permian, sedimentation was widespread and probably continuous on a regional scale, although the section is punctuated by local unconformities and is nowhere complete [Kelley, 1967]. Figure 2 illustrates the abundance of these primarily Carboniferous rocks, mainly in the Atlantic Provinces of Canada and adjacent offshore areas. The Maritime Canadian sequence (Figure 3) has traditionally been divided, in ascending stratigraphic order, into the Horton, Windsor, Canso, Riversdale, Cumberland, and Pictou groups [Bell, 1929]. Because

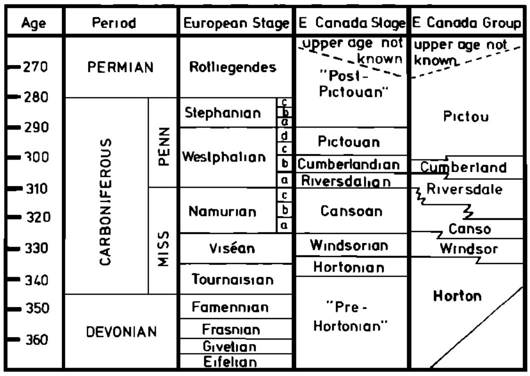

Fig. 3. Stratigraphic terminology for the late Paleozoic of the northern Appalachians. Columns 3 and 5 are adapted from Howie and Barss [1975a], column 4 from Belt [1968], and column 1 from van Eysinga [1975].

palynological studies have shown that these units are, in part, time-transgressive facies equivalents [Hacquebard, 1960; Belt, 1964, 1965; Howie and Barss, 1975a], it is more profitable, in parts of the ensuing discussion, to treat the divisions as stages, defined mainly by spores from reference sections [Belt, 1964].

Horton Group sediments were mainly deposited in fault-bounded basins and, typically, vary rapidly through fanglomerate, fluvial, and lacustrine (including nonmarine limestone and evaporite) facies [Belt, 1968; Bell, 1958; Howie and Barss, 1975a]. These red clastics are significantly coarser and less mature than those deposited during late Carboniferous time [Van de Poll, 1972]. Overlying rocks of Windsorian age (limestones, shales, and evaporites) record shallow marine conditions during medial and late Visean time over much of Maritime Canada, but coarse red fanglomerates near many faults [for example, Schenk, 1969] indicate that the tectonic environment was much the same as that during Horton deposition, despite a regional transgression. The Windsor evaporites locally reach thicknesses in excess of 1 km [Howie and Barss, 1975a]. Subsequent strata of Cansoan through Cumberlandian age (latest Visean through Westphalian B) are mainly fluvial and lacustrine clastics, and fanglomerates are less abundant. Fluvial coal measures of the Upper Carboniferous to Lower Permian Pictou group blanket all earlier Carboniferous units and overstep basement [Kelley, 1967]. Each of the Carboniferous groups locally attains a thickness of 3 km, but because of shifting centers of deposition the maximum total thickness in any one place is not known to exceed 9.1 km [Howie and Barss, 1975a].

Strike Slip Tectonic Framework

A number of workers have emphasized different local aspects of the geologic record in developing a variety of conflicting interpretations of the regional tectonic environment [Bell, 1944; Webb, 1969; Belt, 1968; Van de Poll, 1972; Howie and Barss, 1975b]. Evidence that extension, strike slip, and compressional deformation occurred simultaneously within the 'mobile belt' was a particular source of confusion and controversy. Webb [1963, 1969] and Belt [1968], however, showed that these seemingly incompatible or unrelated features of the Carboniferous record could be readily explained with reference to a strike slip environment. It is now apparent from many well-studied modern examples in California, New

Zealand, the Caribbean, and Anatolia that contemporaneous subsidence, deformation, and volcanism are characteristic of intracontinental transforms [Reading, 1980; Crowell, 1974]. Because the regional tectonic framework bears significantly on the ensuing arguments, a summary of the evidence for strike-slip follows.

Northeast and east trending high-angle faults that juxtapose dissimilar basement blocks are a conspicuous feature of the northern Appalachians [Wilson, 1962]. Those of late Paleozoic age believed to be strike slip faults are shown in Figure 2. Cumulative post-Acadian right-lateral offset on the northeast trending faults has been estimated at 160 km in Newfoundland and 200 km in New Brunswick [Webb, 1969]; right-lateral offset on the east trending Cobequid-Chedabucto fault system in Nova Scotia has been estimated at 200 km [Webb, 1969] to 225 km [McCabe et al., 1980]. Because the Carboniferous faults are roughly parallel to the trend of the orogen, they offset recognizable basement features in only a few known cases. The Taylors Brook fault in Newfoundland (Figure 2) cuts a Devonian granite pluton and dextrally offsets the matching halves by 30 km [Lock, 1969]. Across the Green Bay fault in Newfoundland, two limbs of an Acadian fold have been dextrally offset by 25 km (J.F. Dewey, unpublished map, 1970). Webb [1969] and Belt [1969] suggested 100 km of right-lateral offset across the Long Range fault in Newfoundland (Figure 2), based on the correlation of matching parts of a dismembered Precambrian anorthosite pluton. Anderson [1972] determined a maximum dextral displacement of 16 km on the Catamaran fault in New Brunswick (Figure 2), based on the distribution of a distinctive metavolcanic unit. Right-lateral offsets totaling 9 km are indicated along the Clinton-Newbury and related faults in Massachusetts by the map pattern of Silurian volcanics [Shride, 1976]. On other high-angle faults, strike slip has been interpreted from less direct evidence [Reading, 1980]. Webb [1963, 1969] recognized two instances in New Brunswick where Carboniferous alluvial fans were displaced relative to their source terranes, indicating offsets of 65 km on the Lubec-Belleisle fault (dextral) and 16 km on the Harvey-Hopewell fault (sinistral).

Other evidence for strike slip is less direct, but in a regional context provides additional corroboration. Angular unconformities within the Carboniferous section record local deformation that occurred during Tournaisian in the Moncton Basin [Gussow, 1953], at the end of the Tournaisian in the Mabou Basin [Kelley, 1958], during the Visean in the Deer Lake Basin [Belt, 1969; Hyde and Ware, 1981], during Namurian in western Cape Breton Island [Currie, 1977], and during Westphalian B in southern New Brunswick [Webb, 1963]. This deformation, which has been variously labelled the Maritime disturbance [Poole, 1976], the Hercynian orogeny [Rast and Grant, 1973], and the Alleghanian orogeny [Rodgers, 1970], was clearly diachronous and coeval with uninterrupted subsidence elsewhere in the Fundy Basin. Localized alkaline to tholeiitic volcanism, attributed to extension, occurred during Tournaisian in western Cape Breton Island [Kelley and Mackasey, 1965], Visean in the Magdalen Islands [Sanschagrin, 1964], Namurian in southern New Brunswick [Howie and Barss, 1975a], and Westphalian B in the Narragansett Basin [Skehan et al., 1979]. Similarly, numerous local fanglomerates record fault motions with at least some dip slip component from late Devonian through Westphalian [Belt, 1968]. Table 1 summarizes the evidence for diachronous rapid subsidence of various pull-apart basins.

Carboniferous deformation occurred in most areas of thick accumulation, but was strongest in compressional segments of strike slip faults. The style is characterized by asymmetric, overturned, and steeply plunging folds related to thrusts whose vergence is

TABLE 1. Late Paleozoic Strike Slip Basins in the Northern Appalachians

BASIN	AGE	AREA	BASIN FILL	VOLCANISM	COMMENTS	REFERENCES
MAGDALEN	Tournaisian and Visean; possibly also Late Devonian	25,000 sq km	8 km: Horton clastics; Windsor clastics, limestone, evaporites, and volcanics.	Visean: Abundant basalt and andesite within 800 meter section of evaporites and clastics.	Inferred dextral pull-apart formed between strike-slip faults in Newfoundland and New Brunswick. Known mainly from drilling and geophysical surveys. Overlain by extensive thermal subsidence basin.	Howie and Barss, 1975a Sanschagrin, 1964 Sheridan & Drake, 1968 Watts, 1972
DEER LAKE	(1) Tournaisian (2) Late Visean through Namurian	2000 sq km	8 km: Horton clastics; Canso-Riversdale fluvial and lacustrine clastics.	Late Visean: 1.5 meter basalt flow (Hyde, 1981, pers. comm.).	Probably a dextral pull-apart formed about the junction of the Green Bay, Hampden, Taylors Brook, and other parallel faults. Subsidence was interrupted by transpressional deformation during the Visean.	Hyde and Ware, 1981 Belt, 1969
WHITE BAY	Tournaisian	3000 sq km	1.5 km: Horton nonmarine fanglomerate through lacustrine facies. Source areas to east and west.	None known	The basin, located mainly offshore, is located between the dextral Taylors Brook and Hampden Faults. Probably a pull-apart basin.	Baird, 1966 Belt, 1969 Knight, 1982
ST. GEORGES	(1) Tournaisian (2) Late Visean through Namurian	4000 sq km	8 km: Horton clastics; Windsor evaporites and clastics; Canso-Riversdale clastics. Source from Long Range Fault.	None known	A dextral pull-apart bounded on the east by the Long Range Fault and on the west by the offshore St. Georges Fault. Probably opened in two distinct pulses: (1) the southern half during Early Carb.; (2) the entire basin during Medial Carb.	Baird and Cote, 1964 Belt, 1969
MABOU	Tournaisian through Namurian	1500 sq km	7.5 km: Horton clastics; Windsor clastics and evaporites; Canso-Riversdale fluvial and lacustrine clastics.	Late Devonian to Tournaisian: intermediate to siliceous volcanics of Fisset Brook Fm., about 300 meters.	Complex origin in area of Hollow, Aspy, and other unnamed faults in Cape Breton Island. Tectonic environment uncertain.	Belt, 1965 Kelley, 1958 Bell, 1958 Howie and Barss, 1975a Kelley & Mackasey, 1965
STELLARTON	Late Visean through Westphalian B or C	200 sq km	8 km: Nonmarine alluvial fluvial, and lacustrine clastics of Windsor, Canso, Riversdale and Cumberland Groups	None known	Interpreted by Fralick and Schenk (1980) as a dextral pull-apart that opened between the Hollow and Cobequid Faults. Major subsidence during Westphalian A through C; earlier phase recorded by Windsor fanglomerates along Hollow Ft.	Fralick and Schenk, 1980 Bell, 1958 Belt, 1968
MINAS	(1) Tournaisian (2) Namurian B to Westphalian A	600 sq km	4 km: Horton clastics; Windsor limestone and evaporites; Canso-Riversdale fluvial and lacustrine facies.	None known	Interpreted as a dextral pull-apart formed between parallel strands of Cobequid-Chedabucto Fault system. Major subsidence during Canso-Riversdale deposition (includes angular unconf.). Earlier subsidence during Horton deposition.	McCabe et al., 1980 Belt, 1965
CUMBERLAND	Westphalian B	2500 sq km	3.3 km: Coal-bearing fluvial and lacustrine facies of the Cumberland Group.	None known	Complex origin near junction of dextral Cobequid-Chedabucto and sinistral Harvey-Hopewell Faults. Subsidence was sufficiently rapid to preserve trees 9 meters tall in growth position.	Bell, 1958
MONCTON	Late Devonian through Namurian	3000 sq km	8.5 km: Horton clastics; Windsor evaporites and clastics; Canso clastics. Sources from north and south.	Visean: 30 meter ash bed at base Windsorian Hillsboro Formation.	Complex basin formed between the Lubec-Belleisle and Pollet River-Clover Hill Faults, and cut by several other high angle faults inferred to be dextral. Two angular unconformities occur within Lower Carboniferous section.	Webb, 1963 Gussow, 1953 Greiner, 1962 Carr, 1968
NARRAGANSETT	Namurian B to Stephanian B or C	2500 sq km	4 km: Nonmarine fanglomerate and fluvial facies.	Westphalian B: Basalt and rhyolite common in 300 meter section of Wamsutta Conglomerate.	Considered by McMaster et al. (1980) to be a sinistral pull-apart, but the opposite interpretation as a dextral pull-apart may be equally possible. Basin geometry altered by Permian orogeny.	McMaster et al., 1980 Skehan et al., 1979 Mutch, 1968

regionally and even locally unpredictable. In general, fold axes are parallel with adjacent strike slip faults, but some, in the Moncton, Minas, and Deer Lake basins, are arranged en echelon in a manner consistent with dextral shear [Webb, 1963; Benson, 1967; Hyde and Ware, 1981]. Deformation was typically nonpenetrative except in a few fault zones where a slaty cleavege developed, as in the bend of the Cobequid-Chedabucto fault zone where it emerges onshore in southern New Brunswick (described, but interpreted differently, by Ruitenberg et al. 1973). Webb [1963] pointed out the resemblance between this structural style and that along the San Andreas which has since come to be known as 'flower structure' [Harding and Lowell, 1979].

Although Carboniferous alkaline to tholeiitic volcanics can readily be interpreted as products of extension within the regional strike slip framework, the relationship between a number of late Paleozoic granite plutons and this tectonic environment is less clear. Late Devonian and Carboniferous radiometric ages of late Acadian calc-alkaline (and rarely, peralkaline) granites have been reported from Newfoundland [Bell and Blenkinsop, 1977], Nova Scotia [Keppie, 1979], New Brunswick [Fyffe et al., 1981], and Maine and New Hampshire [Lyons, 1979]. The strong resemblance between these rocks and older, synkinematic Acadian granites and an apparently continuous range of ages between the two groups seem to suggest that the magmatism occurred not in response to Carboniferous extension but to Acadian crustal thickening. Granite intrusion and regional metamorphism of Carboniferous pull-apart strata in southern New England [Skehan et al., 1979] are Permian events best related to Alleghanian convergence and crustal thickening.

Silurian to Carboniferous paleomagnetic data have recently been interpreted as evidence for 1000-2000 km of left-lateral displacement of the Avalon zone with respect to cratonic North America [Kent and Opdyke, 1978, 1979, 1980; Morris, 1976; Irving, 1979; Van der Voo et al.; 1979, Van der Voo, 1980; Harland, 1980]. LeFort and Van der Voo [1981] further bracketed the age of offset as Visean through Westphalian. Compelling geologic evidence in support of this hypothesis has not yet been discovered [Ludman, 1981]. With the exception of the Harvey-Hopewell fault (Figure 2), on which 16 km of sinistral slip occurred during Westphalian B [Webb, 1963], all reported Carboniferous strike-slip was dextral [Webb, 1969]. The resolution of this dilemma, by detailed mapping and further paleomagnetic work, ranks among the most urgent problems in Appalachian tectonics.

SUBSIDENCE OF THE MAGDALEN BASIN

Rift Phase

Isopachs and geologic evidence for the timing of strike slip suggest that a major pull-apart, the Magdalen Basin [Sheridan and Drake, 1968], opened during late Devonian through Visean between dextral faults systems in New foundland and New Brunswick. This synchronous strike slip and basin subsidence led Belt [1968] to conclude that the composite Fundy Basin (his Fundy Rift) originated as a 'wrench graben', or in modern terminology, a pull-apart. With an area of roughly 25,000 km^2 the basin is by far the largest of late Paleozoic age in the northern Appalachians, but the onshore exposure is limited. The existence of a deep Carboniferous basin in the Gulf of St. Lawrence is based on seismic refraction [Sheridan and Drake, 1968], gravimetry [Watts, 1972], magnetometry [Watts, 1972], drill holes [Howie and Barss, 1975a], and exposures in the Magdalen Islands [Sanschagrin, 1964]. These studies have indicated the presence of up to 8 km of post-Acadian sedimentary rocks whose structure is dominated by diapirs cored by Windsor evaporites, which were deposited, at least in early Carboniferous, in a fault-bounded basin or basins [Watts, 1972]. Rocks of the rift phase of the Magdalen Bain include the Horton and Windsor groups. Approximately 800 m of conglomerate, sandstone, shale, limestone, evaporites, and volcanics exposed in the Magdalen Islands has been assigned a Windsorian age [Sanschagrin, 1964; Howie and Barss, 1975a]. In the Gulf of St. Lawrence, Sarep HQ Brion Island No. 1 Well penetrated to a depth of 2.5 km into Windsor evaporites [Howie and Barss, 1975a]. The existence of 2-4 km of Horton clastics beneath the Windsor is based on geophysical data and remains to be substantiated by deep drilling. Although the extent and depth of the basin have been roughly established by this evidence, the rhomboidal shape of the basin illustrated in Figure 2 is a schematic representation of what is undoubtedly a more complex basin geometry.

The identification of the Magdalen Basin as a pull-apart rests on the following observations: (1) The basin subsided rapidly to receive up to 6.7 km of sediments in about 20 m.y. [Howie and Barss, 1975a]. (2) The basin fill (conglomerates, evaporites, and volcanics), suggests an extensional environment. (3) The major right-lateral movement on faults in New Brunswick (the Lubec-Belleisle and probably also the Petitcodiac-Berry's Mills, Pollet River-Clover Hill, and Harvey-Hopewell faults) coincided with the subsidence of the Moncton Basin (Figure 2) during latest Devonian through Namurian [Webb, 1963]. These movements are dated by deformed fault scarp fanglomerates that are overlain unconformably by undeformed fluvial sandstone of the Boss Point formation of Westphalian A age. (4) In the subsurface, these faults pass beneath the Gulf of St. Lawrence, where their trend coincides with the northwestern margin of the Magdalen Basin as it is shown, for example, by the Horton and Windsor isopach maps of Howie and Barss [1975a]. (5) Continuation of this trend past the Magdalen Basin, however, leads into the northward narrowing portion of the Gulf between Quebec and insular Newfoundland. Marine geophysical surveys have found no evidence of important throughgoing faults in this area [Haworth, 1978] , nor are any known from onshore in Labrador and Quebec. (6) Right-lateral faults were active in western Newfoundland during early Carboniferous, including the Long Range, Taylors Brook, and Grand Lake faults (Figure 2) [Belt, 1969; Webb, 1969]. (7) Because major strike slip displacements cannot vanish [Kingma, 1958; Wilson, 1965], it must be concluded that the simultaneous motions in New Brunswick and Newfoundland also took place across the intervening terrane, which in a dextral fault system must be a zone of extension, and is the site of the Magdalen

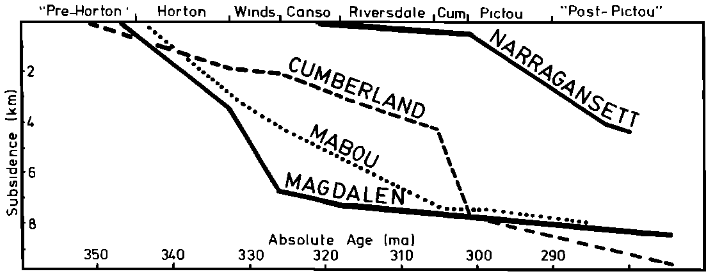

Fig. 4. Selected subsidence curves of four late Paleozoic basins. Episodes of rapid subsidence are attributed to stretching of the lithosphere; gradual subsidence is attributed to thermal decay. Other late Paleozoic basins show more ambiguous subsidence histories.

Basin. Data comparing this and other late Paleozoic basins in the northern Appalachians are given in Table 1.

The subsidence curve of the Magdalen Basin (Figure 4) is typical of extensional basins [McKenzie, 1978]. Thicknesses used in plotting the curve are means of 50 values obtained by placing a grid over the isopach maps of Howie and Barss [1975a], a procedure followed to minimize the effects of post-Pictouan diapirism of the Windsor salt, which altered the thickness of all units above the Horton by an unknown amount. Using McKenzie's [1978] equation 1, the stretching factor β ($\beta = 1$ for unstretched lithosphere; $\beta = \infty$ for lithosphere attenuated to zero thickness) of the Magdalen Basin is calculated to be 1.4, using for the initial subsidence the inflection point of the curve in Figure 4 and 40 km for the post-Acadian crustal thickness in the Gulf of St. Lawrence. A similar result, $\beta = 1.6$, is obtained from the total subsidence, using equation 2 of LePichon and Sibuet [1981].

Thermal Subsidence Phase

A predicted result of this high degree of stretching over a large area is the subsequent development of an enlarged thermal subsidence basin, corresponding to the horns of the steer's head (Figure 1), that progressively onlaps basement. Many workers have noted just such a widening of the composite Fundy Basin through the Carboniferous and have ascribed varying degrees of importance to the phenomenon [Van de Poll, 1972; Kelley, 1967; Bell, 1958; Belt, 1968; Carrol et al., 1973; Howie and Barss, 1975a, b]. Van de Poll, [1972] demonstrated this broad scale aspect of the Fundy Basin, which had led Kay [1951] to label it an epieugeosyncline, with a map showing that the age of post-Acadian strata lying directly on basement decreases toward the basin margins. These onlapping strata are here attributed to thermal subsidence due mainly to stretching in the Magdalen Basin, with possible minor local effects of stretching in smaller pull-aparts. Most clearly belonging to the thermal subsidence regime are the fluvial strata of the late Carboniferous Pictou group, which blankets all earlier Carboniferous units and many Carboniferous faults and onlaps basement [Kelley, 1967]. Except perhaps during Westphalian C in the Stellarton Subbasin (Table 1), the basin of Pictou deposition was not fault bounded, nor did faults control the distribution of facies within the basin. In areas north and west of the Magdalen Basin, where no important post-Cansoan tectonism occurred, the present edge of the Carboniferous system mimics the outline of the Magdalen Basin. In this region, thermal subsidence is believed to have proceeded without interruption following the rift phase.

Older blanket deposits in the composite Fundy Basin may also record thermal subsidence, but these units (notably the Riversdalian Boss Point sandstone and the transgressive Windsor limestones) differ in an important way from the Pictou in that the former units were deposited when strike slip was still taking place to the east and south of the Magdalen Basin, resulting in more complex facies and subsidence patterns. The Boss Point formation, with an average thickness of less than 0.5 km and a maximum of 1.5 km, blanketed the Moncton Basin (Figure 2, Table 1) during Riversdalian time (Westphalian A), burying faults that had been active during early Carboniferous [Webb, 1963]. Simultaneously, the fault-bounded Minas, Mabou, and Stellarton basins (probable pull-aparts summarized in Table 1) were opening in eastern Nova Scotia and contain Riversdalian strata as thick as 3.5 km [Howie and Barss, 1975a]. Thus while thermal subsidence may have been dominant in the west, contemporaneous stretching of the lithosphere resulted in faster subsidence in the east. It is likely, but difficult to demonstrate, that thermal subsidence also affected this region of pull-aparts, thereby imposing two simultaneously acting subsidence mechanisms.

Perhaps the earliest regional expression of thermal subsidence was the Windsor transgression, which, during Visean time, reached as far west as western New Brunswick and as far south as southern Nova Scotia [Howie and Barss, 1975a, b]. It is not clear whether the Windsor transgression was due to local subsidence, a eustatic rise in sea level, or both. Although Ramsbottom [1973] has documented repeated sea level changes in northwestern Europe during the early Carboniferous, these fluctuatuons may be due only to a change in the relative rate of local subsidence with respect to a longer-term sea level trend [Pitman, 1978]. Hallam [1977] noted a long-term fall in sea level that began in about Visean time, which is consistent with the interpretation favored here that the Windsor transgression was a result of subsidence in eastern Canada. As during Boss Point deposition, Windsorian strike slip generated local complexities such that a simple saucer-shaped thermal subsidence basin did not develop.

OTHER LATE PALEOZOIC BASINS IN THE NORTHERN APPALACHIANS

Smaller basins in the northern Appalachians subsided during and after the opening of the Magdalen Basin; critical data are summarized in Table 1, and selected subsidence curves are plotted in Figure 4. Among these basins, several have been interpreted as pull-aparts: the Stellarton Subbasin [Fralick and Schenk, 1980], the Minas Basin [McCabe et al., 1980], the Narragansett Basin [McMaster et al., 1980], the Deer Lake Basin [Hyde and Ware, 1981], and St. George's Basin [Belt, 1969]. A similar origin is considered likely for the White Bay Basin (Table 1) and for small upper Paleozoic outliers that lie along faults such as the Norumbega [Wones, 1980], Tetagouche [Skinner, 1974], Perry [Schluger, 1973], Red Indian Lake [Belt, 1969], and Terrenceville [Bradley, 1962] basins (shown in Figure 2 but not listed in Table 1). The Moncton and Mabou basins probably also developed in response to extension within the regional strike slip system, as is indicated by volcanism during subsidence, but both appear to be more complex than simple rhombochasms. The Cumberland Basin is believed to have originated in response to extension in the zone between the sinistral Harvey-Hopewell fault, the dextral Cobequid-Chedabucto fault, and the zone of transpression in southern New Brunswick (equivalent to Rast and Grant's [1973] Variscan front and Ruitenberg et al.'s [1973] Fundy cataclastic zone). A possible modern analog occurs at the East Anatolian intracontinental triple junction of dextral, sinistral, and convergent plate boundaries, which is the site of the rapidly subsiding Neogene Karliova Basin [Şengör, 1979]. In Figure 4 the subsidence curves of four basins from Table 1 have been plotted using average values from the isopach compilations of Howie and Barss [1975a] and other sources [Bell, 1958; Skehan et al, 1979; Belt, 1965]. The diachronous nature of rapid subsidence is clearly indicated, and the shape of each curve is consistent with the proposed extensional origin. Other late Paleozoic basins show more ambiguous subsidence histories.

DISCUSSION

The diachronous two-stage subsidence of pull-apart basins within a strike slip system satisfactorily describes the major features of the late Paleozoic evolution of the northern Appalachians and supports the following interpretation of the tectonic evolution. Following continental collision in the medial Devonian, the wide Acadian suture zone and part of the Avalonian basement became the site of a major intracontinental transform. Strike slip probably began during the late Devonian and continued through Westphalian B in the north, and somewhat later in the Narragansett Basin. Offsets exceeding 200 km eventually accumulated across a wide zone of anastomosing faults, which bounded basement blocks that rose and subsided episodically [Belt, 1968]. The uplifted blocks and more stable platform areas outside the plate boundary zone supplied sediments that accumulated in adjacent extensional basins. The largest of these, the Magdalen Basin, opened on the site of the Gulf of St. Lawrence during late Devonian through early Carboniferous in response to stretching of its lithosphere by a factor of 1.5 over an area of 25,000 km^2. The decay of the resulting thermal anomaly caused widespread regional subsidence, perhaps first expressed as the Windsor marine transgression and later by Middle and Upper Carboniferous blanket sands that progressively onlapped basement. To the north and west of the Magdalen Basin, thin strata of the thermal subsidence regime were not markedly disturbed by later tectonism, and in cross section, this half of the predicted steer's head configuration is observed. To the south and east of the Magdalen Basin the other half is not seen because of the masking effects of continued strike slip along other faults into late Carboniferous. Such complications include the opening of small pull-aparts, presumably with high heat flow (giving locally thicker sections), and the interruption of subsidence during local episodes of strike slip deformation (giving locally thinner sections).

In the Maritime Provinces the youngest blanket sands are preserved on Prince Edward Island [Frankel and Crowl, 1969]. Miospore assemblages in the Moncton Basin also suggest that the youngest Pictou rocks occur toward the center of the composite Fundy Basin [Carr, 1968]. Several explanations for this departure from the predicted growth of the thermal subsidence basin are possible, the simplest being that rocks as young as Permian were deposited across the entire region but are preserved only where they originally were thickest. A second possibility is that the rocks of Prince Edward Island record local thermal subsidence over an unrecognized subsurface pull-apart of medial Carboniferous age, as might be suggested by rather thick Canso-Riversdale strata shown on the isopach map of Howie and Barss [1975a]. A third possibility is that these young rocks record a late stage of contraction of the thermal subsidence basin, a predicted response if the lithosphere is assumed to have long-term viscoelastic properties [Beaumont, 1979], as opposed to the long-term elastic properties assumed by Watts et al. [1980]. The complex regional history makes it difficult to select the best explanation for these young rocks in the composite Fundy Basin.

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