[AMERICAN JOURNAL OF SCIENCE, VOL. 307, JANUARY, 2007, P. 216–264, DOI 10.2475/01.2007.07]

SILURIAN EXTENSION IN THE UPPER CONNECTICUT VALLEY, UNITED STATES AND THE ORIGIN OF MIDDLE PALEOZOIC BASINS IN THE QUÉBEC EMBAYMENT

D. W. RANKIN*, R. A. COISH**, R. D. TUCKER***, Z. X. PENG***,
S. A. WILSON**, and A. A. ROUFF**

ABSTRACT. Pre-Silurian strata of the Bronson Hill arch (BHA) in the Upper Connecticut Valley, NH-VT are host to the latest Ludlow Comerford Intrusive Suite consisting, east to west, of a mafic dike swarm with sheeted dikes, and an intrusive complex. The rocks are mostly mafic but with compositions ranging from gabbro to leucocratic tonalite. The suite is truncated on the west by the Monroe fault, a late Acadian thrust that carries rocks of the BHA westward over Silurian-Devonian strata of the Connecticut Valley-Gaspé trough (CVGT). Dikes intrude folded strata with a pre-intrusion metamorphic fabric (Taconian?) but they experienced Acadian deformation.

Twenty fractions of zircon and baddeleyite from three sample sites of gabbro-diorite spanning nearly 40 km yield a weighted ^{207}Pb/^{206}Pb age of 419 ± 1 Ma. Greenschist-facies dikes, sampled over a strike distance of 35 km, were tholeiitic basalts formed by partial melting of asthenospheric mantle, with little or no influence from mantle or crustal lithosphere. The dike chemistry is similar to mid-ocean ridge, within-plate, and back-arc basin basalts. Parent magmas originated in the asthenosphere and were erupted through severely thinned lithosphere adjacent to the CVGT.

Extensive middle Paleozoic basins in the internides of the Appalachian orogen are restricted to the Québec embayment of the Laurentian rifted margin, and include the CVGT and the Central Maine trough (CMT), separated from the BHA by a Silurian tectonic hinge. The NE-trending Comerford intrusions parallel the CVGT, CMT, and the tectonic hinge, and indicate NW-SE extension. During post-Taconian convergence, the irregular margins of composite Laurentia and Avalon permitted continued collision in Newfoundland (St. Lawrence promontory) and coeval extension in the Québec embayment. Extension may be related to hinge retreat of the northwest directed Brunswick subduction complex and rise of the asthenosphere following slab break-off. An alternative hypothesis is that the basins originated as pull-apart basins between northwest-trending, left-stepping, sinistral strike-slip faults along the southern flanks of the New York and St. Lawrence promontories.

INTRODUCTION

The literature of the Paleozoic tectonic history of central New England is dominated by discussion of island arcs and compressional events. In recent years, there has been an increasing awareness of Silurian crustal extension between the Ordovician Taconian and Devonian Acadian orogenies. The existence of mafic dike swarms along the Upper Connecticut River Valley has been known since the mapping of Billings (1937) and White and Billings (1951), but little has been made of the tectonic significance of these rocks. The discovery of sheeted dikes in those dike swarms and the field association of those dikes with a mafic intrusive complex led to our hypothesis that the mafic intrusions were generated during Silurian extension that produced the Connecticut Valley-Gaspé trough (CVGT) and the Silurian tectonic hinge of northwestern Maine (fig. 1). We present the results of a joint study involving field mapping, U-Pb isotopic dating, and geochemistry in order to determine the distribution, age, possible magmatic source areas, and tectonic environment of the suite.

*U. S. Geological Survey, 926A National Center, Reston, Virginia 20192; dwrankin@usgs.gov
**Geology Department, Middlebury College, Middlebury, Vermont 05753
***Department of Earth and Planetary Sciences, Washington University, Saint Louis, Missouri 63130-4899

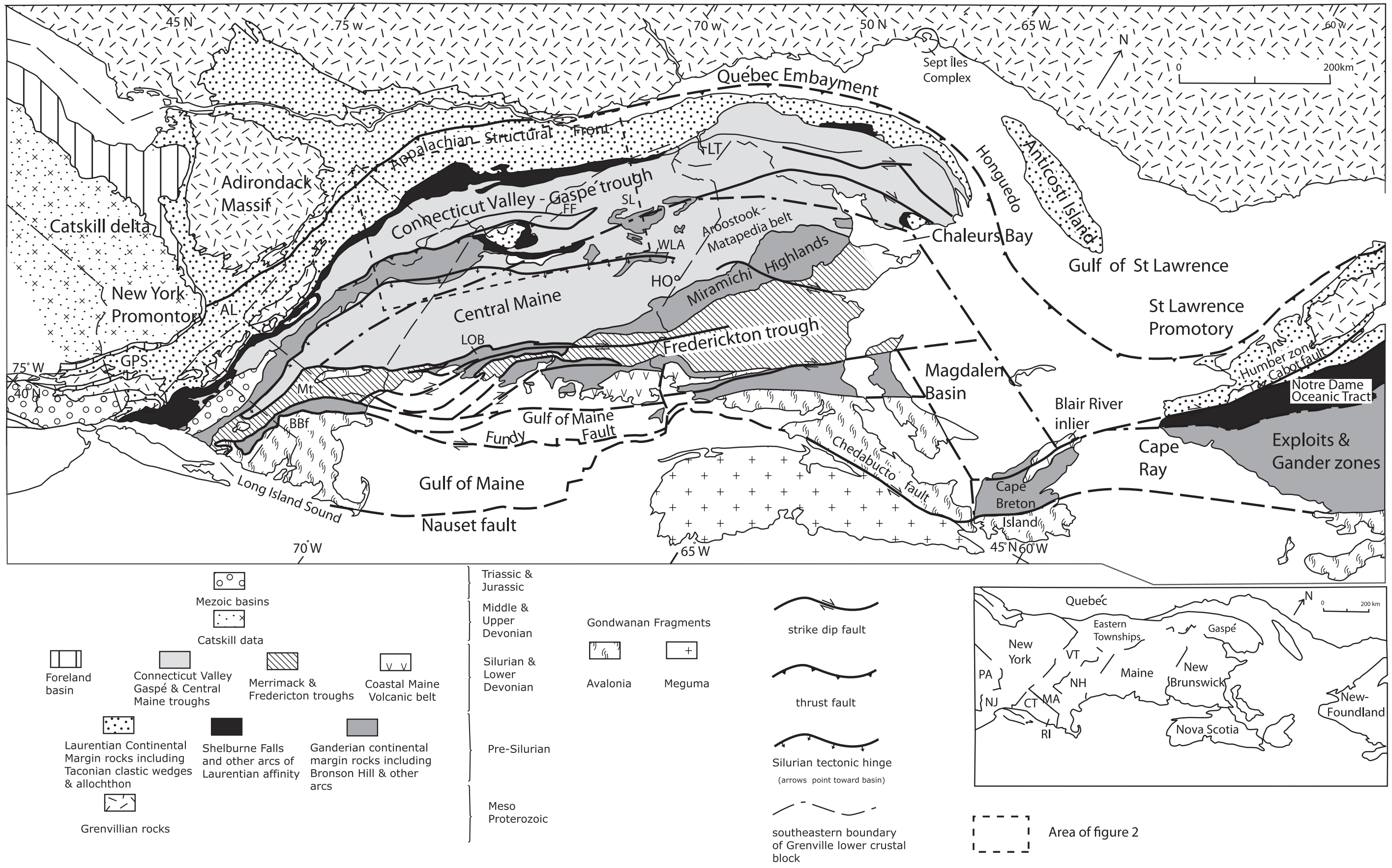


Fig. 1. Regional geologic map of the Northern Appalachians from New York to Newfoundland showing the setting of the large Silurian-Devonian basins relative to promontories and embayments of Laurentian continental margin. Modified from Hibbard and others (2006). AL, Albany; BBf, Bloody Bluff fault; FF, Frontenac Formation; GPS, Green Pond syncline; HO, Houlton; LOB, Liberty-Orrington belt; LT, Lac Témiscouata; Mt, Merrimack trough; SL, Spider Lake; WLA Weeksboro-Lunksoos arch. Inset in lower right shows political boundaries.

REGIONAL GEOLOGY AND TECTONIC SETTING

At least two major Paleozoic compressional orogenic events affected central New England. During the Middle to Late Ordovician, previously amalgamated terranes collided with a volcanic arc or arcs off the east coast of Laurentia and, as the last remaining crust of the Iapetus Ocean west of that was consumed, the combined mass collided with Laurentia giving rise to the Taconian orogeny (Rodgers, 1971; Rankin, 1994 and references therein). From $^{40}Ar/^{39}Ar$ data, Hames and others (1991) concluded that the thermal maximum of the Taconian metamorphism in southwestern New England was about 445 Ma. A second episode, the Acadian orogeny, dates from the late Early Devonian to early Mississippian (plutonism and associated contact metamorphism) (Osberg and others, 1989; Robinson and others, 1998). Although the timing and effects of that orogeny are well studied, the cause of the orogeny is still under debate.

Controversy continues in central New England as to whether there was a single, long-lived early Paleozoic arc (Stanley and Ratcliffe, 1985; Ratcliffe and others, 1998) or two separate arcs, an earlier western Shelburne Falls arc and a later eastern Bronson Hill arc (Karabinos and others, 1998; Karabinos and Hepburn, 2001). We accept the argument that the Shelburne Falls arc is a separate, older arc (Tucker, in Tucker and Robinson, 1990; Karabinos and Tucker, 1992; Karabinos and others, 1998; Karabinos and Hepburn, 2001) correlative with arc rocks of the Notre Dame oceanic tract, Newfoundland (fig. 1), and is of Laurentian affinity (van Staal and others, 1998). We accept the argument of Robinson and others (1998) and van Staal and others (1998) that the Bronson Hill arc was part of the Ganderian margin of a piece of greater Gondwana. The near-surface trace of the Iapetan suture in central New England is interpreted to be covered by the Silurian-Devonian sediments of the CVGT, although the Laurentian crustal block extends farther east in the subsurface. The Bronson Hill arc was active 469 to 442 Ma (Tucker and Robinson, 1990; Moench and Aleinikoff, 2002).

A period of extension following the Taconian orogeny produced two basins: the CVGT and the Central Maine trough (CMT) (Osberg and others, 1989) (fig. 1). The basins contain mostly Silurian and Devonian marine clastic sedimentary rocks; many are turbiditic, some calcareous, and locally they are interlayered with volcanic rocks. The basins are separated by the remnants of the Bronson Hill arc. The two basins coalesce to the north beyond our study area where outcrops of pre-Silurian rocks are discontinuous. During the Silurian, the Bronson Hill arc remained a topographic high, the Bronson Hill arch (BHA - really more of an uplift or arch rather than an anticlinorium) (Hibbard and others, 2006). Silurian strata are thin to absent along the arch and, where present, are unconformably above rocks of the extinct Bronson Hill arc. The area of the Boundary Mountains, northwest of the BHA, stood as an island during the Silurian and into the Early Devonian (Somerset Island of Boucot and others, 1964; Naylor and Boucot, 1965). Silurian strata thicken markedly to as much as 5 km across a syn-sedimentary tectonic hinge line to the east into the CMT (figs. 1 and 2) (Boone and others, 1970; Hatch and others, 1983; Moench and Pankiwskyj, 1988). Early Silurian clastic wedges of the conglomerate-bearing Rangeley Formation adjacent to the hinge line give way southeastward to turbiditic slates and quartz wackes some of which are calcareous - a stratigraphy that persists through the Silurian (Osberg, 1974; Osberg, 1988). The basin contains local horst-like uplifts (Robinson and others, 1998) such as the Weeksboro-Lunksoos uplift and. at the southeastern edge of the basin, the Miramichi uplift (fig. 1). Robinson and others (1998) note that both of these areas were emergent during the Early Silurian and locally shed debris flows.

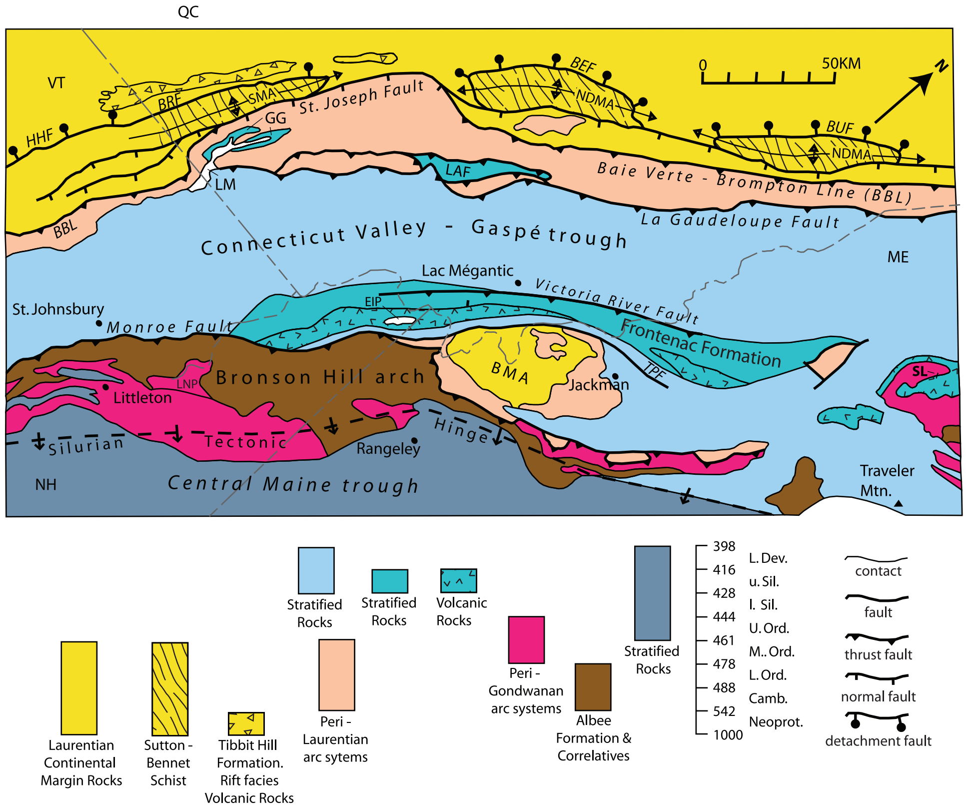


Fig. 2. Lithotectonic map of parts of Vermont, New Hampshire, Maine, and Québec. Modified from Hibbard and others, 2006; Castonguay and Tremblay, 2003; and Hanson and others, 1993. BEF, Bennett fault; BMA, Boundary Mountains arch; BRF Brome fault; BUF, Buckland fault; EIP, East Inlet pluton; GG, Glenbrooke Group; HHF, Honey Hollow fault; LAF, Lac Aylmer Formation; LM, Lake Memphremagog; LNP, Lost Nation pluton; NDMA, Notre-Dame Mountains anticlinorium; Sutton Mountains anticlinorium; SL, Spider Lake; TPF. Thrasher Peaks fault.

In our study area, the BHA is thrust over the CVGT on the now-steeply-dipping late Acadian Monroe fault, (Rankin, 1996a, 1996b; Hannula and others, 1999). In northern Vermont and New Hampshire Devonian rocks of the CVGT are underlain to the east by pelite and sandstone, typically calcareous, interlayered with bimodal volcanic rocks of the Silurian Frontenac Formation (Moench and others, 1995) (fig. 2). Correlative rocks to the northeast in Québec contain a chitinozoan assemblage indicating a late Lochkovian to early Pragian age (Lavoie and Asselin, 2004). This conflict is unresolved.

LOCATION AND STRATIGRAPHY

In our study area, the Upper Connecticut Valley, (fig. 3) stratigraphic units are grouped into three spatially distinct sequences of overlapping ages: the Connecticut Valley, the Bronson Hill, and the Rangeley, which constitutes the rootless Piermont allochthon, carried westward over the Bronson Hill sequence on the late (?) Acadian Bean Brook thrust fault (Timms, 2004).

All rocks have experienced Acadian metamorphism at grades ranging from chlorite to sillimanite (in contact aureoles). For the sake of brevity, the prefix meta is omitted from rock descriptions. Our geochemical samples come from chlorite- or

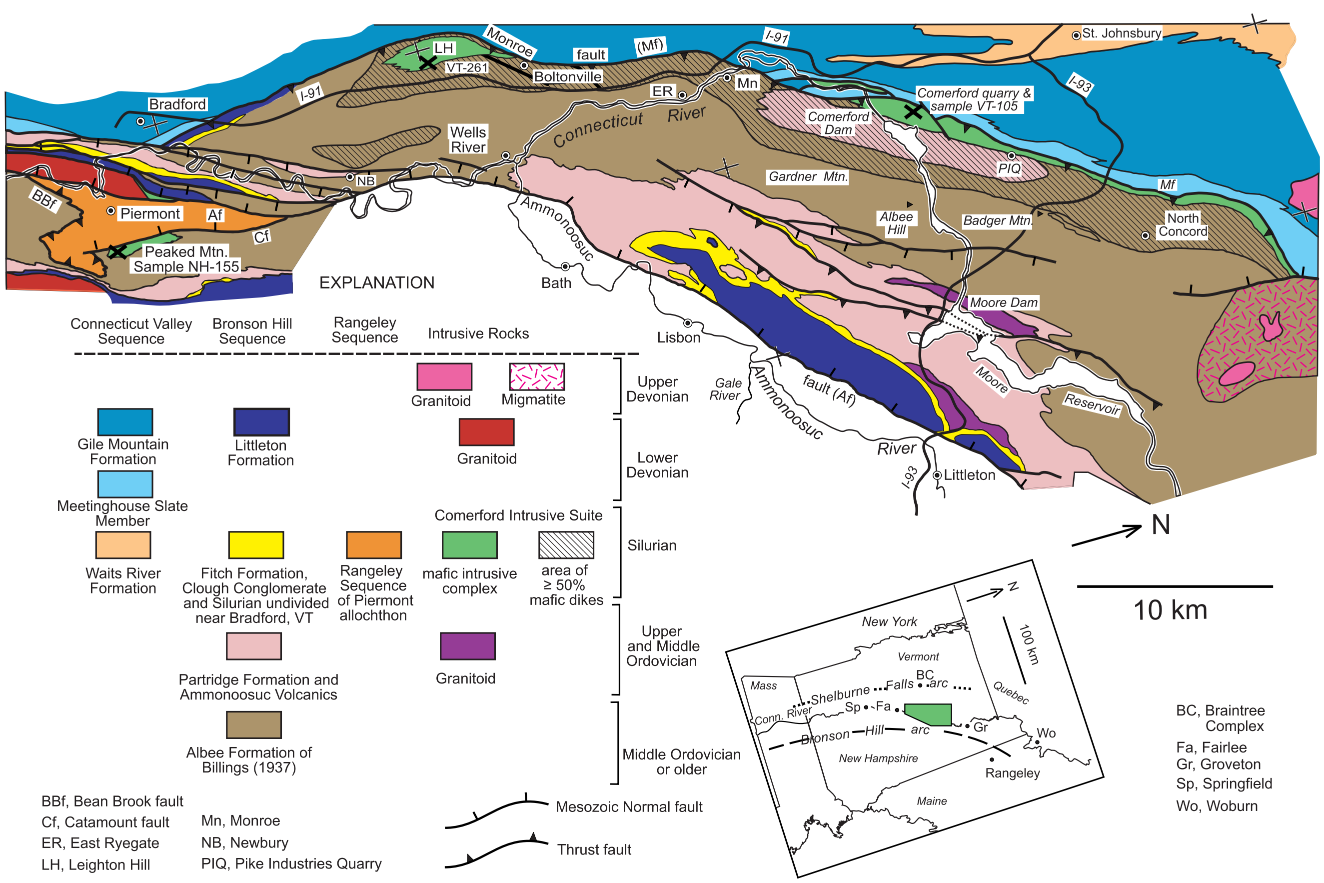


Fig. 3. Geologic map of the Upper Connecticut Valley, New Hampshire and Vermont, showing lithotectonic units and the setting of the Comerford Intrusive Suite. Mapping by Rankin, 1993-2005. Catamount normal fault, from Timms (2004). Inset map in lower right shows the location of the geologic map area as well as the trace of the Shelburne Falls and Bronson Hill arcs.

biotite-grade rocks of the Connecticut Valley metamorphic low shown by Thompson and Norton (1968). The Ammonoosuc fault, a major west-dipping Mesozoic normal fault (Thompson and Norton, 1968; Rodgers, 1970), juxtaposes low-grade rocks (west) against higher-grade rocks (east). At widely separated localities, it can be demonstrated that pre-Silurian strata experienced an earlier metamorphism, interpreted to be Taconian. Dikes of this study intrude folded strata with a pre-intrusion metamorphic fabric (discussed below). Offshoots of the Lost Nation pluton (444.1 ± 2.1 Ma: age refined from Rankin and Tucker, 1999) cut and thermally metamorphosed, strongly folded rocks.

Stratified units of the immediate study area and their correlation are shown in table 1. Relevant aspects of the stratigraphy not covered on table 1 are summarized below.

Bronson Hill Sequence

A decade of fieldwork in the Upper Connecticut Valley has corroborated the stratigraphy of Billings (1937). The high quartz and feldspar content of the bulk of the Albee Formation suggests a continental source. The dark pelite, locally present in the lower part of the Albee, suggests a more distal, deeper-water environment. Moench and others (1987) note a significant volcanic component in rocks here mapped as volcanic-free Albee. However, punky-weathering, fine- to medium-grained rocks, containing as much as 30 percent carbonate, abundant chlorite, and 10 percent muscovite, are commonly interlayered with sedimentary rocks of the Albee Formation. Abundant relict plagioclase, some twinned, is discernable in every thin section examined. These rocks are interpreted to be highly altered mafic to intermediate dikes, not volcanic or calcareous sedimentary rocks, segments of which are preserved where they, the regional foliation, and bedding are nearly parallel. Some may belong to the Comerford Intrusive Suite of this study. As a group, however, they are more altered, typically have higher carbonate content, contain metamorphic muscovite, and most do not contain pale secondary amphibole. These dikes are probably related to the Ordovician Bronson Hill arc. The Albee is stratigraphically beneath the Ammonoosuc Volcanics and is, hence, Middle Ordovician or older.

The age of the Ammonoosuc Volcanics in the study area spans about 25 my in the Middle and Late Ordovician. Near Moore Dam (fig. 3) the unit is intruded by the 469 ± 2 Ma hypabyssal Joslin Turn pluton (Moench and Aleinikoff, 2002). Rhyolite tuff at Bath, NH, (fig. 3) has been dated at 443 ± 4 Ma (Moench and Aleinikoff, 2002).

The younger, post-arc Bronson Hill sequence consists, in ascending order, of the Clough Quartzite of Llandovery age (Boucot and Thompson, 1963), the calcareous Fitch Formation, locally of Pridoli age (Harris and others, 1983), and the turbiditic Littleton Formation, locally of Emsian age (Boucot and Arndt, 1960). Both the Fitch and Littleton have yielded slightly different ages outside the study area. Elbert and others (1988) reported a Lochkovian assemblage in the Fitch from Bernardston, Massachusetts; Boucot and Rumble (1980) report a Pragian assemblage in the Littleton from the Mt. Moosilauke area, about 21 km east of Newbury, Vermont. Both the Clough and Fitch, but particularly the Clough, may be in discontinuous lenses beneath the Littleton.

Connecticut Valley Sequence

The Connecticut Valley sequence is interpreted to be Silurian-Devonian and roughly correlative with the Silurian-Devonian strata of the Bronson Hill sequence (Doll and others, 1961; Hatch and others, 1988). The sequence differs from comparable rocks of the BHA in having a somewhat ambiguous stratigraphy, virtually no fossil control in the United States, greater thickness, and many calcareous clastic rocks. A conclusion of the present fieldwork is that the Meetinghouse Slate, as deduced by

TABLE 1

Stratigraphic units and their correlation for the study area. Geologic time scale from Gradstein and others (2004) and Fortey and others (1995) (Ordovician stages)

CONNECTICUT VALLEY SEQUENCE	BRONSON HILL SEQUENCE	RANGELEY SEQUENCE	AGE			Ma
			Devonian			359.2
				Upper		385.3
				Middle		397.5
Gile Mountain Formation Interlayered fine-grained argillaceous sandstone (some calcareous), graphitic (commonly sulfidic) dark pelite. Rhythmically graded beds common. Mafic volcanic rocks toward western base. Meetinghouse Slate Member, Gile Mountain Fm Dominantly dark pelite at eastern base of main body of Gile Mountain Formation	Littleton Formation Dark, commonly pyritiferous pelite interlayered with sandstone, commonly argillaceous, and sparse grit. Thin graded beds common. Sandstone more abundant higher in the section. Basalt and rhyolite near base; basalt and andesite higher in the section.			Lower	Emsian	407.2
					Pragian	411.2
					Lochkovian	416
	----------Disconformity---------- Fitch Formation Interlayered limestone, dolostone, calcareous sandstone, siltstone, and pelite, as well as limestone conglomerate with calcareous matrix.		"upper" Silurian	Pridoli		418.7
				Ludlow		422.9
Standing Pond Volcanics Mafic volcanic rocks; not in study area. Waits River Formation Interlayered calcareous sandstone, argillaceous limestone, and calcareous and non-calcareous pelite. May be, in part, western facies of Gile Mountain Formation (see text).				Wenlock		428.2
	Clough Quartzite Quartz-pebble conglomerate (rarely with calcareous matrix) and quartzite.	Rangeley Formation Interlayered dark graphitic pelite, sandstone characterized by calcareous lenses, and sparse beds of grit and polymict conglomerate. Greenvale Cove Formation Interlayered pelite, sandstone, and calcsilicate rock.	"lower" SILUR.	Llandovery		443.7
	----------Unconformity---------- Partridge Formation Dark sulfidic pelite, locally sandy, with interlayers of rhyolite. Ammonoosuc Volcanics Rhyolite, andesite, and basalt tuffs and flows; volcanic conglomerate. arkosic wacke. siltstone and pelite (some dark and sulfidic). Coticules and magnetite locally abundant in siltstone and pelite.		Ordovician	Upper	Ashgillian Caradocian	460.9
	Albee Formation (as used by Billngs, 1937) (Middle Ordovician or older) Turbiditic, non-calcareous, quartzo-feldspathic sandstone, siltstone, and pelite, all locally sulfidic. sulfidic. Upper part largely sandstone and siltstone. Graded beds, some showing penecontemporaneous deformation or channeling, locally abundant. Lower part largely dark pelite.			Middle	Llanvirnian	471.8
				Lower	Arenigian Tremadocian	488.3

graded beds on both sides of the contact, is stratigraphically beneath the main body of the Gile Mountain Formation. Most authors interpreted the Waits River to be older than the Gile Mountain (see Hueber and others, 1990). Thompson and others (1997) concluded, however, that the boundary between the two units, as mapped statewide, cannot be a time line but is more likely a boundary between two laterally equivalent facies. Near Springfield, Vermont, (fig. 3 insert) amphibolites of the Standing Pond Volcanics are cut by a 423 ± 4 Ma dike, and to the north in Quebec rocks correlative with the Gile Mountain (Compton Formation) contain late Early Devonian (Emsian) plant fossils (Hueber and others, 1990). Certainly some of the Waits River is Silurian and some of the Gile Mountain is Devonian. The Standing Pond Volcanics is commonly taken to mark the contact between the Waits River and Gile Mountain, although that usage may not reflect the actual distribution of rock types (Thompson and others, 1997).

Rangeley Sequence of the Piermont Allochthon

Moench and others (1987) and Moench (1990) correlated a series of strata in the BHA near Piermont, New Hampshire, with a section, largely Silurian, in the CMT near Rangeley, Maine, and extrapolated that correlation to many of the rocks of the BHA north of Piermont to and beyond the Canadian border. Rocks thus reassigned to the Rangeley sequence in the Upper Connecticut Valley constitute the Piermont-Frontenac allochthon of Moench and others (1995). We briefly mention the allochthon because many of the host rocks for the dikes herein described were included in it (Moench, 1996; 1999). We interpret allochthonous rocks of the Rangeley sequence and the Piermont allochthon to be restricted to the Bean Brook slice (about 25 km^2) near Piermont (fig. 3) (Rankin, 1996a, 1998; Rankin and Tucker, 2000; Timms, 2004).

COMERFORD INTRUSIVE SUITE

Occurrence, Field Relations, and Name

Mafic dikes are abundant in the pre-Clough units of the Bronson Hill sequence. They have not been observed in Silurian-Devonian rocks of the Bronson Hill sequence northwest of the Ammonoosuc fault or in the Piermont allochthon. Dikes are particularly abundant adjacent to and east of the cross cutting Monroe fault from the latitude of Newbury, Vermont, north to North Concord, Vermont (Billings, 1937; White and Billings, 1951; Eric and Dennis, 1958; Hall, 1959). Areas where dikes constitute at least 50 percent of the exposed rock are indicated on figure 3. The eastern boundary of this main zone of abundant dikes is sharply gradational. Half a kilometer east of the mapped boundary, dikes typically constitute less than 5 percent of the outcrops. The dikes are more abundant toward the western border of the main zone, which is marked by the absence of screens of country rock. Dikes are chilled against dikes; they are, indeed, sheeted dikes. West of the main zone of dikes, is an intrusive complex of diabase, gabbro, diorite, and tonalite, all with pegmatitic phases.

Sheeted dikes were first recognized in the present study in the spillway of Comerford Dam (figs. 3 and 4A). The intrusive complex is well-exposed 1.5 km north of Comerford Dam in an abandoned quarry, herein referred to as the Comerford quarry. Diabase dikes, similar to those exposed in the spillway, are present in the intrusive complex in the quarry (fig. 4B). Patches (xenoliths? segregations?) of pegmatitic gabbro or diorite are present in several of the dikes in the spillway (fig. 4C) and are lithologically similar to the pegmatitic gabbro or diorite in the quarry. We interpret the dikes in the spillway and in Comerford quarry to be genetically related to the complex.

Sheeted dikes are also well exposed in road cuts along Interstate Highway I-93 west of Badger Mountain, in the active Pike Industries quarry at West Waterford, Vermont,

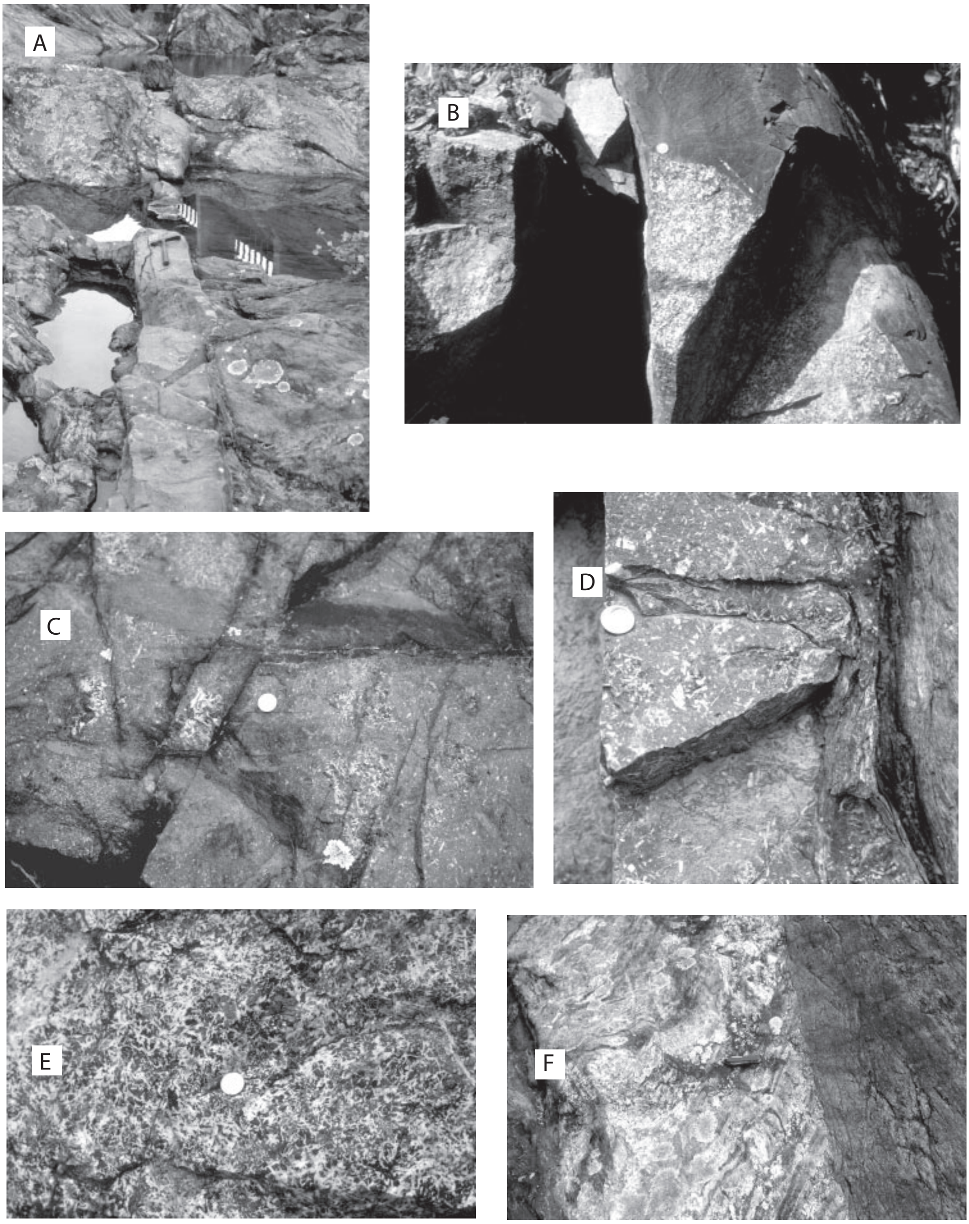


Fig. 4. Outcrop photographs of the Comerford Intrusive Suite. (A) Sheeted dikes in spillway, Comerford Dam. The medium-grained aphyric diabase dike in center is ~ 0.4 m thick, trends N30°E, and is vertical. It is chilled on both sides against plagioclase-phyric diabase. The ladder-like pattern in center of photograph is the reflection in water of a ladder. Hammer in the center is 28.5 cm long. (B) Float block in Comerford quarry showing sharp contact between dark, fine-grained aphyric diabase and light, coarse-grained gabbro-diorite. Coin is 17.5 mm in diameter. (C) Clots of pegmatitic gabbro-diorite in mafic dike, upper end of spillway, Comerford Dam. Coin is 17.5 mm in diameter. (D) Clots of pegmatitic gabbro-diorite in mafic dike, north wall of Pike Industries Quarry. Sheared contact with medium-grained diorite dike on right. Coin is 17.5 mm in diameter. (E) Pegmatitic gabbro-diorite, Comerford quarry. Coin is 17.5 mm in diameter. (F) Mafic dike (dark) cutting folded fine-grained felsic tuffs (light) of the Ammonoosuc Volcanics. Dike margin is chilled against the tuff. Downstream end of the Comerford Dam spillway. Knife is 8.2 cm long.

(90% dikes), and along the Wells River at Boltonville, Vermont (fig. 3). Patches of pegmatitic gabbro or diorite are also present in dikes in the northern part of the Pike Industries Quarry (fig. 4D) and along I-93 north of Badger Mountain. Complexes of mafic intrusive rocks without screens of country rock are well exposed about 6 km west of Wells River, Vermont, on Leighton Hill and along the prominent ridge west of that, and east of the Ammonoosuc fault and the Piermont allochthon on Peaked Mountain, about 2.3 km east of Piermont, New Hampshire (fig. 3). We interpret all of these bodies and dikes to be genetically related and propose the name Comerford Intrusive Suite to include them all, including the Leighton Hill Dike Complex of White and Billings (1951). The type area is designated as the spillway of Comerford Dam and the Comerford quarry.

Most previous workers did not correlate the dikes with the intrusive complexes and their work preceded the concept of sheeted dikes. Eric and Dennis (1958) and Hall (1959) correlated the intrusive complex of Comerford quarry with the Moulton Diorite that in the Littleton-Moosilauke area is metamorphosed but intrudes the Lower Devonian Littleton Formation (Billings, 1937). They mapped the complex (their Moulton Diorite) as being west of and cut by the Monroe fault. Hall (1959) considered the complex to be intrusive into the Meetinghouse Slate Member. Rankin's mapping (1996b and unpublished data) indicates that the northwest side of the intrusive complex is sheared adjacent to the relocated Monroe fault and that the small body of intrusive complex west of Comerford Dam, which also includes pegmatitic phases, shown by Hall to be within the Meetinghouse, is part of a laterally more extensive fault slice of the Monroe fault system (fig. 3). White and Billings (1951) and Billings and White (1950) did interpret the dikes and the Leighton Hill Dike Complex to be genetically related and showed both the complex and adjacent area of dikes to be truncated by the Monroe fault. Hadley (1942) and Rumble (ms, 1969) mapped the abundance of mafic dikes near Peaked Mountain but made no mention of an intrusive complex. Moench (1990, 1996) portrayed the Peaked Mountain area as being underlain by a body of sheeted metagabbro and metadiabase of Devonian or Silurian age intrusive into his Silurian Perry Mountain Formation in the larger Piermont-Frontenac allochthon. We interpret the intrusive complex on Peaked Mountain to be correlative with those at the Comerford quarry and Leighton Hill, to be intrusive into the autochthonous Albee Formation, and to grade eastward and northward into abundant dikes within the Albee.

Dikes

All chemical data presented below pertains to samples collected from the area of abundant dikes and intrusive complex east of the Monroe fault between Newbury and North Concord, Vermont (fig. 3). The gray-green dikes range in thickness from less than 1 to at least 30 m and generally extend along strike farther than outcrop exposure; terminations within an outcrop are rare. Dike compositions range from gabbro to diorite; grain size is typically fine but the interiors of thicker bodies are generally medium-grained. The dikes range from aphyric to plagioclase- and (or) pyribole-phyric. In some, plagioclase laths up to 5 mm long constitute 10 to 15 percent of the rock. Other dikes contain about 20 percent stubby plagioclase phenocrysts that are 3 mm or more wide. Chilled margins are common on one side or both, but no overall systematic "chilling direction" was observed. The dikes locally cut one another at low angles and a dike may be chilled against another dike or against country rock.

Igneous minerals in the dikes are completely replaced by a greenschist-facies assemblage that includes albite, amphibole, chlorite, epidote, calcite, quartz, titanite, and magnetite (leucoxene). The dikes are of two mineralogic types: 1) amphibole-dominant, with actinolite, epidote, plagioclase (twinned), titanite, and magnetite, and 2) chlorite-dominant, with chlorite, calcite, plagioclase (twinned), epidote, titanite and magnetite. Plagioclase grains are commonly replaced partly or entirely by a fine-grained mass of epidote and calcite. Amphibole or chlorite or both are interpreted to have formed from clinopyroxene based on the preservation of remnant clinopyroxene grains surrounded by amphibole in the plutonic rocks associated with the dikes. Calcite may constitute 20 percent of the rock either in veins or as disseminated patches; the resulting rock is punky weathering. A few samples contain as much as 5 percent biotite.

Many dikes preserve remnants of igneous textures such as relict phenocrysts. Where least altered, plagioclase phenocrysts are distinctly zoned. Mafic phenocrysts are now actinolite, presumably after clinopyroxene. Relict diabasic texture is common and coarser varieties preserve sub-ophitic texture or, in places, a poikilitic texture of amphibole with inclusions of epidote or albite, or both. The dikes generally trend northeast parallel to the dominant regional foliation but the strike may range from 330° to 60°. Most are steeply dipping and most dip southeast. Foliation in the thinner dikes and in the margins of thicker dikes has the same orientation as foliation in the host rock. Interiors of the thicker dikes are massive. Regional foliation is commonly displayed as pin-striping in the enclosing metasedimentary rocks, which in turn, may be parallel to coarser stratification interpreted to be bedding. A first impression is that many sheet-like intrusions are sills. In many outcrops, however, bedding and foliation are not parallel. In other outcrops, pin-striping has developed as the transposition of an earlier lamination (also a pin-striping) that is tightly folded. The younger pin-striping and associated foliation are axial planar to those tight folds. Where bedding and regional foliation are at a considerable angle, the dikes are roughly parallel to the foliation, not bedding. This is well displayed on the southwest-facing slope of the 1522-ft hill east of the entrance to the Pike Industries quarry (fig. 3) where dikes make up at least 50 percent of the slope. The country rock is siltstone and tuff of the Ammonoosuc Volcanics that dips southeast, as gently as 45°. Dikes and the regional foliation dip 70° to 80° southeast. Dikes cutting folded layering in siltstone and tuff of the Ammonoosuc Volcanics may be seen in the spillway of Comerford Dam (fig. 4F); planar margins of the dikes are chilled against the country rock. At other places, nearly vertical dikes with quasi-planar chilled contacts cut tightly folded pin striping in the country rock. The above observations lead to the conclusion that the dikes are properly called dikes, not sills, that they are deformed (foliated and locally boudinaged), and that they intruded previously folded strata with a pre-intrusion metamorphic fabric. The pre-dike deformation is thought to be Taconian but a full discussion of this is beyond the scope of this paper.

Intrusive Complex

The intrusive complex is best exposed and characterized at the Comerford quarry but the description below also draws on observations from nearby outcrops as well as those near Leighton Hill. Compositions range from gabbro to leucocratic tonalite; grain size for all ranges from fine to coarse to pegmatitic (fig. 4E). We use the term gabbro-diorite as a nonspecific field term for the coarser-grained darker rocks of the complex. Some aplite is present. All lithologies have experienced greenschist-facies metamorphism but most of the massive rocks are nonfoliated. Coarse-grained gabbro-diorite has a mottled, adcumulate texture with dominant minerals plagioclase (albite), clinopyroxene, epidote, and amphibole along with minor biotite, chlorite, calcite, apatite, titanite, zircon, magnetite, and leucoxene. Plagioclase is partially replaced by epidote, and pyroxene by amphibole. Plagioclase crystals are twinned, in places exhibiting an ophitic texture with spindle-like pyroxene crystals (fig. 4E). Larger pyroxene crystals show a remnant exsolution texture. Pyroxenes are surrounded by amphibole, biotite and small amounts of chlorite. Some thin sections contain tiny plagioclase veins, in which the mineral appears as tiny laths associated with rounded calcite and quartz crystals. Tonalite contains as much as 25 percent quartz. Pegmatitic gabbro-diorite consist of prominent amphibole and plagioclase with apatite and minor amounts of biotite. Locally, magnetite makes up as much as 15 percent of the rock. Pegmatitic gabbro-diorite on Leighton Hill contains baddeleyite as well as zircon. Amphibole-rich pods locally contain amphibole crystals as long as 15 cm and, locally, plagioclase-rich pegmatites cut the pegmatitic gabbro-diorite. Diabase dikes in the Comerford quarry trend 30° and are vertical. In places, the dikes are chilled against gabbro-diorite or contain inclusions of gabbro-diorite; however, in other places, coarse gabbro-diorite patches with irregular boundaries partly intrude dikes. Epidosite and quartz-plagioclase-chlorite-calcite veins are present.

No systematic age relationship is apparent among the components of the intrusive complex, although diabase dikes are relatively young and aplite veins appear to be the youngest. Contacts between the components range from sharp to gradational.

The intrusive complex of Peaked Mountain has been studied only by reconnaissance. It differs from other parts of the Comerford Intrusive Suite in being of higher metamorphic grade, consistent with its location southeast of the Ammonoosuc fault. Mafic dikes are amphibolites and pelites in the adjacent Albee Formation are characterized by the assemblage garnet-biotite-chlorite. The intrusive complex here includes metamorphosed diabase and gabbro-diorite. Phenocryst content and textural varieties, including pegmatitic phases, are similar to those at Comerford quarry.

Geochronology

Samples of gabbro-diorite pegmatite from the composite intrusions at Peaked Mountain, Leighton Hill, and the Comerford quarry were collected for isotopic dating (fig. 2; Appendix A). Zircon ($ZrSiO_4$) was separated from all three samples (Peaked Mountain, Leighton Hill, Comerford Quarry) and in addition, the sample from Leighton Hill yielded trace amounts of baddeleyite (Zr_2O_4). The zircons are clear, colorless, and short prismatic crystals typical of those in igneous rocks (fig. 5). Analytical methods are described in Appendix B.

Results of U-Pb geochronology.—Analytical results are reported in table 2 and age results are summarized on the concordia diagrams in figure 6. Six to seven mineral fractions were analyzed for each rock. Because many of our analyses are concordant (12 of 20), the cited age for each rock is the mean $^{207}Pb/^{206}Pb$ age weighted by the inverse variance of the individual analyses. The validity of this approach is confirmed by the reproducibility of the $^{207}Pb/^{206}Pb$ ages that are portrayed graphically in figure 6. By inference, the lower intercepts are 0 my.

Two of the seven zircon analyses from Peaked Mountain are slightly discordant; the other five are concordant (at 2 sigma). The two discordant analyses share a common $^{207}Pb/^{206}Pb$ age with the concordant analyses. These two grains have the highest U values (table 2) and, therefore, have accumulated the most radiation-induced damage to their crystal structures. Baddeleyite from Leighton Hill is also discordant. The baddeleyite crystals are small, delicate fragments that would not survive air-abasion; the lack of abrasion may explain the discordance. Baddeleyite shares a common $^{207}Pb/^{206}Pb$ age with concordant zircon in the rock. In each case the slight discordance observed in the Peaked Mountain and Leighton Hill samples is attributable to modern-day Pb-loss amounting to 9 percent or less.

Our ages are best interpreted as the crystallization age of the intrusive complexes. We see no evidence from either the isotopic data or the minerals themselves of inheritance, resorption, or metamorphic overgrowth. The Comerford analyses are concordant; the age is the time of zircon growth. The ages are: 418.5 ± 2 Ma, 419.3. ± 1.3 Ma, and 419.8 ± 2.6 Ma, for the Peaked Mountain, Leighton Hill, and Comerford quarry, respectively. The three dates overlap at 95 percent confidence and imply that the igneous complexes, now separated by a distance of ~40 km, were emplaced in a

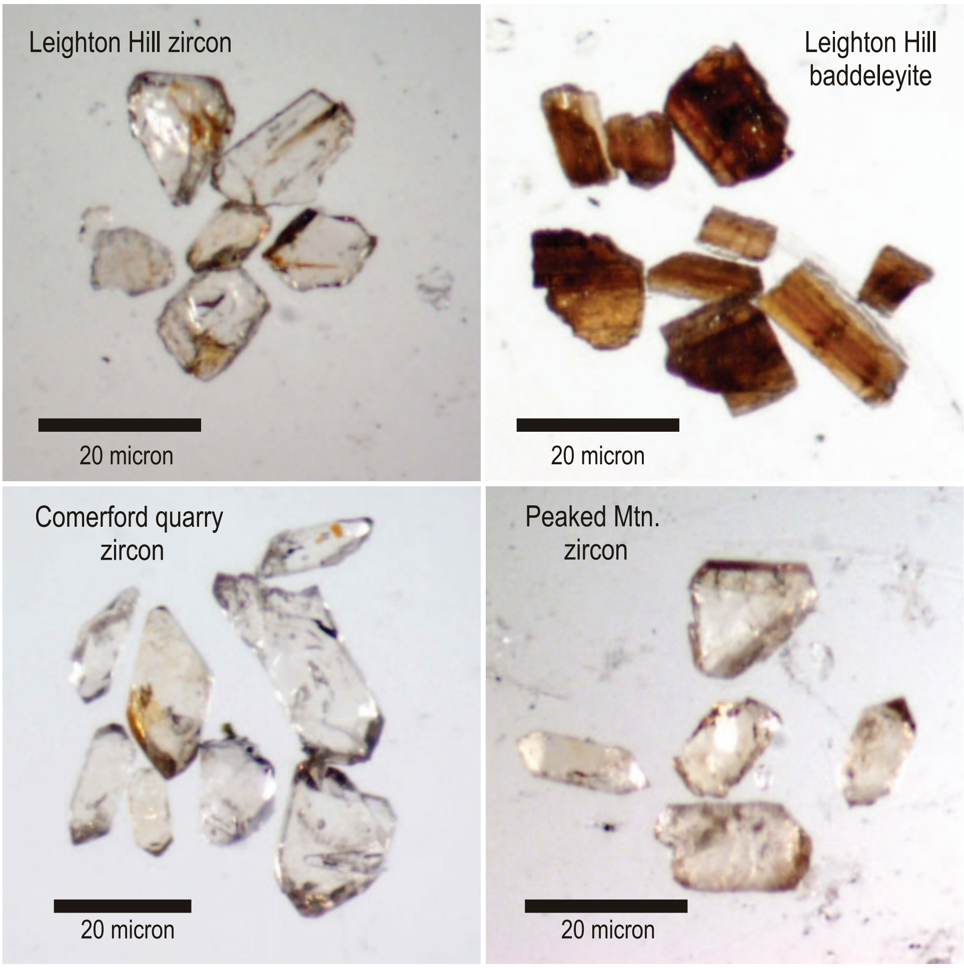


Fig. 5. Minerals analyzed for U-Pb geochronology include euhedral zircon and baddeleyite from the gabbro-diorite of Leighton Hill, euhedral zircon in coarse gabbro-diorite from the Comerford quarry, and euhedral zircon from the gabbro-diorite at Peaked Mountain.

remarkably short period near the Pridoli-Ludlow boundary of 418.7 (Gradstein and others, 2004). If all 20 analyses are grouped to a single regression, a precise ^{207}Pb/^{206}Pb age of 418.9 ± 0.9 Ma (that is 419 ± 1 Ma; MSWD = 0.321) is obtained (fig. 4). Because the intrusive complexes and sheeted dikes are linked chemically (see below), petrographically through xenoliths/segregations, and by their setting, we infer that the mean age of 419 ± 1 also establishes the time of sheeted dike emplacement.

Geochemistry

Chemistry of mafic dikes.—Sample locations are given in Appendix A. In spite of metamorphism, many elemental variations in mafic rocks reflect igneous trends and careful use of selected elements can provide much useful information about the igneous origin of metamorphosed rocks. Al, Ti, P, Zr, Y, Sc, and the REE are among the elements that have been shown to have the lowest mobility during metamorphism (Coish, 1977; Hellman and others, 1979; Hajash and Archer, 1980; Rollinson, 1993; Winter, 2001).

TABLE 2

U-Pb Isotope Dilution Analyses, Comerford Intrusive Suite

FRACTIONS		CONCENTRATIONS					ATOMIC RATIOS							AGE [Ma]	
No.	Properties (1)	Wt. [μg] (2)	Pb rad [ppm] (2)	U [ppm] (2)	Pb com [pg] (3)	$\frac{Th}{U}$ (4)	$\frac{^{206}Pb}{^{204}Pb}$ (5)	$\frac{^{207}Pb}{^{206}Pb}$ (6)	±	$\frac{^{207}Pb}{^{235}U}$ (6)	±	$\frac{^{206}Pb}{^{238}U}$ (6)	±	$\frac{^{207}Pb}{^{206}Pb}$ (6)	±
	PEAKED MOUNTAIN														
	Gabbro-diorite [NH-99-155]														
1	Z, cl, c, A	46	5.76	75.5	1.7	0.801	8,719	0.05510	7	0.5149	8	0.06778	9	416.2	2.7
2	Z, cl,c, A	30	7.92	103	1.3	0.850	10,248	0.05515	6	0.5104	8	0.06713	10	418.4	2.2
3	Z, 1, Cl,c,s-p, NA	16	8.63	115	6.6	0.773	1,195	0.05513	14	0.5099	27	0.06709	36	417.6	5.6
4	Z, Cl,c,s-p, NA	24	8.00	112	4.0	0.602	2,885	0.05513	9	0.5053	11	0.06647	12	417.6	3.8
5	Z, Cl,c,s-p, NA	27	6.53	88.8	5.6	0.724	1,889	0.05507	11	0.5032	12	0.06628	10	414.9	4.3
6	Z, cl,c,NA	51	13.9	183	6.9	0.994	5,498	0.05522	5	0.4889	11	0.06422	15	420.9	2.1
7	Z, Cl,c,s-p, NA	8	21.3	315	5.1	0.755	1,871	0.05520	16	0.4588	19	0.06028	30	420.4	6.6
	LEIGHTON HILL														
	Gabbro-diorite [VT-99-261]														
8	Z, ,c,s-p, NA	6	10.4	129	3.2	1.08	1,074	0.05507	17	0.5064	17	0.06670	13	414.9	6.8
9	B, pbl,c,s-p	19	14.5	205	13.2	0.660	1,270	0.05524	12	0.4912	14	0.06450	13	421.8	4.9
10	B, pbl,c,s-p	22	10.9	161	27.8	0.498	538.4	0.05523	12	0.4889	12	0.06421	9	421.4	4.8
11	B, pb,cl,c,s-p	26	12.4	187	15.3	0.493	1,343	0.05512	15	0.4841	17	0.06369	16	417.0	6.0
12	B, pb, Cl,c,t-p	37	6.62	97.1	10.7	0.610	1,378	0.05517	6	0.4812	8	0.06327	9	419.0	2.3
13	B, pb,c,t-p	24	14.1	216	11.8	0.518	1,800	0.05516	6	0.4729	8	0.06217	10	418.8	2.6
14	B, pb,	34	15.6	235	13.8	0.506	2,287	0.05518	6	0.4709	8	0.06190	9	419.5	2.3
	COMERFORD QUARRY														
	Gabbro-diorite [VT-94-105]														
15	Z, Cl,c	28	4.48	66.7	2.4	0.598	3,401	0.05513	13	0.5094	15	0.06702	13	417.3	5.2
16	Z, Cl,c	40	4.04	52.9	2.8	0.837	3,305	0.05521	12	0.5098	14	0.06697	13	420.9	4.9
17	Z, Cl,c	11	7.08	94.8	2.1	0.734	2,150	0.05525	20	0.5115	21	0.06715	13	422.3	8.2
18	Z, Cl,c	40	3.80	52.5	1.4	0.617	6,492	0.05521	8	0.5106	9	0.06708	9	420.7	3.0
19	Z, Cl,c	28	6.55	85.6	2.3	0.845	4,496	0.05524	10	0.5101	12	0.06698	12	421.9	4.1
20	Z, Cl,c	33	3.05	40.6	1.4	0.778	4,276	0.05508	11	0.50972	12	0.06711	9	415.6	4.5

Notes:

(1) B = baddeleyite; Z = zircon. Cardinal number indicates the number of mineral grains analyzed (e.g. 35 grains); all mineral grains were selected from non-paramagnetic separates at 0° tilt at full magnetic field in Frantz magnetic Separator; +200 = size in mesh (>75 μm); a = anhedral; c = colorless; cr = cracked; dbr = dark brown; eq = equant; eu = euhedral; f = faceted; fl = flat; fr = fragment; I = inclusion rich; 1-p = long-prismatic; n = needles; m-p = middle parts of prisms; p = prismatic; pb = pale brown; s-p = short-prismatic; t-p = tips from prisms; vpb = very pale brown. NA = not abraded; A = air-abraded following Krogh (1982).

(2) Concentrations are known to ± 30% for sample weights of about 30 μg and ±50% for samples < 3 μg.

(3) Corrected for 0.0125 mole fraction common-Pb in the ^{205}Pb-^{235}U spike.

(4) Calculated Th/U ratio assuming that all ^{208}Pb in excess of blank, common-Pb, and spike is radiogenic ($\lambda\ ^{232}Th = 4.9475 \times 10^{-11}\ y^{-1}$)

(5) Measured, uncorrected ratio.

(6) Ratio corrected for fractionation, spike, blank, and initial common-Pb (at the determined age from Stacey and Kramers, 1975). Pb fractionation correction = 0.094%/amu (±0.025%, 1σ); U fractionation correction = 0.111%/amu (±0.02% 1σ). U blank = 0.2 pg; Pb blank $\leq$ 10 pg. Absolute uncertainties (1σ) in the Pb/U and $^{207}Pb/^{206}Pb$ ratios calculated following Ludwig (1980). U and Pb half-lives and isotopic abundance ratios from Jaffey and others (1971).

The dikes range in composition, but within fixed limits typical of basalts (Winter, 2001). Critical parameters have the following ranges: SiO_2 (45 – 53 %), TiO_2 (1.1 – 3.5 %), Al_2O_3 (10 – 18 %), Fe_2O_3 (12 – 18 %), Zr (80 – 350 ppm), Y (35 – 65 ppm), Sc (35 – 50 ppm), and V (225 – 480 ppm) (table 3). Furthermore, all samples fall in the tholeiitic basalt field on a Zr-P2O5 diagram (fig. 7).

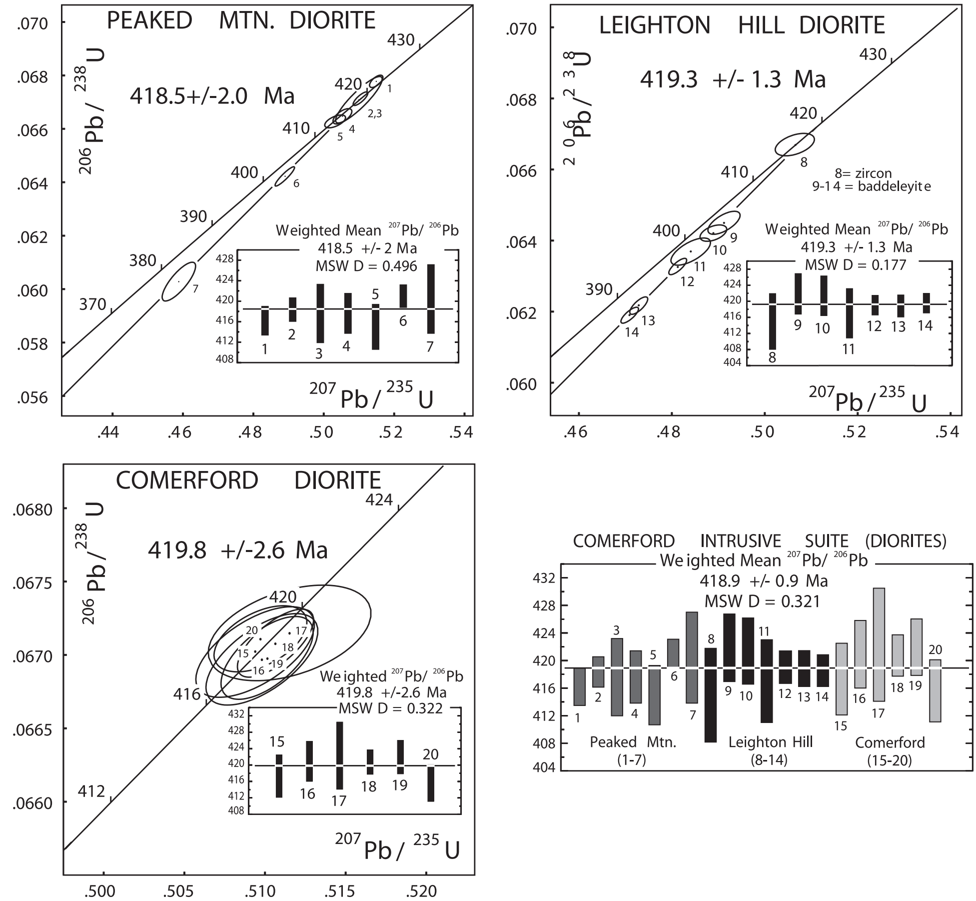


Fig. 6. Concordia diagrams for diorite from Peaked Mountain, Leighton Hill, and Comerford quarry. Numbered analyses of zircon and baddeleyite are keyed to table 1; 95% confidence ellipses are shown for individual analyses.

Samples from all locations overlap in most of their chemical constituents and thus appear to have been derived from the same or similar magmas. Many major and trace elements, especially the immobile elements, have ranges in compositions that mostly fall along well-defined trends (fig. 8). These variations are consistent with simple fractionation of common basaltic minerals during magma cooling. Although other processes, such as partial melting and contamination, may have affected these magmas, we describe the most straightforward and most likely process of crystal fractionation. Mg number (Mg/Mg+Fe) decreases during fractionation of basaltic magma and is thus used as a fractionation indicator (Cox, 1988; Wilson, 1989). In dikes from this study, Mg number shows a wide range, from somewhat fractionated (~60) to highly fractionated (~35) (fig. 8). Variation of other elements with Mg number provides useful information about the minerals that may have crystallized to produce the variation. In the Silurian dikes, FeO, TiO_2, Zr, V, and Y increase whereas Al_2O_3, Ni, and Cr decrease as Mg number decreases (fig. 8). Also, europium decreases relative to other REE as total REE concentration increases giving rise to a negative Eu anomaly in fractionated samples (fig. 9). The decrease in Ni and Cr with Mg number suggests that

TABLE 3

Major and trace element analyses of Silurian dikes and intrusive complexes, northeastern Vermont. Majors reported in wt. % and traces in ppm.

LEIGHTON HILL REGION DIKES (numbers 20A to 21 are from chilled margins, 01 to 44 are fine-grained, 2A to 40 are coarse-grained)

								Boltonville Dam							
Field #	SW-00-20A	SW-00-20B	SW-00-21	SW-00-01	SW-00-03	SW-00-15	SW-00-16	SW-00-17	SW-00-19	SW-00-24	SW-00-25	SW-00-27	SW-00-30	SW-00-31	SW-00-33
SiO_2	46.55	45.73	49.12	47.70	48.19	45.85	46.94	46.33	48.33	47.60	48.90	48.02	49.65	47.33	49.26
TiO_2	1.75	1.66	2.06	1.66	1.72	2.08	1.88	2.24	1.93	2.06	1.72	1.96	1.76	1.97	1.65
Al_2O_3	13.92	14.02	13.32	13.43	14.20	13.16	13.73	13.60	13.42	13.94	13.74	13.82	13.65	13.74	13.27
Fe_2O_3(t)	12.28	11.84	13.58	11.66	12.22	12.67	12.31	14.24	12.82	12.27	12.69	11.85	12.48	13.27	11.84
MnO	0.24	0.24	0.21	0.22	0.22	0.20	0.19	0.22	0.19	0.20	0.19	0.22	0.19	0.20	0.19
MgO	6.64	6.58	5.83	6.58	6.88	5.66	5.89	5.95	6.11	6.67	6.83	6.06	6.60	6.24	6.18
CaO	10.84	10.82	9.94	10.20	10.15	9.34	8.78	9.29	10.17	9.45	10.02	10.36	9.57	8.92	10.06
Na_2O	1.57	1.79	1.35	0.71	1.61	1.15	3.06	2.77	1.19	2.35	2.70	2.97	2.82	3.02	1.18
K_2O	0.06	0.09	0.93	0.99	0.10	2.01	0.10	0.15	0.22	0.31	0.08	0.15	0.11	0.19	1.31
P_2O5	0.18	0.16	0.22	0.14	0.17	0.20	0.19	0.23	0.16	0.23	0.18	0.24	0.18	0.20	0.16
LOI	4.7	5.2	2.2	3.9	3.2	6.7	5.7	3.1	3.0	3.1	2.2	2.9	2.1	2.4	3.7
Total	98.72	98.16	98.71	97.21	98.65	99.05	98.73	98.11	97.59	98.21	99.22	98.50	99.14	97.51	98.78
Mg#	*51.7*	*52.5*	*46.0*	*52.8*	*52.7*	*47.0*	*48.7*	*45.3*	*48.6*	*51.9*	*51.7*	*50.3*	*51.2*	*48.2*	*50.9*
K/P	*0.7*	*1.1*	*8.2*	*13.1*	*1.2*	*18.8*	*1.0*	*1.2*	*2.5*	*2.5*	*0.8*	*1.2*	*1.1*	*1.9*	*15.2*
Trace Elements															
Sc	43	43	45	47	44	43	43	46	40	41	44	45	38	41	41
V	359	353	384	349	325	366	350	407	357	358	330	328	330	384	326
Cr	191	202	40	245	236	108	136	95	120	183	144	181	169	153	178
Co	42	38	53	54	48	53	52	51	46	45	51	43	46	54	51
Ni	68	63	45	74	69	54	55	45	126	73	55	51	70	71	66
Cu	105	108	74	107	15	48	54	93	152	16	66	33	52	37	94
Zn	91	87	12	33	82	19	52	42	102		26	28	9	21	28
Sr	227	219	255	217	213	199	194	178	206	207	204	191	168	159	248
Y	39	38	47	42	39	46	45	50	42	37	39	40	44	44	38
Zr	105	104	130	111	107	128	122	140	144	137	104	128	104	123	106
Ba	12	16	198	179	13	131	9	14	22	72	9	26	17	30	157

TABLE 3

(continued)

LEIGHTON HILL REGION DIKES															
								Boltonville Dam							
Field #	SW-00-35	SW-00-36	SW-00-37	SW-00-41	SW-00-42	SW-00-43	SW-00-44	SW-00-2A	SW-00-2B	SW-00-14	SW-00-18	SW-00-22	SW-00-23	SW-00-26	SW-00-29
SiO_2	49.43	50.92	48.82	48.27	48.41	47.98	51.47	48.84	46.86	46.08	44.94	49.00	45.83	48.77	43.41
TiO_2	2.24	2.18	2.34	1.63	2.19	1.50	2.16	1.40	1.48	1.76	1.15	1.97	1.28	1.60	1.70
Al_2O_3	13.31	12.85	13.77	15.28	13.83	14.18	13.61	14.56	15.01	14.17	14.88	14.35	14.24	14.89	14.76
Fe_2O_3(t)	13.03	13.20	12.84	11.09	13.28	10.05	12.97	11.00	10.92	10.82	8.90	12.63	10.04	11.59	11.65
MnO	0.21	0.20	0.20	0.17	0.24	0.18	0.23	0.16	0.14	0.17	0.14	0.20	0.16	0.19	0.19
MgO	5.44	5.12	5.66	7.07	5.64	4.71	5.33	7.16	7.34	6.26	7.61	5.86	7.12	6.13	6.83
CaO	9.38	8.64	8.15	10.04	9.42	12.04	9.01	9.63	9.11	8.45	9.74	9.87	9.64	8.85	8.04
Na_2O	2.60	2.99	3.18	3.11	2.76	2.72	2.42	2.56	2.76	2.27	2.75	2.63	3.13	3.56	3.25
K_2O	0.50	0.26	0.39	0.07	0.39	0.08	0.49	0.30	0.32	0.39	0.14	0.26	0.09	0.06	0.26
P_2O5	0.27	0.29	0.29	0.17	0.28	0.15	0.24	0.12	0.13	0.20	0.09	0.24	0.14	0.14	0.18
LOI	1.7	1.6	2.0	2.4	1.7	4.9	1.9	3.7	3.4	6.7	6.9	2.1	6.2	4.0	8.5
Total	98.14	98.22	97.66	99.30	98.16	98.50	99.85	99.38	97.43	97.29	97.29	99.10	97.88	99.80	98.77
Mg#	*45.3*	*43.4*	*46.7*	*55.8*	*45.7*	*48.2*	*44.9*	*56.4*	*57.2*	*53.4*	*62.9*	*47.9*	*58.4*	*51.2*	*53.7*
K/P	*3.6*	*1.7*	*2.5*	*0.8*	*2.7*	*1.0*	*4.0*	*4.7*	*4.8*	*3.6*	*2.9*	*2.0*	*1.2*	*0.8*	*2.7*
Trace Elements															
Sc	41	41	43	40	43	34	41	42	43	41	35	41	38	40	37
V	363	355	380	307	357	270	345	296	296	298	235	342	272	303	298
Cr	61	51	59	260	103	178	63	270	288	229	304	175	270	174	230
Co	52	42	44	50	53	47	52	49	49	47	44	50	44	47	47
Ni	56	42	44	79	53	66	45	87	88	80	119	82	92	63	107
Cu	39	45	28	72	8	126	40	71	74	65	71	51	56	40	13
Zn	37	22	26	30	23	26	11	64	57	36	97	7	27	23	3
Sr	207	185	156	183	196	293	163	171	180	241	162	206	150	158	166
Y	47	50	52	35	46	35	47	32	34	46	25	45	31	35	38
Zr	156	168	166	94	143	95	158	84	89	152	82	132	85	97	119
Ba	107	50	84	14	68	18	44	56	21	21	64	48	51	34	7

TABLE 3

(continued)

LEIGHTON HILL REGION DIKES	*Boltonville Dam*					*Newbury Quarry*							*I-91*		
Field #	SW-00-32	SW-00-34	SW-00-38	SW-00-39	SW-00-40	SW-00-52	SW-00-53	SW-00-54	SW-00-55	SW-00-56	SW-00-57	SW-00-58	SW-00-04	SW-00-05	SW-00-06
SiO_2	47.31	48.12	47.67	47.11	47.79	47.93	48.29	46.96	47.49	48.01	46.64	43.79	48.17	47.02	47.70
TiO_2	1.36	1.50	1.36	1.58	1.56	1.80	2.08	2.05	1.33	1.66	1.89	1.73	2.34	2.44	1.66
Al_2O_3	16.08	15.78	15.32	14.37	14.68	15.22	13.63	12.58	15.44	14.22	12.14	13.62	12.52	12.98	14.56
Fe_2O_3(t)	10.50	10.82	10.10	11.87	11.00	11.58	13.10	12.30	9.78	11.03	12.38	10.88	13.14	13.90	10.67
MnO	0.18	0.15	0.15	0.17	0.15	0.19	0.20	0.23	0.16	0.19	0.17	0.18	0.22	0.24	0.17
MgO	6.53	6.41	7.55	7.19	7.28	6.35	5.78	4.78	7.37	6.83	5.13	5.63	4.56	5.28	6.86
CaO	9.45	8.65	10.39	9.32	9.40	9.82	9.88	7.70	10.65	10.21	8.62	9.10	7.56	8.13	10.25
Na_2O	2.84	3.44	2.60	2.44	2.68	2.76	2.50	2.32	2.31	2.68	2.56	2.23	2.24	2.99	2.71
K_2O	0.05	0.24	0.03	0.12	0.40	0.51	0.70	1.58	0.33	0.42	0.12	1.01	1.65	1.48	0.16
P_2O5	0.12	0.14	0.13	0.16	0.15	0.23	0.21	0.24	0.14	0.18	0.17	0.17	0.33	0.29	0.15
LOI	4.3	3.6	3.5	2.9	4.7	2.3	1.9	8.4	2.7	2.1	9.4	11.0	6.5	3.6	3.4
Total	98.72	98.84	98.84	97.24	99.83	98.72	98.26	99.10	97.65	97.52	99.20	99.30	99.25	98.33	98.31
Mg#	*55.2*	*54.0*	*59.7*	*54.6*	*56.8*	*52.1*	*46.6*	*43.5*	*59.9*	*55.1*	*45.1*	*50.7*	*40.8*	*43.0*	*56.1*
K/P	*0.7*	*3.1*	*0.5*	*1.4*	*5.0*	*4.2*	*6.5*	*12.6*	*4.6*	*4.6*	*1.3*	*11.6*	*9.7*	*9.8*	*2.0*
Trace Elements															
Sc	41	38	39	41	40	36	42	39	35	39	40	34	37	40	36
V	393	291	273	312	294	271	353	337	263	297	358	283	329	379	270
Cr	143	216	298	213	250	166	77	43	240	274	62	177	63	69	219
Co	52	49	47	54	49	44	51	42	44	44	47	46	45	36	48
Ni	64	69	99	78	81	71	48	32	124	93	46	90	48	39	101
Cu	36	48	62	74	66	55	64	41	86	62	76	52	27	35	88
Zn	26	47	38	36	26	42	39	109	82	85	30	40	48	41	22
Sr	158	198	212	169	176	203	165	169	181	191	156	208	125	130	186
Y	37	32	30	35	33	41	46	45	34	37	44	36	58	51	35
Zr	120	88	84	94	97	133	137	157	108	129	130	105	202	163	109
Ba	32	80	30	31	9	89	116	129	48	85	24	157	94	154	7

TABLE 3

(continued)

	LEIGHTON HILL REGION DIKES									**COMERFORD REGION DIKES**					
	I-91				*Leighton Hill*					*Comerford Dam*					
Field #	SW-00-07	SW-00-08	SW-00-09	SW-00-10	SW-00-46	SW-00-47	SW-00-48	SW-00-49	SW-00-51	AR-97-8	AR-97-13	AR-97-14	AR-97-15	AR-97-16b	AR-97-17a
SiO_2	48.51	46.30	47.67	48.41	47.67	50.20	49.25	47.98	45.24	49.97	44.86	46.43	48.96	48.50	49.22
TiO_2	2.64	1.54	2.00	1.85	1.72	2.28	2.21	1.64	1.92	1.70	1.58	2.33	1.85	3.32	2.45
Al_2O_3	12.08	14.20	14.15	15.26	14.25	13.48	13.35	12.99	14.84	15.88	12.82	12.16	16.00	12.85	14.51
Fe_2O_3(t)	14.28	10.43	12.49	11.79	12.13	14.49	14.12	13.58	13.96	12.63	10.64	12.29	9.81	15.62	13.56
MnO	0.24	0.30	0.20	0.18	0.19	0.23	0.22	0.20	0.24	0.13	0.17	0.23	0.16	0.24	0.21
MgO	4.14	5.18	6.04	6.67	7.16	4.87	4.95	5.18	7.09	7.23	6.25	4.75	5.45	5.28	6.46
CaO	7.50	9.39	7.52	8.46	9.71	8.17	9.07	9.52	9.84	3.59	8.36	9.35	11.21	9.09	8.30
Na_2O	0.14	2.90	2.17	3.23	2.81	3.27	2.85	3.09	2.51	2.48	2.57	2.60	3.26	3.08	3.79
K_2O	1.46	0.28	1.09	0.28	0.05	0.13	0.10	0.27	0.08	0.04	0.05	0.25	0.13	0.42	0.17
P_2O5	0.28	0.17	0.25	0.20	0.15	0.24	0.27	0.16	0.17	0.18	0.15	0.25	0.14	0.28	0.34
LOI	6.8	8.2	4.3	2.6	2.7	1.6	1.8	4.5	2.4	4.7	9.7	9.3	3.4	2.0	3.0
Total	98.09	98.91	97.87	98.92	98.53	99.00	98.18	99.08	98.30	98.49	97.13	99.97	100.32	100.66	101.95
Mg#	*36.5*	*49.6*	*49.0*	*52.9*	*54.0*	*40.0*	*41.0*	*43.1*	*50.2*	*52.4*	*53.8*	*43.4*	*52.4*	*40.2*	*48.6*
K/P	*10.1*	*3.0*	*8.3*	*2.7*	*0.7*	*1.1*	*0.7*	*3.1*	*0.9*	*0.4*	*0.6*	*1.9*	*1.8*	*2.8*	*0.9*
Trace Elements															
Sc	38	36	36	41	39	38	38	45	46	45	43	43	45	44	42
V	404	261	289	315	300	336	373	289	336	297	288	352	284	418	318
Cr	31	212	163	185	209	55	48	295	315	245	208	46	218	39	159
Co	40	41	41	48	47	41	51	33	60						
Ni	36	55	85	70	80	34	47	147	88	80	64	61	81	44	84
Cu	120	10	72	48	77	39	30	19	12	19	38	62	142	149	91
Zn	43	142	92	60	44	42	131	70	151						
Sr	249	157	161	202	165	155	199	124	165	114	85	104	200	112	143
Y	55	35	46	43	35	50	46	47	34	42	41	57	44	61	57
Zr	177	110	139	149	90	142	182	133	110	136	127	212	136	229	205
Ba	171	34	85	44	9	9	23	13	13	11	8	23	21	56	23

Table 3

(continued)

COMERFORD REGION DIKES

	Comerford Dam									*Comerford Quarry*					
Field #	AR-97-32	AR-97-33	AR-97-34	AR-97-35	AR-97-36a	AR-97-37	AR-97-38	AR-97-40a	VT-92-16	AR-97-1	AR-97-4	AR-97-5	AR-97-6	AR-97-7	AR-97-10
SiO_2	49.21	48.42	48.42	45.21	48.73	48.73	49.29	47.77	49.90	48.04	49.93	47.57	49.40	47.84	49.33
TiO_2	1.58	1.42	1.78	1.69	2.63	1.95	2.03	1.92	2.40	2.28	3.18	3.40	3.46	1.88	1.63
Al_2O_3	15.87	16.77	12.85	13.93	13.77	14.43	15.29	14.90	13.50	12.90	13.33	12.62	12.80	14.03	14.28
Fe_2O_3(t)	10.92	9.35	11.21	10.97	13.95	12.36	11.38	12.13	13.60	15.00	15.94	16.64	16.67	13.08	11.83
MnO	0.18	0.13	0.21	0.18	0.22	0.20	0.21	0.19	0.23	0.23	0.26	0.26	0.27	0.21	0.18
MgO	6.71	6.41	5.52	6.51	5.44	6.00	5.81	6.56	5.59	5.34	5.86	4.83	4.80	6.49	6.59
CaO	9.38	5.99	9.48	9.26	8.73	9.55	10.68	10.41	8.88	9.69	9.86	9.32	9.21	10.50	9.75
Na_2O	3.69	4.16	1.97	3.02	3.21	3.29	2.10	2.64	3.68	3.26	2.94	3.04	3.09	3.08	3.64
K_2O	0.14	0.07	0.16	0.05	0.35	0.20	0.34	0.14	0.19	0.20	0.52	0.27	0.22	0.16	0.12
P_2O5	0.15	0.14	0.17	0.15	0.27	0.19	0.19	0.20	0.27	0.08	0.32	0.38	0.36	0.22	0.14
LOI	2.7	6.4	8.9	10.1	2.7	2.3	3.0	2.0	2.4	1.1	0.1	1.0	0.9	1.3	1.7
Total	100.55	99.23	100.64	101.04	99.97	99.22	100.35	98.84	100.59	98.15	102.24	99.30	101.20	98.81	99.20
Mg#	*54.9*	*57.6*	*49.4*	*54.1*	*43.6*	*49.0*	*50.3*	*51.8*	*44.9*	*41.0*	*42.2*	*36.5*	*36.4*	*46.3*	*52.5*
K/P	*1.8*	*0.9*	*1.8*	*0.7*	*2.4*	*2.0*	*3.4*	*1.4*	*1.3*	*4.8*	*3.1*	*1.4*	*1.2*	*1.4*	*1.6*
Trace Elements															
Sc	44	34	40	43	43	40	44	42	42.1	41	46	43	43	40	44
V	295	245	304	302	381	335	313	322	380	360	477	478	481	324	289
Cr	242	240	141	236	106	133	113	203	32	47	83	57	57	84	129
Co									40.7						
Ni	64	72	54	74	57	54	57	87	33	48	61	66	65	52	54
Cu	24	71	35	25	32	66	25	36	29	92	52	63	53	64	55
Zn									88						
Sr	197	147	141	98	157	182	222	254	158	90	150	147	124	136	147
Y	41	37	49	45	59	46	49	45	43	47	58	67	67	44	40
Zr	126	125	183	152	225	155	186	148	180	119	197	241	234	135	127
Ba	27	11	16	10	45	34	27	19	11	25	148	47	27	37	26

Table 3
(continued)

COMERFORD REGION DIKES

	Comerford Quarry			*Pike Industries Quarry*					*Badger Mountain*			*River Rd*
Field #	AR-97-11	AR-97-18b	AR-97-19	VT-93-50	VT-93-51	VT-93-108	VT-93-109	VT-93-54	VT-93-74	VT-93-75	VT-93-76	VT-92-6
SiO_2	48.20	45.95	49.17	45.50	48.70	44.10	43.70	48.70	46.60	47.30	49.10	48.40
TiO_2	2.68	3.32	1.47	2.07	1.45	1.44	2.70	1.81	1.49	2.14	2.72	1.65
Al_2O_3	13.26	12.75	14.38	12.50	15.10	13.70	13.80	14.40	14.00	13.10	13.60	15.00
Fe_2O_3(t)	16.23	17.77	11.82	12.60	10.80	9.92	14.20	12.00	10.40	11.60	13.50	11.20
MnO	0.26	0.27	0.18	0.24	0.19	0.16	0.23	0.20	0.17	0.19	0.23	0.20
MgO	5.45	5.61	7.15	5.69	7.53	6.61	5.50	6.97	7.15	5.06	5.38	7.16
CaO	9.49	10.11	9.31	9.11	11.00	10.10	7.76	10.80	10.60	8.48	8.98	11.20
Na_2O	3.04	2.24	3.52	2.22	3.01	3.12	2.83	2.83	3.26	2.99	2.57	2.75
K_2O	0.20	0.22	0.12	0.46	0.07	0.07	1.14	0.35	0.10	0.76	0.86	0.15
P_2O5	0.22	0.32	0.14	0.23	0.20	0.15	0.35	0.22	0.16	0.28	0.34	0.20
LOI	1.2	1.4	1.8	10.3	2.7	10.2	6.8	2.5	5.8	8.8	3.4	2.7
Total	100.19	99.99	99.05	100.96	100.72	99.57	99.02	100.74	99.68	100.72	100.65	100.56
Mg#	*40.0*	*38.5*	54.6	*47.3*	*58.0*	*56.9*	*43.4*	*53.5*	*57.7*	*46.4*	*44.1*	*55.9*
K/P	*1.7*	*1.3*	1.6	*3.8*	*0.7*	*0.9*	*6.2*	*3.0*	*1.2*	*5.2*	*4.8*	*1.4*
Trace Elements												
Sc	46	48	45	40	40	35	37	40	40	37	40	41
V	415	438	272	360	280	280	390	310	290	330	410	300
Cr	52	78	118	74	269	223	100	214	277	62	109	200
Co				42	41	38	42	41	40	34	37	30
Ni	51	59	64	38	76	74	50	57	58	27	51	67
Cu	63	125	25	49	44	28	40	50	73	23	44	7
Zn				84	89	85	96	90	85	96	62	88
Sr	104	87	125	73	194	162	104	166	164	150	215	215
Y	64	67	36	39	28	27	56	36	28	42	57	30
Zr	232	194	107	156	116	100	235	144	108	210	245	116
Ba	27	30	29	47	19	18	215	55	17	138	186	33

TABLE 3

(continued)

COMPOSITE INTRUSIVE									
					Comerford Quarry				
Field #	AR-97-2	AR-97-3	AR-97-9	AR-97-24	AR-97-41a	AR-97-42	AR-97-43	AR-97-45	AR-97-46
SiO_2	48.24	50.77	43.12	47.04	47.24	50.54	49.89	46.56	48.59
TiO_2	0.93	0.82	0.42	0.57	1.90	0.79	0.71	0.60	0.85
Al_2O_3	16.39	15.06	20.25	19.09	14.73	17.37	16.72	16.82	17.33
Fe_2O_3(t)	8.38	7.65	5.21	6.59	11.99	6.28	7.46	6.31	6.88
MnO	0.15	0.15	0.09	0.11	0.19	0.11	0.14	0.11	0.12
MgO	6.68	8.02	1.14	6.58	6.49	5.22	5.95	6.62	6.33
CaO	10.98	14.08	18.26	11.91	10.29	12.16	11.65	12.48	12.33
Na_2O	3.61	2.54	3.26	3.21	2.61	3.54	3.25	2.68	3.04
K_2O	0.11	0.08	0.26	0.20	0.06	0.07	0.08	0.08	0.15
P_2O5	0.09	0.07	0.09	0.06	0.06	0.09	0.07	0.06	0.08
LOI	2.8	1.1	8.6	2.4	3.0	1.8	1.9	7.8	2.0
Total	98.40	100.31	100.76	97.78	98.54	98.00	97.80	100.07	97.64
Mg#	*61.3*	*67.5*	*30.2*	*66.5*	*51.8*	*62.3*	*61.3*	*67.6*	*64.6*
K/P	*2.3*	*2.4*	*5.4*	*6.3*	*1.9*	*1.5*	*2.2*	*2.9*	*3.6*
Trace Elements									
Sc	37	50	13	31	30	38	39	39	42
V	206	215	98	140	144	178	189	173	191
Cr	234	223	57	321	331	117	177	261	210
Co									
Ni	80	92	29	94	90	41	48	71	66
Cu	54	49	28	55	66	18	31	25	49
Zn									
Sr	216	153	605	256	230	184	120	164	194
Y	20	20	41	22	20	32	29	23	28
Zr	43	45	163	57	50	116	127	54	78
Ba	65	40	96	54	54	52	32	60	65

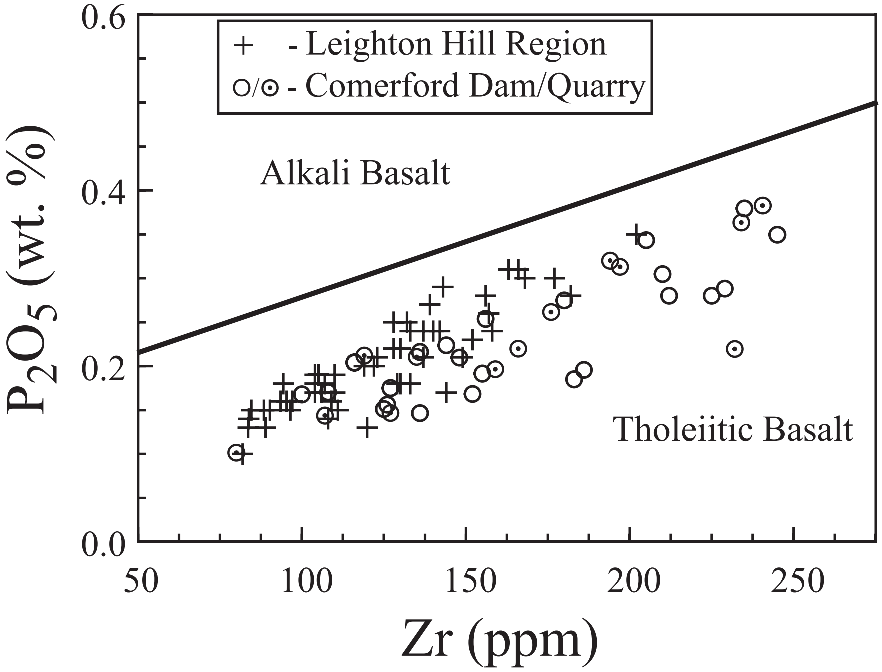


Fig. 7. Classification of Comerford and Leighton Hill dikes. Dikes fall in the tholeiitic basalt field in a Zr - P_2O_5 diagram (Winchester and Floyd, 1976). On this and following figures circles with a central dots represent analyses of the intrusive complex.

olivine (possibly with chromian spinel) fractionated from the primitive magmas of the dikes. Clinopyroxene is also a mineral that carries Cr. However, because Sc, which is preferentially incorporated in clinopyroxene, does not vary systematically with Mg number, clinopyroxene was probably not an important fractionating phase. The decrease in Al_2O_3 with Mg number and the presence of small negative Eu and large Sr anomalies is consistent with fractionation of Ca-rich plagioclase. The increase in Zr, V, Y, and REE with decreasing Mg number is consistent with fractionation of phases with low partition coefficients for those elements, for example, olivine and plagioclase. P-Zr (fig. 7), Ti-Zr (fig. 10B), and Y-Zr are positively correlated, as would be expected if they were behaving as incompatible elements. TiO_2 increases systematically with V and both increase with decreasing Mg number, indicating they both behaved incompatibly (accumulated in the residual liquid) during fractionation, which in turn suggests that titanomagnetite did not fractionate from the magma.

REE values range from about 15x to 50x chondrite; patterns are generally flat to slightly enriched in the light REE relative to heavy REE ($(La/Yb)_N$ ratios are from 1.1 to 2.5 with an average of 1.4) (fig. 9). A few dikes from the Comerford Dam spillway have higher total rare earths than other samples - this is probably a reflection of the degree of fractionation of those samples as suggested by the positive correlation of total REE with Ti content (fig. 11). Note that the rest of the sampled dikes at Comerford Dam have compositions similar to dikes from the other sites (figs. 8, 9, and 11), suggesting that all of the dikes are part of the same magmatic suite. In spider diagrams, dike samples show relatively flat patterns (at 10 to 30x mantle values in high field-strength elements (HFSE)), with notable negative anomalies in Sr. Elements on the left side of the diagrams show "spiky" patterns, often attributed to chemical mobility of these elements during metamorphism (fig. 12).

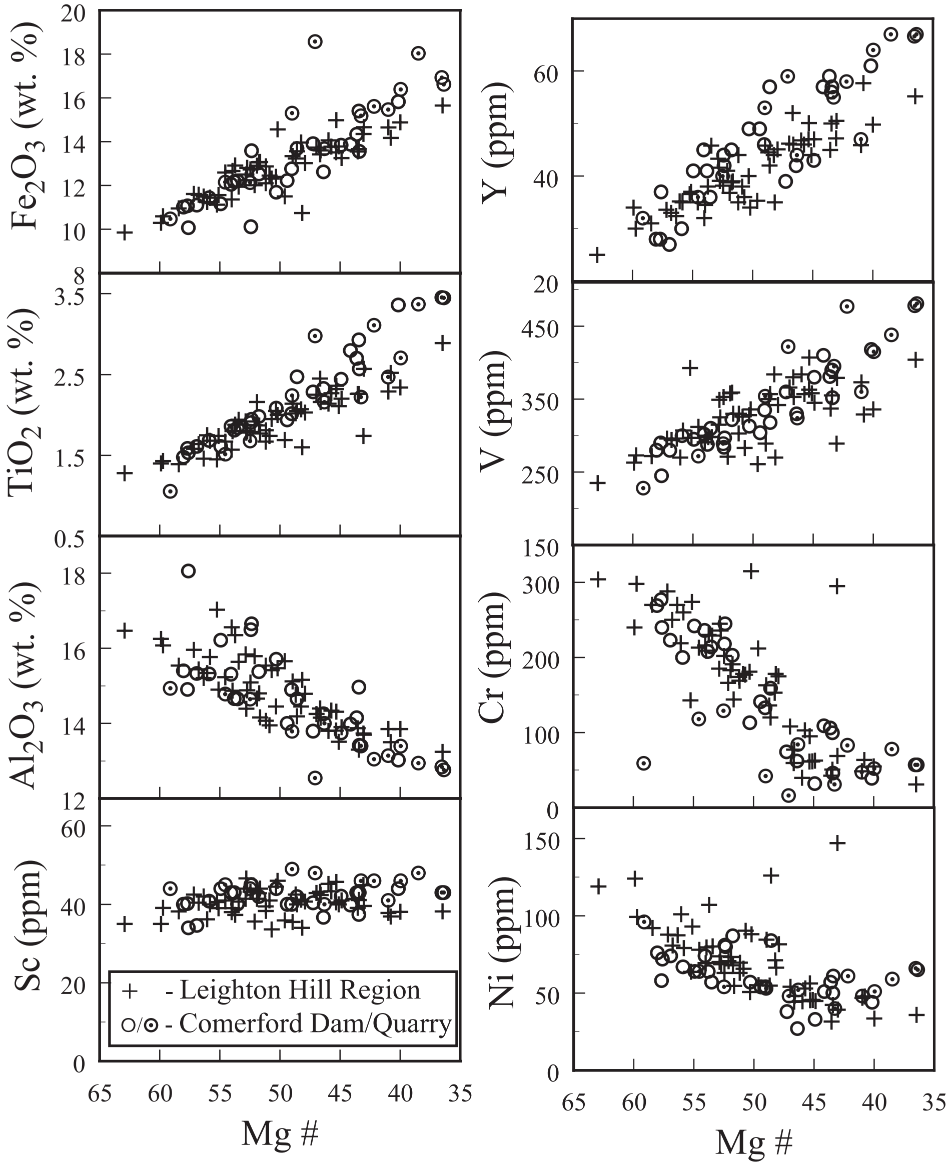


Fig. 8. Variation of selected elements with Mg number (Mg/Mg + Fe^{+2}) for dikes. Note the increase in Fe, Ti, Y, and V, decrease in Al, Cr, and Ni and near constancy of Sc as Mg number decreases.

If we assume the entire spread in incompatible element compositions is due to fractional crystallization, we can estimate the total amount of fractionation. We can calculate this treating Y as an incompatible element by using the simple Rayleigh fractionation equation, $C_l / C_o = 1 / F$, where C_l is concentration of trace element in fractionated magma, C_o is concentration of trace element in original magma, and F is fraction of magma remaining. For the Silurian dikes of this study, if we take the minimum (32 ppm) and maximum (67 ppm) Y values to represent the most primitive and most fractionated magmas respectively, then the total amount of fractionation is

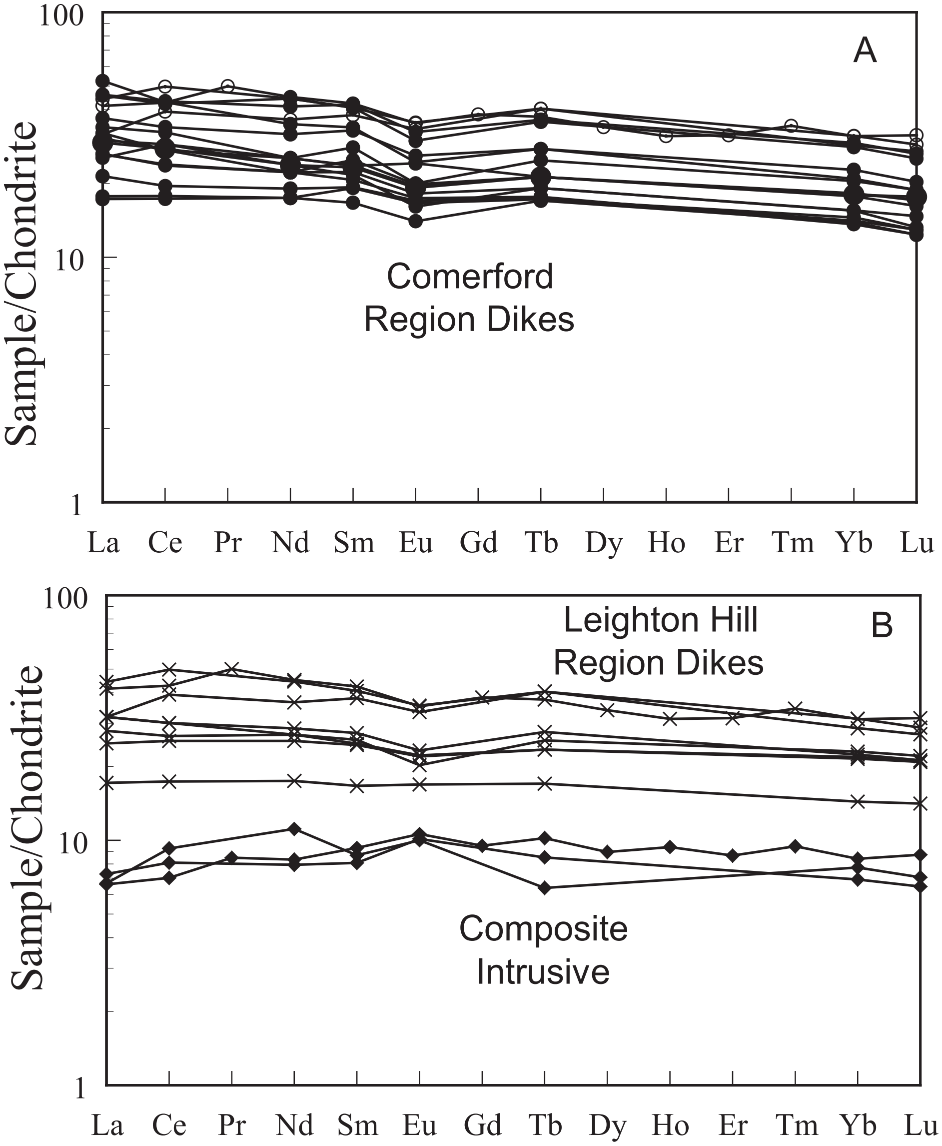


Fig. 9. Rare earth element patterns normalized to chondritic meteorite (Nakamura, 1974) for Silurian dikes and gabbro-diorite of the Comerford Intrusive Suite. (A) Dikes from the Comerford region. (B) Dikes from the Leighton Hill region and gabbro-diorite of the intrusive complex of Comerford quarry. In the Comerford region, closed symbols are samples from the dam site and open symbols from the quarry site.

about 50 percent. This estimate is consistent with another incompatible element, La, which ranges in concentration from 6x to about 14x chondrite (fig. 9).

Chemistry of the composite intrusive.—Plutonic rocks from the Comerford quarry and Leighton Hill area range in composition from gabbro to leucocratic tonalite (Rankin, 1996a). Their chemistry is significantly different from the mafic dikes: the gabbro-diorite samples have a wider range of MgO contents, higher Al_2O_3, and lower P_2O_5, and TiO_2. Zr and Y contents are lower in most samples but do overlap with dike

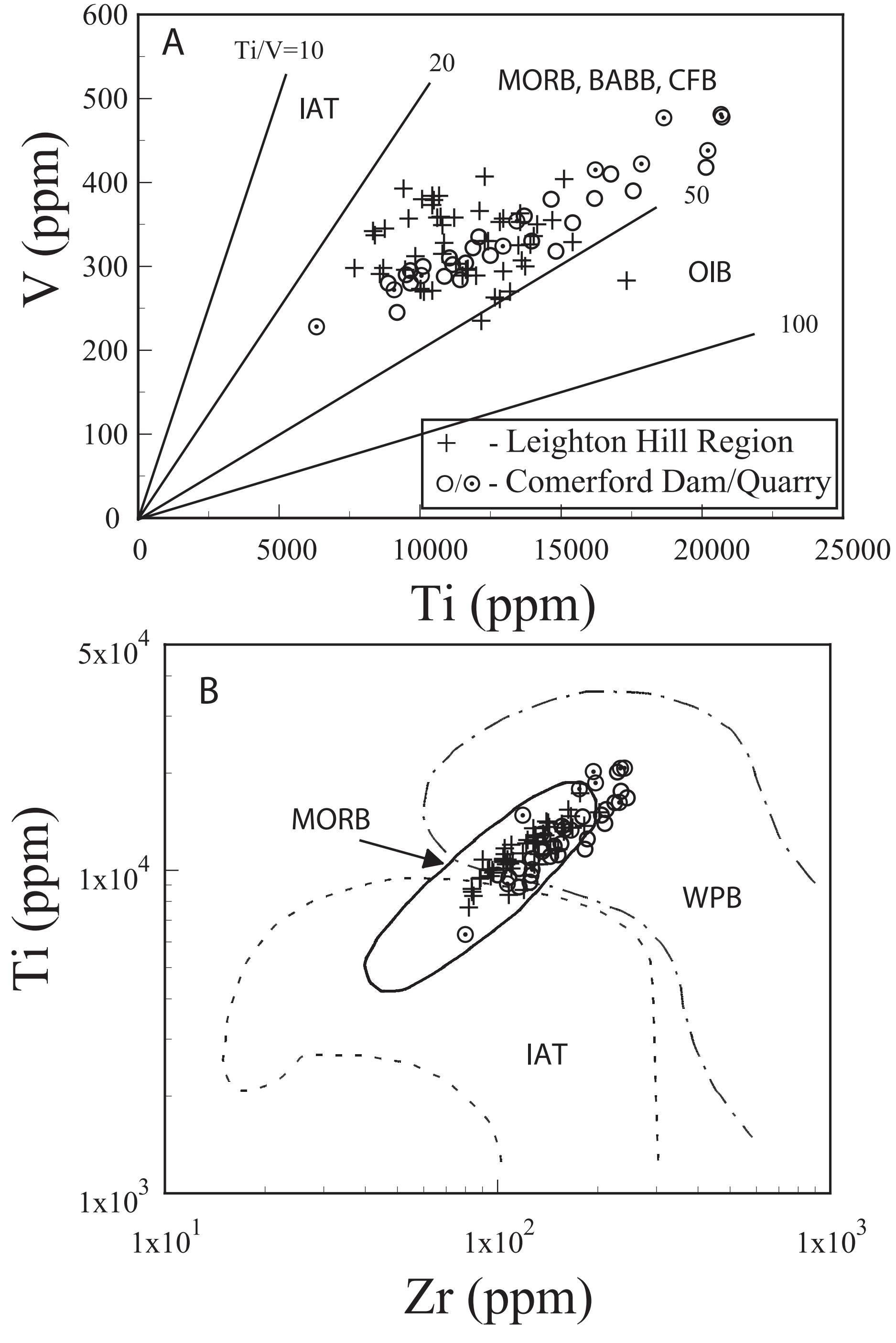


Fig. 10. Tectonic discriminant diagrams for Silurian dikes of the Comerford Intrusive Suite. The dikes fall within the mid-ocean ridge (MORB) – back-arc basin (BABB) – continental flood basalt (CFB) in a Ti-V diagram (Shervais, 1982), and in MORB and with-in plate (WPB) fields in a Ti-Zr diagram (Pearce, 1982).

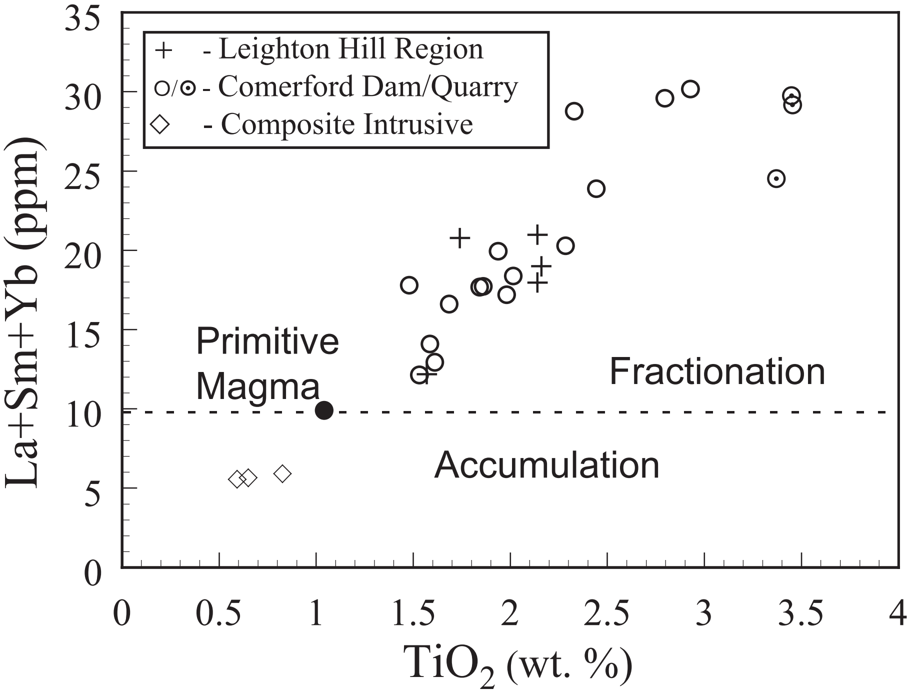


Fig.11. Variation of TiO_2 and total rare earth element contents in Silurian dikes and gabbro-diorite of the Comerford Intrusive Suite. Solid dot represents a possible primitive magma from which fractionation led to the dike compositions and accumulation to some of the gabbro-diorite complex compositions.

compositions. The REE content is lower (less than 10x chondrite) than in the dikes (generally greater than 30x chondrite). Furthermore, gabbro-diorite complex samples have positive Eu and Sr anomalies in chondrite-normalized diagrams (figs. 9 and 12). These latter characteristics are consistent with the observation that the samples are plagioclase-rich. We surmise that the gabbro-diorite formed, at least in part, by the accumulation of plagioclase crystals from the same primitive magma that fractionated to form the dikes (fig. 11). The accumulation diluted element concentrations of most REE and other trace elements, except Eu (and Sr), which are strongly partitioned into plagioclase. Thus, many of the gabbro-diorite samples do not represent liquid compositions, but rather some mixture of solid plus magma.

DISCUSSION

Tectonic environment of formation.—Field evidence suggests the Comerford Intrusive Suite formed in a continental region. The Silurian dikes intrude the Albee Formation and rocks of the Bronson Hill arc, which is built on the Albee. The quartz-rich sandstones that characterize the Albee certainly had a continental source and the prevalence of turbidites indicates deposition in a large body of water. In the Littleton area, the Ammonoosuc Volcanic unit is about 50 percent rhyolite, some characterized by quartz (and plagioclase) phenocrysts as large as 5 mm. Thus the Littleton segment of the Bronson Hill arc probably developed close to a continental margin. All pre-Silurian rocks of the Bronson Hill sequence were deformed and metamorphosed before intrusion of the Comerford Intrusive Suite. Thus, the dikes were emplaced into an already deformed continental setting probably undergoing active extension.

Tectonic discriminant diagrams indicate considerable overlap in tectonic environments of formation for the dikes (fig. 10). Close analysis, however, yields one useful

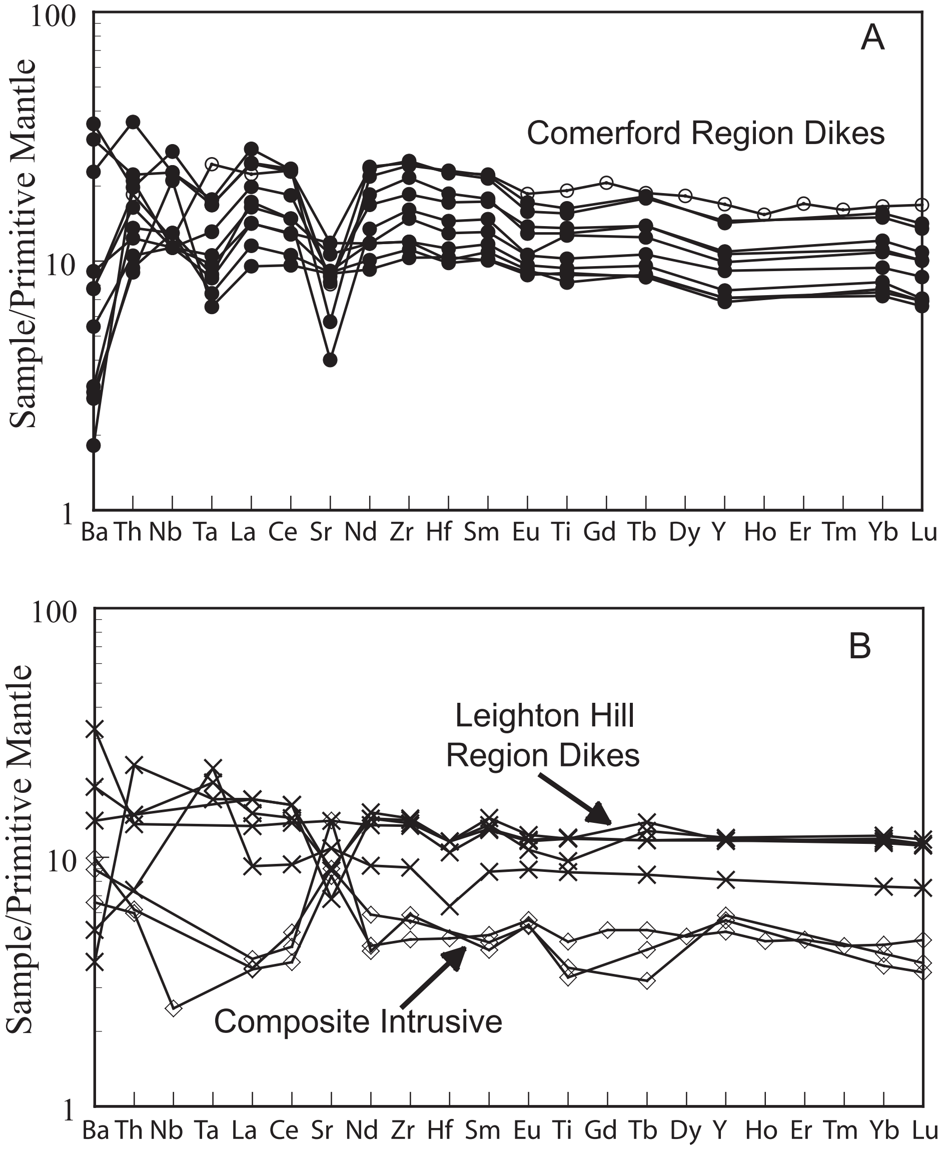


Fig. 12. Element-normalized diagrams (after Hofmann, 1988) for Silurian dikes and composite intrusive of this study. (A) Dikes from the Comerford region. (B) Dikes from the Leighton Hill region and gabbro-diorite of the intrusive complex of Comerford quarry. In the Comerford region, closed symbols are samples from the dam site and open symbols from the quarry site.

conclusion: the composition of the dikes is not consistent with their origin in a volcanic arc. Two examples illustrate this. In a Ti-V diagram (fig. 10A) the dikes have Ti/V ratios between 20 and 50 (fig. 10A) and plot in a region of overlap between mid-ocean ridge, back-arc basin, and continental flood basalts. In Ti-Zr space (fig. 10B), the dikes fall in the overlap fields of ocean-floor and within-plate basalts. The fields in which the dikes plot (ocean floor, within-plate, and back-arc basin) all are extensional environments; all typically have a significant component of asthenospheric mantle in their sources (Wilson, 1989) and have compositions that overlap considerably.

Magma sources.—La/Ta ratios have been used to distinguish between asthenospheric and lithospheric magma sources in rift related environments (Fitton and others, 1988; Leat and others, 1988; Thompson and Morrison, 1988). Leat and others (1988) suggested that rocks with La/Ta < 22 are derived from an asthenospheric source and have undergone little to no contamination from continental crust or mantle lithosphere. Thompson and Morrison (1988) proposed that values of La/Ta < 22 indicate an asthenospheric source only, values of 22 to 30 show no crustal contamination but perhaps some mantle lithospheric contamination, and values >30 indicate significant crustal or mantle lithospheric contamination. Based on 16 samples with reliable Ta values, the La/Ta ratios in the Silurian dikes of this study average about 25 (range 7 – 34, table 4). We conclude then that the main source of the magmas was asthenospheric mantle with a small contribution from lithospheric mantle.

Ti/Yb ratios have been used to determine crustal contamination levels (Leeman and Hawkesworth, 1986) because Ti is typically present in low concentrations in crustal material. High ratios, typically in the thousands, suggest that crustal contamination is not significant, whereas low ratios are inconclusive. The Ti/Yb ratios for the Silurian dikes range from 2100 to 3300 (table 4). Thus Ti/Yb ratios in the dikes are consistent with little crustal contamination.

Lithospheric attenuation.—If magmas for the Silurian dikes were generated from asthenospheric mantle in an extensional continental environment and erupted through the lithosphere with minimal contamination, how thick was that lithosphere? Ellam (1992) argued that Ce/Yb ratios in basaltic rocks can be used as a measure of lithospheric thickness. He suggested that, in areas of thick lithosphere, melt segregates at great depths after having undergone low degrees of partial melting of garnet peridotite. Because the magmas are in equilibrium with garnet, they have high Ce/Yb ratios (20–100). In areas of thin or highly attenuated lithosphere, melts form at shallow depths from higher degrees of melting of spinel lherzolite producing basalts with low Ce/Yb ratios (5–10). Ce/Yb ratios of the Silurian dikes of this study range from 4.6 to 7.9 (table 4), with an average of 5.8, implying a segregation depth of less than 20 km, suggesting highly attenuated lithosphere.

In the vicinity of Comerford Dam and quarry, the width of the dike swarm is as much as 2.5 km across strike. The dikes are near vertical and many of them are sheeted. At 50 percent dikes, the amount of crustal extension is about 1.2 km. The intrusive complex exposed in the Comerford quarry is as much as 1 km thick and, absent magmatic stoping, represents 100 percent extension. Thus the Comerford Intrusive Suite represents crustal extension of as much as 2.2 km over a distance of 3.5 km, or 160 percent extension for this segment of the BHA (Rankin, 1996a). Based on the field evidence for crustal extension and the Ce/Yb ratios for the dikes, we conclude that the lithosphere under the BHA was highly attenuated and asthenosphere was near the surface at the time of dike intrusion.

REGIONAL TECTONIC IMPLICATIONS

Numerous workers have argued for a period of post-Taconian crustal extension leading to the development of the CVGT and CMT (Osberg and others, 1989; Keppie and Dostal, 1994; van Staal and de Roo, 1995; Rankin, 1996a; Karabinos, 1998; Bourque and others, 2000; Moench and Aleinikoff, 2002; Castonguay and Tremblay, 2003; Tremblay and Pinet, 2005). The locus of late Silurian lithospheric attenuation that we have documented for the BHA is spatially between the two basins and we seek a common cause for the extension. A proposed cause of the extension must be considered within broad aspects of Appalachian geology such as the very existence of the large middle Paleozoic basins, their location, Silurian paleogeography, structural evidence for Silurian extension, and the basins' coexistence with documented Silurian

TABLE 4

REE, Hf, Th, Ta, and Nb concentrations (ppm) in Silurian dikes and gabbro-diorite complexes of the Comerford Intrusive Suite

	Leighton Hill Region Dikes					**Comerford Region Dikes**							
	BD	*BD*	*NQ*	*I-91*	*LH*	*CD*	*CD*	*CD*	*CD*	*CD*	*CD*	*CQ*	*CQ*
Field #	SW00-21	SW00-34	SW00-53	SW-00-09	SW-00-49	AR-97-33	AR-97-34	AR-97-35	AR-97-37	AR-97-40a	VT-92-16	AR-97-6	AR-97-18b
La	8.2	5.7	9.2	10.5	10.5	5.7	11.2	9.9	9.7	8.4	12.2	14.6	10.5
Ce	22.0	15.0	23.0	26.0	26.0	15.0	28.0	25.0	24.0	25.0	29.4	43.0	34.0
Nd	16.0	11.0	17.0	18.0	17.0	11.0	16.0	15.0	15.0	16.0	20.0	28.0	23.0
Sm	5.0	3.4	5.0	5.6	5.2	3.4	4.8	4.4	4.7	4.8	6.7	8.3	7.7
Eu	1.7	1.3	1.7	1.8	1.6	1.1	1.5	1.2	1.5	1.9	2.0	2.7	2.6
Tb	1.1	0.8	1.1	1.3	1.2	0.8	1.0	0.9	1.0	1.0	1.3	1.9	1.9
Yb	4.8	3.2	4.7	4.9	5.1	3.1	3.9	3.4	4.0	4.0	5.0	6.9	6.3
Lu	0.7	0.5	0.7	0.7	0.8	0.4	0.6	0.5	0.6	0.6	0.7	1.0	0.9
Hf	2.8	1.7	3.1	3.1	3.1	2.4	3.8	3.1	3.4	3	4.6	5.80	4.40
Ta		0.8	0.7		0.6				0.4	0.7	0.46		
Th	1.1	0.6	1.2	1.2	1.9	0.8	1.5	1	1.1	0.7	1.7	1.5	0.3
Ti/Yb	2229	2976	2735	2605	2060	3008	2953	3259	3049	2960	2927	3003	3204
Ce/Yb	4.6	4.7	4.9	5.3	5.1	4.9	7.1	7.3	6.1	6.2	5.9	6.2	5.4
La/Ta		7.1	13.2		17.5				24.3	12.0	26.5		

	Comerford Region Dikes										**Composite Intrusive**		
	CQ	*BM*	*BM*	*BM*	*RR*	*PIQ*	*PIQ*	*PIQ*	*PIQ*	*PIQ*	*CQ*	*CQ*	*CQ*
Field #	AR-97-5	VT-93-74	VT-93-75	VT-93-76	VT-92-6	VT-93-50	VT-93-51	VT-93-108	VT-93-109	VT-93-54	AR-97-3	AR-97-24	AR-97-45
La	13.7	7.1	17.3	15.1	8.7	10.1	10.6	5.9	15.2	8.7	2.2	2.4	2.2
Ce	37.0	16.9	37.2	36.6	20.7	23.7	23.7	15.4	37.5	20.5	6.1	7.0	8.0
Nd	28.4	12.0	22.0	28.0	14.0	16.0	14.0	11.0	26.0	14.0	5.2	5.0	7.0
Sm	8.6	3.9	6.9	8.3	4.5	5.7	4.2	3.9	8.5	5.1	1.9	1.6	1.8
Eu	2.7	1.3	1.9	2.3	1.4	1.5	1.3	1.3	2.5	1.5	0.8	0.8	0.8
Tb	1.8	0.8	1.3	1.7	0.9	1.2	0.8	0.8	1.7	1.0	0.5	0.4	0.3
Yb	6.9	3.1	4.6	6.2	3.4	4.5	3.0	3.2	6.5	3.9	1.8	1.5	1.7
Lu	1.1	0.4	0.6	0.9	0.5	0.6	0.4	0.4	0.9	0.6	0.3	0.2	0.2
Hf	6.07	2.63	4.99	6.03	3.0	3.87	2.70	2.77	6.17	3.46	1.27		
Ta	0.86	0.26	0.62	0.59	0.3	0.37	0.31	0.23	0.59	0.34			
Th	1.5	0.8	2.9	1.8	0.85	1.3	1.1	0.7	1.6	1.0	0.5	0.2	0.5
Nb	8	8	14	14	7.0	7	8	13	17	7			
Ti/Yb	3012	2881	2789	2630	2901	3041	2953	3016	2719	2436	2680	2338	2289
Ce/Yb	5.4	5.5	8.1	5.9	6.1	5.3	7.9	4.8	5.8	5.3	3.3	4.6	4.7
La/Ta	16.0	27.2	27.9	25.6	28.9	27.3	34.2	25.4	25.8	25.6			

BD - Boltonville Dam, NQ - Newbury Quarry, LH - Leighton Hill, CD - Comerford Dam, CQ - Comerford Quarry, BM - Badger Mountain, RR - River Road, PIQ - Pike Industries Quarry metamorphism and compressional events in Newfoundland, the Miramichi Highlands of New Brunswick, and southern Maine.

Middle Paleozoic Basins

A first order feature of the Appalachian orogen is the presence of large middle Paleozoic basins in the internides of New England, Québec, and New Brunswick and their absence from the internides of the southern and central U. S. Appalachians, Nova Scotia, and Newfoundland (Williams, 1978; Rankin, 1994). From northwest to southeast, these basins are the Connecticut Valley-Gaspé, Central Maine (and the continuation into New Brunswick and southern Gaspé as the Aroostook-Matapedia, Aroostook-Percé and Chaleurs Bay belts), and Fredericton-Merrimack troughs (fig. 1). Overall, the sedimentary record ranges from Late Ordovician to Late Devonian. In New England, strata younger than Early Devonian (Emsian) are rare and strata older than upper Silurian are not confirmed in the CVGT. The relationship of the Fredericton and Merrimack troughs to the two larger basins to the northwest is unclear to us and will be discussed briefly at the end of the paper.

Silurian-Devonian (mostly Silurian) rocks in the internides of Newfoundland occur in relatively narrow, discontinuous belts that do not correspond to mainland belts (Williams, 1995). The long, narrow Green Pond syncline (fig. 1) within Mesoproterozoic rocks of the New Jersey and Hudson Highlands, and extending north into Taconian foreland basin (Williams, 1978), contains Silurian-Devonian strata including Catskill-delta-related rocks. It is best considered part of the external regime.

The CVGT and CMT exhibit differences between one another and along strike. In the following discussion, the term Connecticut Valley trough (CVT) is used to specifically refer to that part of the CVGT that is separated from the CMT by the BHA. The CVT is essentially all within the United States. The age of strata in the CVT is poorly constrained. What data there are leave open the possibility that the strata are Ludlow or younger, although the Frontenac Formation along the eastern border of the CVT is as old as Llandovery (see below). Along the western margin, rocks within the trough are stratigraphically above the thin, discontinuous, and conglomeratic Shaw Mountain Formation, or its correlatives to the south in Massachusetts and Connecticut. In northern Vermont, brachiopods in the Shaw Mountain "can be of Ludlow and Pridoli age, although they could be as old as upper Llandovery (C_3 or younger) or as young as lower Gedinnian" (Boucot and Drapeau, 1968). Ratcliffe and Aleinikoff (2000) correlate the Shaw Mountain with the Glenbrooke Group along strike to the north at Lake Memphremagog (fig. 2). The Glenbrooke contains Ludlow age brachiopods (Boucot and Drapeau, 1968). The 423 ± 4 Ma age for the dike near Springfield (Hueber and others, 1990) is within the 95 percent confidence envelope of the 419.1 Ma Comerford Intrusive Suite. A tuff and dike in the volcanic-rich eastern part of the Frontenac Formation yielded a U-Pb zircon age of 418 ± 4 Ma (Moench and others, 1995); the U-Pb zircon age of the hypabyssal granitic East Inlet pluton (fig. 2) is 430 ± 4 Ma and of a felsic tuff, also in the Frontenac, is 432 ± 10 Ma (Lyons and others, 1997). Thompson and others (1997 and references therein) argued that in southeastern Vermont and adjacent New Hampshire, the contact between the Bronson Hill and Connecticut Valley sequences is an east facing unconformity marked by a conglomerate interpreted by them to be basal Littleton Formation. Armstrong and others (1997) include many of these conglomerates in an expanded Waits River Formation of Silurian-Devonian age. By correlation with the Compton Formation in the Eastern Townships, Québec, some of the rocks in the trough are as young as Emsian (Hueber and others, 1990). None of the sedimentary strata of the CVT are post-Acadian.

The bulk of the sediment from the denudation of the Taconic highlands of New England was shed eastward (Zen, 1991). The volume of sediment represented by the CMT is far greater than that in the CVT. Stewart (1989) noted that the volume of sediments per strike kilometer inferred to be in the CMT is comparable to that of the post-Lower Jurassic slope-rise sediments of the present Atlantic margin from central Long Island to central Nova Scotia. Zen (1991) pointed out that the thickness, extent, and nature of the filling of the CMT is similar to those of the post-Acadian Upper Devonian Catskill delta (fig. 1).

Post-arc sedimentation in the western CMT began in the Llandovery (Moench and Pankiwskyj, 1988); transport direction was from the west across the Silurian tectonic hinge (fig. 2) (Moench and Pankiwskj, 1988; Hanson and others, 1993). Throughout much of northern Maine northwest of the hinge, Silurian strata are thin, most are Wenlock or younger, shallow-water deposits, exposed only around uplifts of pre-Silurian rocks, and covered by Lower Devonian strata (Roy, 1980; Hanson and others, 1993). The Silurian tectonic hinge continues, but not so named, across Maine to and along the Weeksboro-Lunksoos uplift (fig. 1)(Neuman, 1967; Hanson and others, 1993).

Extension-Related Igneous Rocks of Silurian Age In and Near the CVGT and CMT

The Comerford Intrusive Suite is truncated on the west by the late Acadian Monroe fault; the CVGT sequence immediately west of the fault is interpreted to be of Early Devonian age and thus younger than the dikes. There is no geophysical expression of an extensive mafic complex under the present-day CVGT. However, extension-related Silurian volcanic rocks of the largely mafic Standing Pond Volcanics are a minor but important constituent of the CVGT in Vermont (Hepburn, 1991; Richardson, ms, 1997; Karabinos, 1998; Karabinos and Hepburn, 2001). Tholeiitic basalts have La/Yb ratios near 1.0 (Hepburn, 1991), similar in composition to the dikes of this study. Karabinos and Hepburn (2001) note that the back-arc geochemical signature of some of the flows in the Standing Pond is indistinguishable from that of undated mafic dikes in the pre-Silurian rocks west of the CVGT in Massachusetts and Vermont.

Sills of the Charlemont Mafic Intrusive Suite cut pre-Silurian rocks west of the CVGT in northwestern Massachusetts (Kim and Jacobi, 1996). The sills have back-arc basin compositional affinity and intrude the Dell Metatrondhjemite [Pb/Pb evaporation age of 434 ± 8 Ma, (Karabinos and Hepburn, 2001)] and rocks of the Shelburne Falls arc. Ratcliffe and Aleinikoff (2000) reported a diorite-granite intrusive complex at Braintree, Vermont (fig. 3 insert) that intrudes pre-Silurian rocks west of the CVGT and is interpreted by them to have been generated in an intra-plate rifting environment following Taconian accretion and metamorphism. The eastern part of the outcrop belt of the Frontenac Formation (fig. 2) contains a Silurian bimodal suite of volcanic and intrusive rocks including sheeted dikes at the international border (Hatch, 1963; Green, 1968; Marvinney, ms, 1986; Moench and others, 1995). Mafic rocks consistently have Fe- and Ti-rich compositions that are characteristic of basalts from an extensional environment (Moench, 1990 and references therein). Thus, an episode of Silurian extension is represented by igneous rocks within and on both sides of the CVGT in New England.

Hadley (1950) reported sizable areas of mafic sill-like or dike-like bodies in the Gile Mountain Formation in the Fairlee-Bradford area, Vermont, (fig. 3). We have not seen these but in reconnaissance Rankin observed mafic intrusive bodies in the Gile Mountain about 7.5 km north of Bradford. These are prime targets for future work to determine their isotopic age, if possible, and their geochemical signature.

Support for Silurian extension in the CMT and Gaspé comes from the geochemical signature of magmatic suites in Maine, Gaspé, and New Brunswick (Bédard, 1986; Dostal and others, 1989, 1993; Hon and others, 1992; Fitzgerald and Hon, 1994). Recent papers, (for example, Dostal and others, 1989, 1993; Hon and others, 1992; Keppie and Dostal, 1994; Tremblay and Pinet, 2005), considered the Late Silurian and

Early Devonian igneous rocks a cogenetic group and proposed a common extensional environment for the group. We suggest that this may be ill advised and urge that, where age control is adequate, Silurian and Devonian suites be considered separately. Late Silurian rocks are transitional to tholeiitic basalts with enriched LREE whereas Early Devonian rocks include intermediate rocks as well as basalts (Dostal and others, 1993). Late Silurian rocks in Gaspé are similar in age to dikes in this study but are chemically different, particularly in their higher LREE contents. A bimodal basalt-rhyolite suite within the upper Silurian Rocky Mountain and limestone-rich Five-Mile-Brook Formations in northwestern-most Maine adjacent to the Quebec border (Schwartz and others, 1984; Roy, 1989; Roy and others, 1991) and the Spider Lake Formation (fig. 2) (Hall, 1970; Fitzgerald and Hon, 1994) were interpreted to have been generated during intra-continental crustal rifting (Hon and others, 1992).

The Five-Mile-Brook, Rocky Mountain, and Spider Lake Formations were included by Hon and others (1992) in the Piscataquis volcanic belt; we disagree with this inclusion. The name Piscataquis magmatic belt is here used for the assembly of mafic and felsic igneous rocks of Early Devonian age that extend from near Houlton, ME (fig. 1), to southern New Hampshire in a belt mostly just east of the Bronson Hill arc (Lyons and others, 1997; Bradley and others, 2000; Rankin and Tucker, 2000; Hibbard and others, 2006) (fig. 3 insert). We note the remarkable continuity in space and time (ages cluster around 407 Ma) of the igneous rocks and their close association with coeval flyschoid sedimentary rocks of Emsian age. Peraluminous compositions characterize some of the felsic units of the belt as opposed to the peralkaline compositions in the Rocky Mountain Formation and some rocks of the Spider Lake Formation (K. J. Schulz, oral communication, June 2003).

Structural and Stratigraphic Evidence for Silurian Extension

The most complete middle Paleozoic sections are in Gaspé where rocks are well dated by fossils and Acadian metamorphism is minimal (Malo and Kirkwood, 1995; Malo, 2004). Silurian extension is well documented. A widespread late Ludlow-early Pridoli unconformity (disconformity to angular unconformity) is correlated with the Salinic disturbance [named by Boucot (1962) for the Salina Group in New York] and attributed to extensional tectonics (Bourque, 2001). Northwest-trending syn-sedimentary normal faults, down-dropped to the southwest and parallel to the southwest side of the St. Lawrence promontory, were active in eastern Gaspé from Late Silurian to Earliest Devonian (Malo and Kirkwood, 1995; Bourque and others, 2000; Bourque, 2001). Salinic extension produced listric block faulting and tilting that, combined with eustatic sea-level fall, exposed the blocks to subaerial erosion (Bourque, 2001). In places the unconformity is below Pridoli conglomerates that are derived from uplifted fault blocks (Bourque, 2001). Late Silurian to Earliest Devonian extensional and listric normal faults are reported along the northwest boundary of the CVGT from Lake Témiscouata (fig. 1) to northeastern Gaspé (Lavoie, 1992; Malo and Kirkwood, 1995). The normal faults were reactivated as dextral strike-slip or oblique-movement faults in the Acadian orogeny (Bourque and others, 2000). They are shown on figure 1 as strike slip-faults and are part of the extensive system of orogen parallel, dextral, strike-slip faults of Devonian and younger age in New England and Atlantic Canada (for example, Lavoie, 1992; Malo and others, 1992; van Staal and de Roo, 1995; Ludman and West, 1999).

In the Humber zone of southern Québec, Castonguay and Tremblay (2003) described southeast-directed Silurian back-thrusting on the Brome-Bennett faults on the northwest side of the Sutton Mountains and Notre-Dame Mountains anticlinoria and extrapolate a similar interpretation for the west-dipping reverse fault delineating the west flank of the Green Mountain anticlinorium (Honey Hollow fault of Thompson and Thompson, 2003) in northern Vermont (fig. 2). Movement on the Brome-

Bennett faults combined with younger Silurian normal movement (down to the southeast) on the St. Joseph fault on the southeast side of the anticlinoria result in higher-grade anticlinal cores flanked by lower grade rocks. In light of the accumulating evidence for widespread Silurian extension in Québec and central New England, the less favored hypothesis of Castonguay and Tremblay (2003) of overall extension analogous to Cordilleran metamorphic core complexes has much appeal.

Although large middle Paleozoic basins are absent from Newfoundland, the smaller basins include Silurian terrestrial sandstone and conglomerate; some basins are bounded by steep faults (Williams, 1995), possibly indicating extension. Silurian bimodal magmatism of central Newfoundland includes the A-type Topsails Igneous Suite. Whalen and Currie (1990) interpreted the A-type geochemical signature of the Topsails to be source-related (partial melting of a depleted continental crust) and emplaced in a continental plate overriding a subduction zone. Nonetheless, central Newfoundland was the locus of crustal shortening during the Silurian.

Silurian Compression and Metamorphism

Western and central Newfoundland (Karlstrom and others, 1982; Dunning and others, 1990; O'Brien and others, 1991; Cawood and others, 1994; Lin and others, 1994; van Staal and de Roo, 1995), the Miramichi Highlands of New Brunswick (van Staal, 1994; van Staal and others, 1998, 2003), and Cape Breton Island (Lin and others, 1994) experienced Silurian metamorphism and compressional deformation. The cited authors argued that the partitioning of Ordovician to Devonian deformation into the Taconian and Acadian orogenies is too simplistic and that compressional deformation was continuous from the Ordovician into the Devonian. Others have suggested using the name Salinic orogeny for the Silurian compression (Dunning and others, 1990; Cawood and others, 1994, 1995; Bourque and others, 2000). We disagree with this proposal because we interpret the Salinic disturbance to be extensional. Although evidence for Silurian compressional deformation is strong in parts of Newfoundland and the Miramichi, it is absent in the CVGT, the BHA, and most of the CMT. Possible exceptions are folds and a related ENE-trending sinistral shear zone interpreted to reflect north-south-directed shortening oblique to the orogen in northern Maine (Hibbard and Hall, 1993). How can we reconcile Silurian compression in Newfoundland and New Brunswick with Silurian extension in central New England and Québec?

Silurian Paleogeography

We assume that the configuration of the promontories and embayments along the Laurentian margin survived the Taconian orogeny and assert that the geometry of the framing New York promontory, Québec embayment, and St. Lawrence promontory (Rodgers, 1975; Rankin, 1976; Thomas, 1977) was a necessary condition for the formation of the large middle Paleozoic basins. The Laurentian rifted margin as portrayed by Rankin (1976) along the positive Bouguer gravity high of the Green Mountain and Notre Dame Mountains anticlinoria does not coincide with the edge of Grenvillian crust at depth, which lay considerably farther southeast (Harrison and others, 1987; Stockmal and others, 1990; Stewart and others, 1993; Dorais and Paige, 2000). The gravity high probably marks the locus of an autochthonous failed Neoproterozoic continental rift (Rankin, 1994), analogous to the failed rifts of the on-shore Mesozoic basins of eastern United States. The southeastern limit of the Grenville lower crustal block (GLCB) (Stockmal and others, 1990) traces a broad curve concave to the southeast (fig. 1), perhaps indicating that its shape has been modified during Paleozoic deformation in the core of the orogen. Continental shelf and slope/rise strata above the GLCB were telescoped by Taconian thrusting. Lebel and Hubert (1995) estimated Taconian shortening of about 100 km in the Eastern Townships, by which their Laurentian margin would roughly coincide with the southeast edge of the GLCB.

Figure 13, modeled after Stockmal and others (1990) and Malo and others (1992), is a reconstruction of the geometry of the Taconian orogen in the Gulf of St. Lawrence area at the time of the formation of the middle Paleozoic basins derived through the stepwise removal of the post-Silurian deformation. This is clearly a first approximation. Only the movement on a few faults is considered and the reconstruction becomes progressively less valid toward the New York promontory. Nevertheless, the reconstruction provides some insights into the setting of Silurian extension near the Gulf of St. Lawrence.

Closing the Carboniferous Magdalen basin (fig. 1), which opened as a pull-apart basin along right-stepping, dextral, strike-slip faults (Bradley, 1982), and removing 120 km east-west offset on Middle Devonian, dextral, strike-slip faults on southeast trending segments of the Baie Verte-Brompton line in eastern Gaspé (Malo and others, 1992) results in the rough alignment of the Baie Verte-Brompton line and the southwest end of the Grenvillian Blair River inlier, Cape Breton Island (fig. 1). The cumulative amount of post-Taconian dextral offset is difficult to assess, but was major, particularly in the more outboard parts of the orogen. From coastal New Brunswick to Long Island Sound, the result has been the successive truncation of numerous terranes southward against these faults (Rankin, 1994; Stewart and others, 1995). The craton, bordered by the Appalachian structural front, is assumed to have been a rigid block. Treating the retrofitted structural blocks also as rigid blocks results in distortions of shapes of the blocks or repetition of structural elements. These distortions are included in figure 13 and demonstrate that the model only takes into account some of the obvious requirements of retrofitting.

The edge of the GLCB along the southwestern edge of the St. Lawrence promontory is interpreted to be co-extensive with the reconstructed trace of the Baie Verte-Brompton line in eastern Gaspé and to have originated as a Late Neoproterozoic transform fault named the Sept Îles transform (Cousineau and Longuépée, 2003). The Sept Îles Complex (figs. 1 and 13), on the northwestern projection of the transform, is a large (50 km by 70 km), largely mafic, alkaline, shallow intrusive body, with a U-Pb zircon age of 565 ± 4 Ma, generated from mantle melts during Iapetan rifting (Higgins and Doig, 1986; Higgins and Van Breemen, 1998). A pronounced aeromagnetic anomaly trends north-northwest from the north shore of Gaspé through the Sept Îles Complex and continues another 50 km to the north-northwest (Lamontagne and others, 2003) suggesting that the effects of transform (or a failed rift) extended into the GLCB of the Québec embayment. If the GLCB remained rigid, Neoproterozoic offset of the Laurentian continental margin on the Sept Îles transform was on the order of 350 km (fig. 13).

Stockmal and others (1990) proposed that, prior to the opening of the Magdalen basin, the Gander-Avalon contact was a continuous, linear feature from New Brunswick, through Cape Breton Island to Newfoundland. They hypothesized a pre-Middle Devonian dextral strike-slip fault through the Strait of Canso, Nova Scotia, subparallel to the Neoproterozoic Sept Îles transform fault along the southwestern margin of the St. Lawrence promontory. Implicit in this is that the Sept Îles transform was reactivated at least once in the Paleozoic. Reconstruction by moving the Central and Avalon lower crustal blocks (Stockmal and others, 1990) southeast on the Canso fault leaves a gap between lower crustal blocks southwest of the transform of about 200 km (fig. 13). The gap could be related to Silurian crustal extension [Stockmal and others (1990) suggested a back-arc basin]. Malo and Kirkwood (1995) and Kirkwood (1999) calculated Acadian shortening across the CVGT to Chaleurs Bay (fig. 1) of about 80 percent or 400 km along an azimuth of about 315° (present directions). Thus, in Early Devonian time, the CVGT basin extended as far southeast as the present location of Cape Breton Island (fig. 13). Silurian extension determined by a) the offset of lower

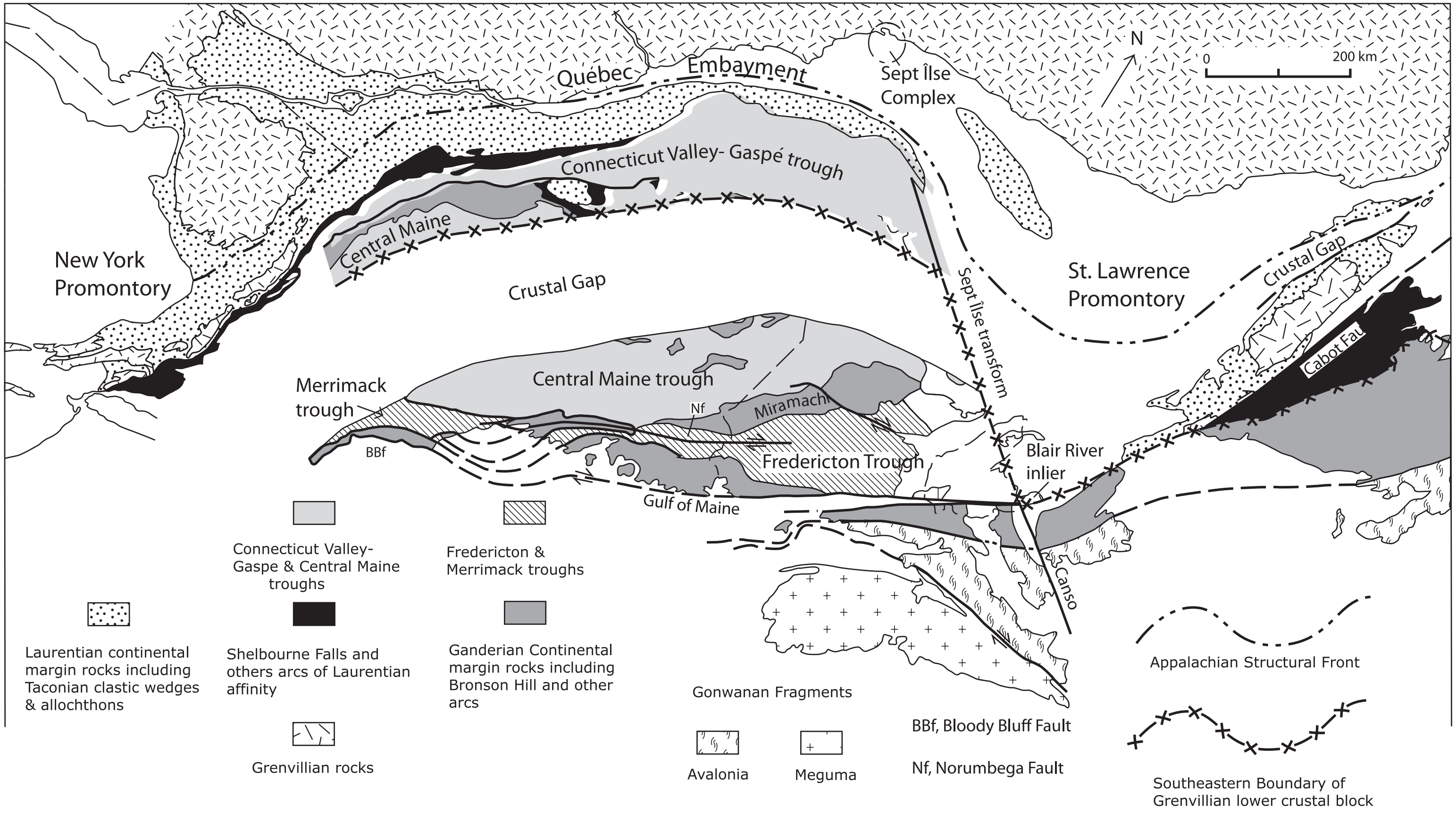


Fig. 13. Tectonic map of the Northern Appalachians from New York to Newfoundland following restoration by removing (1) Carboniferous right-lateral motion on the Canso fault (Stockmal and others, 1990), (2) Carboniferous right-lateral motion on faults that opened the Magdalen pull-apart basin (Stockmal and others, 1990), and (3) Middle Devonian right-lateral motion on strike-slip faults in eastern Gaspé (Malo and others, 1992). Note that in this restoration, the Canso fault, the edge of the Grenville lower crustal block along the southwestern edge of the St. Lawrence Promontory, and the trace of the segment of the Baie Verte-Brompton line in eastern Gaspé are essentially co-linear. Dashed outline shows present position of Cape Breton Island relative to Gaspé. Units and line symbols are the same as used in figure 1.

crustal blocks on the Canso fault and b) palinspastic reconstruction of the CVGT is of the same order of magnitude. We have made no comparable analysis for central New England but point out that the CMT and particularly the CVGT are much more constricted there.

It is within this palinspastic framework that we consider Silurian extension. We emphasize that we are focused on a relatively short time period from significantly after the beginning of the Silurian, possibly about 430 Ma, into the earliest Devonian.

Diachronous Collision

The concept that in closing ocean basins, collisions will occur first at promontories goes back to Wilson (1966). Assuming that the right-lateral offset of the ophiolite belts and arcs at the Sept Îles transform does not pre-date accretion, the accretion must have been diachronous with collision occurring first along the St. Lawrence promontory and later in the Quebec embayment (Stockmal and others, 1987; Bradley, 1989; Stockmal and others, 1990; Cawood and Suhr, 1992; Keppie and Dostal, 1994; Lavoie, 1994; Lin and others, 1994; van Staal and de Roo, 1995; van Staal and others, 1998; Bourque and others, 2000; Pincivy and others, 2003). Stratigraphic and sedimentologic records show that foundering and burial of the Taconian foreland on the St. Lawrence promontory occurred 10 to 15 my earlier (Middle Ordovician) than in the St. Lawrence lowlands and near Albany, New York of the Québec embayment (Upper Ordovician) (Lavoie, 1994; Knight and others, 1995 and references therein). Obduction of ophiolites may have begun as early as Tremadocian on the St. Lawrence promontory (Cawood and Suhr, 1992; van Staal and others, 1998). Obduction of ophiolites in the Humber zone of northern Gaspé dates from the Caradocian (Pincivy and others, 2003). Various mechanisms have been proposed for the continuation of crustal shortening at the St. Lawrence promontory while subduction continued in the Québec embayment (Colman-Sadd, 1982; Stockmal and others, 1990; Cawood and Suhr, 1992; van Staal and others, 1998). The important point is that diachronous collision provides a setting in which this can happen. Less straightforward is the explanation of coeval Silurian extension in the Aroostook-Matapedia belt and compression in the Miramichi belt.

Cause of Extension

Silurian strata probably accumulated 1) on a newly developed passive margin facing the remnants of the Iapetus Ocean, 2) on a newly developed convergent margin, or 3) in an intracontinental extensional basin formed over the recently sutured Laurentia and Ganderia (modified from Robinson and others, 1998; Tucker and others, 2001). Tectonic models must explain the absence of clear evidence for Silurian and Early Devonian oceanic crust (Hall and Robinson, 1982), as well as continuous sedimentation in the Témiscouata-Gaspé region and the Aroostook-Matapedia belt from the Caradocian/Ashgillian to Ludlow (Pavlides and others, 1968; van Staal, 1994; Bourque and others, 2000; Malo, 2004). The deep-water, siliciclastic, lower sections are syn-Taconian even though they grade up into larger post-Taconian 'successor' basins.

Tremblay and Pinet (2005) reviewed and illustrated earlier tectonic models for Silurian extension. They note, as do we, that only about 20 my lapsed between foreland-directed motion and the onset of extension in the Québec embayment. Lithospheric delamination at the boundary (derived from an east-dipping zone) between Laurentia and Medial New England (Robinson and others, 1998) resulted in the upwelling of hot asthenospheric mantle producing partial melting of the crust, within-plate magmatism, localized basement uplifts and continued extension to form the CVT and CMT (Tremblay and Pinet, 2005).

The model that best fits our understanding of the data and regional geology is that of van Staal and de Roo (1995), Van Staal and others (1998), and Van Staal and others (2003) particularly as it applies to New Brunswick, Québec, and New England. In these papers evidence is presented for the 475 to 455 Ma opening of the Tetagouche back-arc basin [1100 – 2000 km wide (van Staal and others, 1998)] in the Miramichi belt, a result of splitting the Popelogan arc on the Ganderian margin of Iapetus (fig. 14A). Hinge retreat of southeast dipping subduction zone generating the Popelogan arc and the Tetagouche basin eventually produced a collision between the arcs and the already modified margin of Laurentia. Closure of the back-arc basin took place on a new northwest-directed subduction zone, the Brunswick subduction complex, between 455 and 430 Ma (Late Ordovician to early Silurian) (van Staal and others, 2003) (fig. 14B). The small-volume arc andesites of the late Llandovery Pointe aux Trembles Formation near Lake Témiscouata, Québec (figs. 1 and 14B) (David and Garipéy, 1990) were attributed to this subduction. Possibly the ~430 Ma East Inlet pluton and tuff in the Frontenac Formation (fig. 2) are related to this subduction also, but corroborating petrochemical data are absent. Hinge retreat during this relatively short period of subduction may have initiated extension in the upper plate leading to the formation of the CMT (after van Staal and de Roo, 1995) and the sub-basin of the CVGT in which the Frontenac Formation was deposited (fig. 14B).

Subduction presumably terminated with the attempted entrance of thick Gondwanan crust into the subduciton complex (van Staal and de Roo, 1995). The complex was, in part, unroofed by late Llandovery; the oldest strata of the unconformably overlying rocks of the Matapedia cover sequence along the northwest margin of the Miramichi belt (here, upper Llandovery) contain pebbles of basalt and serpentine (van Staal and others, 2003). Continued oblique collision resulted in deformation and low-pressure metamorphism [D_2 and M_2 of van Staal and de Roo (1995)] accompanied sinistral transpression resulting in late Silurian north- to northeast-directed shortening in addition to uplift and erosion. In the preferred model of van Staal and de Roo (1995), detachment of oceanic lithoshpere from continental crust of the descending Gondwanan plate by asymmetrical boudinage placed hot asthenosphere against cool lithosphere of both upper and lower plates giving rise to the generation of intraplate magmas and thermal expansion (extension) of the lithosphere (fig. 14C).

The accreted Popelogan arc and its counterpart in Newfoundland, the Victoria arc, lie east of the Red Indian line, which marks the suture zone between the Notre Dame subzone of the Dunnage zone, characterized by a Laurentian fauna, and the Popelogan-Victoria arc characterized by a Celtic fauna. In the sense of bringing the two faunal provinces together it represents the closing of the Iapetus Ocean by middle or late Caradocian and the trace of the line mostly agrees with the southeastern edge of the Grenville lower crustal block (Stockmal and others, 1990). The Red Indian line must continue into New England such that it separates the Shelburne Falls and the Bronson Hill arcs (van Staal and others, 1998) but the details of that projection are poorly understood.

While we accept that the above scenario best fits the data, we offer an alternative tentative hypothesis based on the overall geometry of the CVGT and CMT, Silurian dikes in the Upper Connecticut Valley, Silurian tectonic hinge, and the locus of the basins in the Québec embayment. We entertain the possibility that the basins originated as northeast-trending pull-apart basins between northwest trending, left-stepping, sinistral, strike-slip faults. The length/width ratio of the composite Silurian-Devonian basin, however, is anomalous for pull-apart basins. Aydin and Nur (1982) found that for 70 pull-apart basins or rhomb graben and horsts of dimensions ranging over several orders of magnitude, the length (direction of extension)/width ratio is approximately 3. The middle Paleozoic basins, excluding the Fredericton trough,

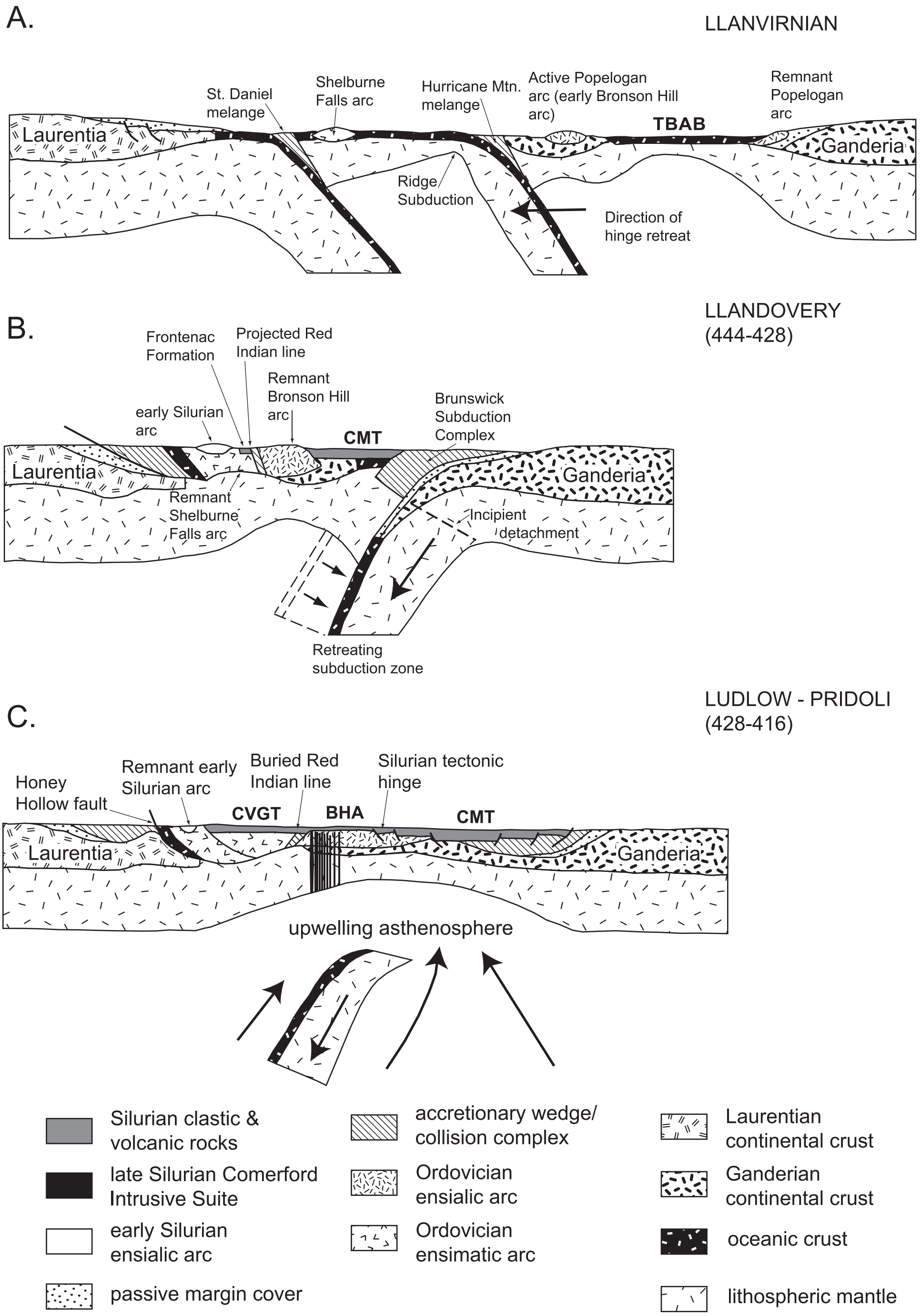


Fig. 14. Schematic cross sections from near the Vermont-Québec border to the Miramichi Highlands, New Brunswick, showing stages in the evolution of Silurian extensional basins. Modified from van Staal and de Roo (1995) and van Staal and others (1998). Considerable latitude is taken in projecting features onto generalized sections. Movement out of the plane of the sections is ignored. BHA, Bronson Hill arch; CMT, Central Maine trough; CVGT, Connecticut Valley-Gaspé trough; TBAB, Tetagouche back-arc basin. (A) Opening of the Tetagouche back-arc basin. (B) Termination of arc volcanism and incipient Silurian extension. (C) Slab detachment (assymetrical boudinage model of van Staal and de Roo, 1995), rise of hot asthenosphere, and Silurian extension.

cover an area roughly 200 km by 1000 km. The length/width ratio for the composite basin is now about 0.2. Whether this is mechanically feasible is not certain. Note that NW-SE map-length of the composite middle Paleozoic basin does not take into account the extensive relative northwest shortening of the orogen in the middle Paleozoic [possibly as much as 400 km in Gaspé (Kirkwood, 1999)].

In this pull-apart basin model, the southern flanks of the New York and St. Lawrence promontories should be the locus of sinistral strike-slip faults trending roughly northwest. Possibly a promontory-promontory (St. Lawrence and Cabot) collision in Newfoundland (Lin and others, 1994) reactivated the Sept Îles transform, which apparently extended some distance into the craton, as a sinistral fault. Possibly the sinistral offset was greater at the St. Lawrence promontory than at the New York promontory, resulting in a wedge-like opening. Subsequent Acadian deformation has profoundly altered the geometry of the region, making a more detailed Silurian structural analysis impossible at this time. Much of the southern flank of the New York promontory is covered either by water, Pleistocene deposits, Coastal Plain sediments, or Mesozoic basins. Much of the southern flank of the St. Lawrence promontory is covered by Carboniferous sedimentary rocks (Sanford and Grant, 1990; Reed and others, 2004) as well as hidden beneath the lower St. Lawrence River, Honguedo Strait and the Gulf of St. Lawrence. Until Silurian left-lateral faults are identified, however, the pull-apart basin hypothesis is speculative.

Finally, we comment on rocks in coastal Maine because some interpretations place these adjacent to the CMT during the Silurian; the interpretation presented in this paper questions that. Silurian deformation and regional metamorphism affected rocks of the 1) Liberty-Orrington belt (late Silurian between 422 and 418 Ma) (West and others, 2003), 2) Fredericton trough and St. Croix terrane (prior to 424 – 419 Ma plutons) (West and others, 1992, 2003; Stewart and others, 1995; Stewart, 1998; Bradley and others, 2000; Tucker and others, 2001), and 3) Nashoba terrane of eastern Massachusetts (beginning ~ 425 Ma) (Hepburn and others, 1995) (fig. 1). Did these Silurian events, including the intrusion of the 424 to 419 Ma plutons, take place as part of the amalgamation of composite Avalon at a significant distance from composite Laurentia (West and others, 1992; Stewart and others, 1993, 1995; Rankin, 1994; Hepburn and others, 1995) or were they part of the collision (Acadian orogeny) of composite Avalon with composite Laurentia (Hibbard and Hall, 1993; van Staal and others, 1998; Bradley and others, 2000; and Tucker and others, 2001). Robinson and others (1998) succinctly summarized the fossil evidence for a biogeographic separation of the CMT and composite Avalon during the Silurian and Earliest Devonian. Van Staal and others (1998) have challenged the evidence for separation. Paleomagnetic data indicate Avalon was at a high southern paleolatitude during the Middle and Upper Ordovician, whereas Laurentia including at least some of the Central Mobile belt was at equatorial latitudes (van der Voo, 1988). We cannot solve all of the ambiguities here.

SUMMARY AND CONCLUSIONS

The Comerford Intrusive Suite, which crops out along the western edge of the BHA in the Upper Connecticut Valley, consists of a suite of mafic dikes, sheeted dikes, and intrusive complexes of mafic dikes and plutonic rocks, mostly mafic, but with compositions ranging from gabbro to leucocratic tonalite. The suite intrudes strata of the pre-Silurian Albee Formation and overlying Ammonoosuc Volcanics of the Bronson Hill sequence that can locally be shown to have a pre-intrusion metamorphic fabric (Taconian?). The suite and host rocks were deformed and metamorphosed during the Acadian orogeny. Dikes are increasingly abundant and sheeted to the northwest where they pass into the intrusive complex. The suite and host rocks are truncated on the northwest by the Monroe fault, a late Acadian thrust fault that carries rocks of the Bronson Hill sequence over Silurian-Devonian strata of the Connecticut Valley trough.

The age of the suite is well constrained as latest Ludlow; 20 fractions of zircon and baddeleyite from three sample sites of gabbro-diorite spanning nearly 40 km yield a weighted Pb/Pb age of 419 ± 1 Ma. Greenschist-facies dikes, sampled over a strike distance of 35 km, were tholeiitic basalts that formed by partial melting of asthenospheric mantle, with little or no contamination by mantle or crustal lithosphere. Dike compositions are similar to mid-ocean ridge, with-in plate, and back-arc basin basalts, all suggesting an extensional environment. The composition of the gabbro-diorite suggests that those rocks formed, at least in part, by the accumulation of plagioclase crystals from the same primitive magma that fractionated to form the dikes. The intrusive complex is interpreted to be the interior and perhaps deeper part of an extensional complex where the crust opened enough to allow the rise of a sizeable body of magma. As the body cooled and developed incipient fractures, new material flowed into the fractures. The process may have been repeated several times. We conclude that the parent magmas of the Comerford Intrusive Suite originated in the asthenosphere and were erupted through severely thinned lithosphere adjacent to the CVGT.

Extensive middle Paleozoic sedimentary basins in the internides of the Appalachian orogen are restricted to the Québec embayment of the Iapetan rifted margin of Laurentia. They include the CVGT trough to the west and the CMT to the east separated by the BHA. Silurian strata are thin to absent along the BHA but thicken markedly across a Silurian tectonic hinge into the CMT. The northeast-trending Comerford intrusions indicate relative northwest crustal extension. Silurian igneous rocks of extensional affinity occur on both flanks of and within the CVGT, and within the BHA and the CMT. Extension, beginning only 20 my after the end of foreland-directed motion, may have initiated through hinge retreat of the northwest-directed Brunswick subduction complex in the late Llandovery. Extension may have begun earlier in the CMT than in the CVT. Rise of the asthenosphere, through delamination caused by slab break off produced the Silurian extensional magmatism and further crustal extension. Convergence of the irregular margins of composite Laurentia and Avalon resulted in the continuation of collisional tectonics through the Silurian in Newfoundland (St. Lawrence promontory) and permitted extensional tectonics during the Silurian in central New England.

A tentative alternate hypothesis is that the basins originated as northeast trending pull-apart basins between northwest trending, left-stepping, sinistral strike-slip faults along the southern flanks of the New York and St. Lawrence promontories. Collision at the St. Lawrence promontory may have reactivated the Sept Îles transform as a sinistral strike slip fault that extended into the craton. Comparable faults at the New York promontory have not been recognized.

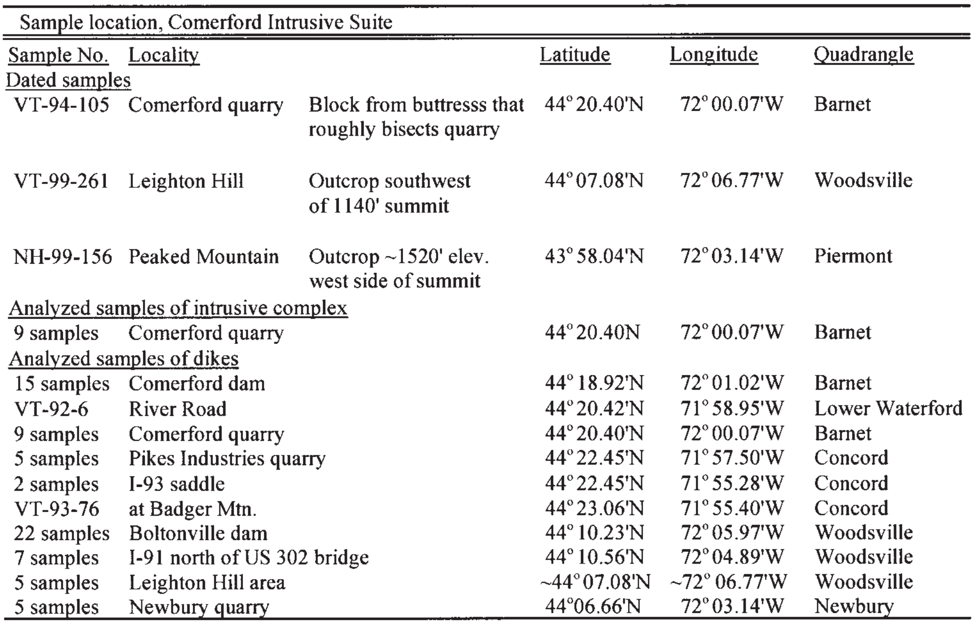
ACKNOWLEDGMENTS

We thank W. C. Burton, P. J. Thompson, R. P. Tollo, R. P. Wintsch, and D. P. West, Jr. (earlier draft) for their helpful reviews. D. R. would like to thank J. P. Hibbard, R .J. Marvinney, N. M. Ratcliffe, D .B. Stewart, J. B. Thompson, Jr., and C. R. van Staal for numerous discussions, some in the field, that have challenged and sharpened his understanding of Appalachian geology. D. R. would also like to thank his wife, Mary B. Rankin, for her assistance in the field. Finally, he would like to acknowledge that much of the stimulation for the broader concepts discussed in this paper originated from simply staring at Hank Williams' Tectonic Lithofacies Map of 1978 and observing the

broad areas of Silurian-Devonian rocks in the internides of the Northern Appalachians. Courage to think in those terms, to a considerable extent, comes from a long, learning association with John Rodgers beginning with his visit in 1957 to D. R.'s dissertation area in Baxter State Park, Maine, and with his association as mentor and advisor to R. D. T. at Yale University.

Appendix A

Sample location, Comerford Intrusive Suite



Sample location, Comerford Intrusive Suite

Sample No.	Locality		Latitude	Longitude	Quadrangle
Dated samples					
VT-94-105	Comerford quarry	Block from buttresss that roughly bisects quarry	44° 20.40'N	72° 00.07'W	Barnet
VT-99-261	Leighton Hill	Outcrop southwest of 1140' summit	44° 07.08'N	72° 06.77'W	Woodsville
NH-99-156	Peaked Mountain	Outcrop ~1520' elev. west side of summit	43° 58.04'N	72° 03.14'W	Piermont
Analyzed samples of intrusive complex					
9 samples	Comerford quarry		44° 20.40N	72° 00.07'W	Barnet
Analyzed samples of dikes					
15 samples	Comerford dam		44° 18.92'N	72° 01.02'W	Barnet
VT-92-6	River Road		44° 20.42'N	71° 58.95'W	Lower Waterford
9 samples	Comerford quarry		44° 20.40'N	72° 00.07'W	Barnet
5 samples	Pikes Industries quarry		44° 22.45'N	71° 57.50'W	Concord
2 samples	I-93 saddle		44° 22.45'N	71° 55.28'W	Concord
VT-93-76	at Badger Mtn.		44° 23.06'N	71° 55.40'W	Concord
22 samples	Boltonville dam		44° 10.23'N	72° 05.97'W	Woodsville
7 samples	I-91 north of US 302 bridge		44° 10.56'N	72° 04.89'W	Woodsville
5 samples	Leighton Hill area		~44° 07.08'N	~72° 06.77'W	Woodsville
5 samples	Newbury quarry		44°06.66'N	72° 03.14'W	Newbury

Appendix B

Geochronology: Analytical Methods

Accessory minerals were obtained using established techniques of rock crushing, screening, magnetic susceptibility and density floatation. Zircon and baddeleyite were hand-picked for analysis and zircon was abraded (baddeleyite is too delicate) using the techniques described by Krogh (1982). They were then cleaned in ultrasonic baths using distilled reagents including dilute HNO_3, water, and acetone. Mineral digestion and purification of U and Pb followed the general procedures outlined by Krogh (1973) and described additionally by Tucker and others (2001).

Isotope abundance ratios were determined by the method of isotope dilution. Isotope ratios of lead and uranium were measured in a VG Sector 54 mass using a single-collector procedure with a Daly-type photomultiplier detector operating in pulse-counting mode. Daly bias and nonlinearity were periodically monitored with NIST and CBNM isotopic reference materials, and correction factors for Daly gain were used in data reduction (table 2). Mass dependent fractionation of Pb and U has been monitored regularly since August 1994, and a discrimination factor for Pb ($0.094 \pm 0.04\%$ amu^{-1}; 2 sigma) and U ($0.111 \pm 0.04\%$ amu^{-1}; 2 sigma) has been applied to the measured ratios.

Total-procedure blanks over the period of analysis averaged between 2 pg for Pb and 0.5 pg for U; total common-Pb contents for each analysis are reported in table 2. Common-Pb corrections were made by first correcting the measured ratio for mass-dependent fractionation and introduced spike, then subtracting Pb equal in amount and composition to the laboratory blank. Any remaining ^{204}Pb is assumed to represent a model lead composition given by Stacey and Kramers (1975) at the estimated age of the rock. In all cases the uncertainty in the amount and composition of common-Pb represents an insignificant contribution to the uncertainty of the isotopic ages. Error propagation follows the procedure of Ludwig (1980), and reproducibility of the ^{207}Pb/^{206}Pb ages (fig. 4) confirms that the parameters used in data reduction and their errors have been evaluated correctly.

Appendix C

Samples with the prefix VT were analyzed for major and trace elements, including rare-earth-elements (REE), in the laboratories of the U. S. Geological Survey in Denver (tables 3 and 4). Samples with prefixes SW and AR were analyzed as follows: whole-rock major- and trace- element analyses were determined by inductively coupled argon plasma spectrometry (table 3) at Middlebury College (Kim and others, 2003); REE elements, Ta, Th, and Hf were analyzed by instrumental neutron activation analysis at Activation Laboratories in Ancaster, Ontario (table 4).

References

Armstrong, T. R., Walsh, G. J., and Spears, F. S., 1997, A transect across the Connecticut valley sequence in east-central Vermont, *in* Grover, T. W., Mango, H. N., and Hasenohr, E. J., editors, New England Intercollegiate Geological Conference, 89th Annual Meeting: Castleton, Vermont, Castleton State College, p. A6.1–A6.56.

Aydin, A., and Nur, A., 1982, Evolution of pull-apart basins and their scale independence: Tectonics, v. 1, p. 91–105.

Bédard, J. H., 1986, Pre-Acadian magmatic suites of the southeastern Gaspé Peninsula: Geological Society of America Bulletin, v. 97, p. 1177–1191.

Billings, M. P., 1937, Regional metamorphism of the Littleton-Moosilauke area, New Hampshire: Geological Society of America Bulletin, v. 48, p. 463–566.

Billings, M. P., and White, W. S., 1950, Metamorphosed mafic dikes of the Woodsville Quadrangle, Vermont and New Hampshire: American Mineralogist, v. 35, p. 629–643.

Boone, G. M., Boudette, E. L., and Moench, R. H., 1970, Bedrock geology of the Rangeley lakes-Dead River basin region, western Maine, *in* Boone, G. M., editor, New England Intercollegiate Geological Conference, 62nd Annual Meeting: Syracuse, New York, Guidebook for field trips in the Rangeley Lakes - Dead River Basin region, western Maine, p. 1–24.

Boucot, A. J., 1962, Appalachian Siluro-Devonian, *in* Coe, K., editor, Some aspects of the Variscan fold belt: Manchester, United Kingdom, Manchester University Press, 9th Inter-University Geological Congress, p. 155–163.

Boucot, A. J., and Arndt, R., 1960, Fossils of the Littleton Formation (Lower Devonian) of New Hampshire: United States Geological Survey Professional Paper P 0334-B, p. 41–51.

Boucot, A. J., and Drapeau, G., 1968, Siluro-Devonian rocks of Lake Memphremagog and their correlatives in the Eastern Townships: Quebec, Quebec Department of Natural Resources Special Paper, 44 p.

Boucot, A. J., and Rumble, D., III, 1980, Regionally metamorphosed (high sillimanite zone, granulite facies) Early Devonian brachiopods from the Littleton Formation of New Hampshire: Journal of Paleontology, v. 54, p. 188–195.

Boucot, A. J., and Thompson, J. B., Jr., 1963, Metamorphosed Silurian brachiopods from New Hampshire: Geological Society of America Bulletin, v. 74, p. 1313–1333.

Boucot, A. J., Field, M. T., Fletcher, R., Forbes, W. H., Naylor, R. S., and Pavlides, L., 1964, Reconnaissance bedrock geology of the Presque Isle quadrangle, Maine: Augusta, Maine Geological Survey Quadrangle Mapping Series No. 2, 123 p.

Bourque, P. A., 2001, Sea level, synsedimentary tectonics, and reefs; implications for hydrocarbon exploration in the Silurian-lowermost Devonian Gaspé Belt, Québec Appalachians: Bulletin of Canadian Petroleum Geology, v. 49, p. 217–237.

Bourque, P. A., Malo, M., and Kirkwood, D., 2000, Paleogeography and tectono-sedimentary history at the margin of Laurentia during Silurian to earliest Devonian time: The Gaspé belt, Québec: Bulletin of the Geological Society of America, v. 112, p. 4–20.

Bradley, D. C., 1982, Subsidence in late Paleozoic basins in the northern Appalachians: Tectonics, v. 1, p. 107–123.

——— 1989, Taconic plate kinematics as revealed by foredeep stratigraphy, Appalachian Orogeny: Tectonics, v. 8, p. 1037–1049.

Bradley, D. C., Tucker, R. D., Lux, D. R., Harris, A. G., and McGregor, D. C., 2000, Migration of the Acadian Orogen and foreland basin across the Northern Appalachians of Maine and adjacent areas: United States Geological Survey Professional Paper 1624, 55 p.

Castonguay, S., and Tremblay, A., 2003, Tectonic evolution and significance of Silurian-Early Devonian hinterland-directed deformation in the internal Humber Zone of the southern Quebec Appalachians: Canadian Journal of Earth Sciences, v. 40, p. 255–268.

Cawood, P. A., and Suhr, G., 1992, Generation and obduction of ophiolites; constraints for the Bay of Islands Complex, western Newfoundland: Tectonics, v. 11, p. 884–897.

Cawood, P. A., Dunning, G. R., Lux, D., and van Gool, J. A. M., 1994, Timing of peak metamorphism and deformation along the Appalachian margin of Laurentia in Newfoundland; Silurian, not Ordovician: Geology, v. 22, p. 399–402.

Cawood, P. A., van Gool, J. A. M., and Dunning, G. R., 1995, Collisional tectonics along the Laurentian margin of the Newfoundland Appalachians, *in* Hibbard, J. P., van Staal, C. R., and Cawood, P. A., editors, New perspectives in the Appalachian-Caledonian Orogen, Toronto: Geological Association of Canada Special Paper 41, p. 283–301.

Coish, R. A., 1977, Ocean floor metamorphism in the Betts Cove ophiolite, Newfoundland: Contributions to Mineralogy and Petrology, v. 60, p. 255–270.

Colman-Sadd, S. P., 1982, Two-stage continental collision and plate driving forces: Tectonophysics, v. 90, p. 263–282.

Cousineau, P. A., and Longuépée, H., 2003, Lower Paleozoic configuration of the Quebec reentrant based on improved along-strike paleogeography: Canadian Journal of Earth Sciences, v. 40, p. 207–219.

Cox, K. G., 1988, The Karoo province, *in* Macdougall, J. D., editor, Continental flood basalts: Dordrecht, Kluwer Academic Publishers, p. 239–271.

David, J., and Garipéy, C., 1990, Early Silurian orogenic andesites from the central Quebec Appalachians: Canadian Journal of Earth Sciences, v. 27, p. 632–643.

Doll, C. G., Cady, W. M., Thompson, J. B., Jr., and Billings, M. P., 1961, Centennial geologic map of Vermont: Montpelier, Vermont Geological Survey, scale 1:250,000.

Dorais, M. J., and Paige, M. L., 2000, Regional geochemical and isotopic variations of northern New England plutons; implications for magma sources and for Grenville and Avalon basement-terrane boundaries: Geological Society of America Bulletin, v. 112, p. 900–914.

Dostal, J., Wilson, R. A., and Keppie, J. D., 1989, Geochemistry of Siluro-Devonian Tobique volcanic belt in northern and central New Brunswick (Canada): tectonic implications: Canadian Journal of Earth Sciences, v. 26, p. 1282–1296.

Dostal, J., Laurent, R., and Keppie, J. D., 1993, Late Silurian-early Devonian rifting during dextral transpression in the southern Gaspé Peninsula (Québec): petrogenesis of volcanic rocks: Canadian Journal of Earth Sciences, v. 30, p. 2283–2294.

Dunning, G. R., O'Brien, S. J., Colman-Sadd, S. P., Blackwood, R. F., Dickson, W. L., O'Neill, P. P., and Krogh, T. E., 1990, Silurian orogeny in the Newfoundland Appalachians: Journal of Geology, v. 98, p. 895–913.

Elbert, D. C., Harris, A. G., and Denkler, K. E., 1988, Earliest Devonian conodonts from marbles of the Fitch Formation, Bernardston nappe, north-central Massachusetts: American Journal of Science, v. 288, p. 648–700.

Ellam, R. M., 1992, Lithospheric thickness as a control on basalt geochemistry: Chemical Geology, v. 20, p. 153–156.

Eric, J. H., and Dennis, J. G., 1958, Geology of the Concord-Waterford area, Vermont: Montpelier, Vermont Geological Survey Bulletin 11, 66 p.

Fitton, J. G., James, D., Kempton, P. D., Ormerod, D. S., and Leeman, W. P., 1988, The role of lithospheric mantle in the generation of late Cenozoic basic magmas in the western United States, *in* Cox, K. G., and Menzies, M. A., editors, Oceanic and continental lithosphere; similarities and differences: Journal of Petrology Special Volume, p. 331–349.

Fitzgerald, J., and Hon, R., 1994, Mafic volcanism of the Piscataquis volcanic belt, *in* Hanson, L. S., editor, New England Intercollegiate Geological Conference, 85th Annual Meeting: Salem, Massachusetts, Salem State College, Guidebook to field trips in north-central Maine, p. 91–122.

Fortey, R. A., Harper, D. A. T., Kingham, J. K., Owen, A. W., and Rushton, A. W. A., 1995, A revision of Ordovician series and stages from the historical type area: Geological Magazine, v. 132, p. 15–30.

Gradstein, F. M., Ogg, J. G., Smith, A. G., Bleeker, W., and Lourens, L. J., 2004, A new geologic time scale, with special reference to Precambrian and Neogene: Episodes, v. 27, n. 2, p. 83100.

Green, J. C., 1968, Geology of the Connecticut Lakes-Parmachenee area, New Hampshire and Maine: Geological Society of America Bulletin, v. 79, p. 1601–1638.

Hadley, J. B., 1942, Stratigraphy, structure, and petrology of the Mount Cube area, New Hampshire: Geological Society of America Bulletin, v. 53, p. 113–176.

——— 1950, Geology of the Bradford-Thetford area, Orange County, Vermont: Vermont Geological Survey Bulletin 1, 36 p.

Hajash, A., Jr., and Archer, P., 1980, Experimental seawater/basalt interaction: Effects of cooling: Contributions to Mineralogy and Petrology, v. 75, p. 1–13.

Hall, B. A., 1970, Stratigraphy of the southern end of the Musungun anticlinorium: Maine Geological Survey Bulletin 22, 63 p.

Hall, L. M., 1959, The geology of the Saint Johnsbury Quadrangle, Vermont and New Hampshire: Montpelier, Vermont Geological Survey Bulletin 13, 105 p.

Hall, L. M., and Robinson, P., 1982, Stratigraphic-tectonic subdivisions of Southern New England, *in* St-Julien, P., and Béland, J., editors, Major structural zones and faults of the northern Appalachians: Geological Association of Canada Special Paper 24, p. 15–41.

Hames, W. E., Tracy, R. J., Ratcliffe, N. M., and Sutter, J. F., 1991, Petrologic, structural, and geochronologic characteristics of Acadian metamorphic overprint on the Taconide zone in part of southwestern New England: American Journal of Science, v. 291, p. 887–913.

Hannula, K. A., Onasch, E., Wertheim, J., Lackey, J. S., Mattox, E., and McGrath, G., 1999, Syn-tectonic pluton intrusion during contractional deformation: Microstructural and metamorphic evidence from the aureole of the Acadian Victory Pluton, north-eastern Vermont, USA: Journal of Metamorphic Geology, v. 17, p. 271–286.

Hanson, L. S., Bradley, D. C., and Caldwell, D. W., 1993, Geology and geomorphology of the Acadian orogen central Maine, *in* Cheney, J. T., and Hepburn, J. C., editors, Field trip guidebook for the northeastern United States: 1993 Boston GSA: Amherst, University of Massachusetts, Department of Geology and Geography Contribution 67, v. 2, p. CC1– CC27.

Harris, A. G., Hatch, N. L., Jr., and Dutro, J. T., Jr., 1983, Late Silurian conodonts update the metamorphosed Fitch Formation, Littleton area, New Hampshire: American Journal of Science, v. 283, p. 722–738.

Harrison, T. M., Aleinikoff, J. N., and Compston, W., 1987, Observations and controls on the occurrence of inherited zircon in Concord-type granitoids, New Hampshire: Geochimica et Cosmochimica Acta, v. 51, p. 2549–2558.

Hatch, N. L., Jr., 1963, Geology of the Dixville quadrangle, New Hampshire: Concord, New Hampshire Department of Economic Resources and Development Bulletin 1, 81 p.

Hatch, N. L., Jr., Moench, R. H., and Lyons, J. B., 1983, Silurian-Lower Devonian stratigraphy of eastern and south-central New Hampshire; extensions from western Maine: American Journal of Science, v. 283, p. 739–761.

Hatch, N. L., Jr., Robinson, P., and Stanley, R. S., 1988, Stratigraphy of the Connecticut Valley Belt, *in* Hatch, N. L., Jr., editor, The bedrock geology of Massachusetts: United States Geological Survey Paper P 1366 A-D, p. B1–B34.

Hellman, P. L., Smith, R. E., and Henderson, P., 1979, The mobility of the rare earth elements: evidence and implications from selected terrains affected by burial metamorphism: Contributions to Mineralogy and Petrology, v. 71, p. 23–44.

Hepburn, J. C., 1991, Geochemical evidence for post-Taconic rift origin of the Connecticut Valley-Gaspé Synclinorium, VT-NH: Geological Society of America Abstracts with Programs, v. 23, n. 5, p. 133.

Hepburn, J. C., Dunning, G. R., and Hon, R., 1995, Geochronology and regional tectonic implications of Silurian deformation in the Nashoba Terrane, southeastern New England, U.S.A, *in* Hibbard, J. P., van Staal, C. R., and Cawood, P. A., editors, New perspectives in the Appalachian-Caledonian Orogen, Toronto: Geological Association of Canada Special Paper 41, p. 349–365.

Hibbard, J., and Hall, S., 1993, Early Acadian sinistral shear in north-central Maine, USA: Journal of the Geological Society of London, v. 150, Part 5, p. 815–818.

Hibbard, J. P., van Staal, C. R., Rankin, D. W., and Williams, H., 2006, Lithotectonic map of the Appalachian orogen (north), Canada–United States of America: Geological Survey of Canada Map 02041A, scale 1:1,500,000.

Higgins, M. D., and Doig, R., 1986, Geochemical constraints on the differentiation processes that were active in the Sept Iles complex: Canadian Journal of Earth Sciences, v. 23, p. 670–681.

Higgins, M. D., and Van Breemen, O., 1998, The age of the Step Iles layered mafic intrusion, Canada: implications for the Late Neoproterozoic/Cambrian history of southeastern Canada: Journal of Geology, v. 106, p. 421–431.

Hofmann, A. W., 1988, Chemical differentiation of the Earth: the relationship between mantle, continental crust, and oceanic crust: Earth and Planetary Science Letters, v. 90, p. 297–314.

Hon, R., Fitzgerald, J. P., Sargent, S. L., Schwartz, W. D., Dostal, J., and Keppie, J. D., 1992, Silurian-Early Devonian mafic rocks of the Piscataquis volcanic belt in northern Maine: Atlantic Geology, v. 28, p. 163–170.

Hueber, F. M., Bothner, W. A., Hatch, N. L., and Aleinikoff, J., 1990, Devonian plants from southern Quebec and northern New Hampshire and the age of the Connecticut Valley trough: American Journal of Science, v. 290, p. 360–395.

Jaffey, A. F., Flynn, K. F., Glendenin, L. E., Bentley, W. C. and Essling, A. M., 1971, Precision measurement of half-lives and specific activities of 235U and 238U: Physics Review Section C, Nuclear Physics, v. 4, p. 1889–1906.

Karabinos, P., 1998, Tectonic and stratigraphic development of the Connecticut Valley Trough in the New England Appalachians: Geological Society of America Abstracts with Programs, v. 30, n. 7, p. 191.

Karabinos, P., and Hepburn, J. C., 2001, Geochronology and geochemistry of the Shelburne Falls arc: the Taconic Orogeny in western New England, *in* West, D. P., Jr., and Bailey, R. H., editors, Guidebook to Geological Field Trips in New England: Geological Society of America, p. H1–20.

Karabinos, P., and Tucker, R. D., 1992, The Shelburne Falls arc in western Massachusetts and Connecticut; the lost arc of the Taconian Orogeny: Geological Society of America Abstracts with Programs, v. 24, n. 7, p. 288–289.

Karabinos, P., Samson, S. D., Hepburn, J. C., and Stoll, H. M., 1998, Taconian orogeny in the New England Appalachians; collision between Laurentia and the Shelburne Falls Arc: Geology, v. 26, p. 215–218.

Karlstrom, K. E., van der Pluijm, B. A., and Williams, P. F., 1982, Structural interpretation of the eastern Notre Dame Bay area, Newfoundland; regional post-Middle Silurian thrusting and asymmetrical folding: Canadian Journal of Earth Sciences, v. 19, p. 2325–2341.

Keppie, J. D., and Dostal, J., 1994, Late Silurian-Early Devonian transpressional rift origin of the Quebec Reentrant, Northern Appalachians; constraints from geochemistry of volcanic rocks: Tectonics, v. 13, p. 1183–1189.

Kim, J., and Jacobi, R. D., 1996, Geochemistry and tectonic implications of Hawley Formation meta-igneous units: northwestern Massachusetts: American Journal of Science, v. 296, p. 1126–1174.

Kim, J., Coish, R., Evans, M., and Dick, G., 2003, Supra-subduction zone extensional magmatism in Vermont and adjacent Quebec; implications for early Paleozoic Appalachian tectonics: Geological Society of America Bulletin, v. 115, p. 1552–1569.

Kirkwood, D., 1999, Palinspastic restoration of a post-Taconian successor basin deformed within a transpressive regime, Northern Appalachians: Tectonics, v. 18, p. 1027–1040.

Knight, I., James, N. P., and Williams, H., 1995, Cambrian-Ordovician carbonate sequence, *in* Williams, H., editor, Geology of the Appalachian-Caledonian orogen in Canada and Greenland: Geological Survey of Canada, Geology of Canada, n. 6, p. 67–87.

Krogh, T. E., 1973, A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations: Geochimica et Cosmochimica Acta, v. 37, p. 485–494.

——— 1982, Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique: Geochimica et Cosmochimica Acta, v. 46, p. 637–649.

Lamontagne, M., Keating, P., and Perreault, S., 2003, Seismotectonic characteristics of the lower St. Lawrence seismic zone, Quebec; insights from geology, magnetics, gravity, and seismics: Canadian Journal of Earth Sciences, v. 40, p. 317–336.

Lavoie, D., 1992, Carbonate sedimentation in an extensional tectonic regime; the Lower Devonian Upper Gaspé Limestones, Québec Appalachians: Canadian Journal of Earth Sciences, v. 29, p. 118–128.

——— 1994, Diachronous tectonic collapse of the Ordovician continental margin, Eastern Canada; comparison between the Quebec Reentrant and St. Lawrence Promontory: Canadian Journal of Earth Sciences, v. 31, p. 1309–1319.

Lavoie, D., and Asselin, E., 2004, A new stratigraphic framework for the Gaspé belt in southern Quebec: implications for pre-Acadian Appalachians of eastern Canada: Canadian Journal of Earth Science, v. 41, p. 507–525.

Leat, P. T., Thompson, R. N., Morrison, M. A., Hendry, G. L., and Dickin, A. P., 1988, Compositionally-diverse Miocene-Recent rift-related magmatism in northwest Colorado: partial melting, and mixing of mafic magmas from 3 different asthenospheric and lithospheric mantle sources, *in* Cox, K. G., and Menzies, M. A., editors, Oceanic and continental lithosphere; similarities and differences: Journal of Petrology Special Volume, p. 351–377.

Lebel, D., and Hubert, C., 1995, Géologie de la region de Sain-Malachie (Chaudière-Appalaches): Ministère des Ressources Naturelles du Québec ET 93-03.

Leeman, W. P., and Hawkesworth, C. J., 1986, Open magma systems: trace element and isotopic constraints: Journal of Geophysical Research, v. 91, p. 5901–5912.

Lin, S., van Staal, C. R., and Dube, B., 1994, Promontory-promontory collision in the Canadian Appalachians: Geology, v. 22, p. 897–900.

Ludman, A., and West, D. P., Jr., 1999, Norumbega fault system of the northern Appalachians: Geological Society of America Special Paper 331, 202 p.

Ludwig, K. R., 1980, Calculation of uncertainties of U-Pb isotope data: Earth and Planetary Science Letters, v. 46, p. 212–220.

Lyons, J. B., Bothner, W. A., Moench, R. H., and Thompson, J. B., Jr., 1997, Bedrock geologic map of New Hampshire: U. S. Geological Survey Map, scale 1:250,000, 2 sheets.

Malo, M., 2004, Paleogeography of the Matapédia Basin in the Gaspé Appalachians; initiation of the Gaspé Belt successor basin: Canadian Journal of Earth Sciences, v. 41, p. 553–570.

Malo, M., and Kirkwood, D., 1995, Faulting and progressive strain history of the Gaspé Peninsula in post-Taconian time; a review, *in* Hibbard, J. P., van Staal, C. R., and Cawood, P. A., editors, New perspectives in the Appalachian-Caledonian Orogen, Toronto: Geological Association of Canada Special Paper 41, p. 267–282.

Malo, M., Kirkwood, D., De Broucker, G., and St-Julien, P., 1992, A reevaluation of the position of the Baie Verte-Brompton Line in the Québec Appalachians; the influence of Middle Devonian strike-slip faulting in Gaspé Peninsula: Canadian Journal of Earth Sciences, v. 29, p. 1265–1273.

Marvinney, R. G., ms, 1986, Tectonic implications of stratigraphy, structure, and metamorphism in the Penobscot Lake region, northwestern Maine: Syracuse, New York, Syracuse University, Ph. D. thesis, 269 p.

Moench, R. H., 1990, The Piermont allochthon, northern Connecticut Valley area, New England - preliminary description and resource implications, *in* Slack, J. F., editor, Summary results of the Glens Falls CUSMAP project, New York, Vermont, and New Hampshire: United States Geological Survey Bulletin 1887, p. J1–J23.

——— 1996, Stratigraphic basis for the Piermont-Frontenac allochthon, Bath to Piermont, New Hampshire, and Bradford, Vermont, *in* van Baalen, M. R., editor, Guidebook to field trips in northern New Hampshire and adjacent regions of Maine and Vermont: Cambridge, Massachusetts, Harvard University, New England Intercollegiate Geological Conference, 88th annual meeting, p. 133–153.

——— 1999, Nature of the Albee-Ammonoosuc contact in the Moore Reservoir area, New Hampshire and Vermont: Piermont-Frontenac allochthon, embattled but thriving!, *in* Wright, S. H., editor, Guidebook for field trips in Vermont and adjacent regions of New Hampshire and New York: Burlington, University of Vermont, New England Intercollegiate Geological Conference, 91st Annual meeting, p. 113–135.

Moench, R. H., and Aleinikoff, J. N., 2002, Stratigraphy, geochronology, and accretionary terrane settings of two Bronson Hill arc sequences, northern New England: Physics and Chemistry of the Earth, v. 27, p. 47–95.

Moench, R. H., and Pankiwskyj, K. A., 1988, Geologic map of western interior Maine: United States Geological Survey Miscellaneous Investigations Series Map I-1692, scale 1:250,000.

Moench, R. H., Douglas-Hafner, K., Jahrling, I., and Pyke, A. R., 1987, Metamorphic stratigraphy of the classic Littleton area, New Hampshire, *in* Roy, D. C., editor, Geological Society of America, Northeastern Section: Geological Society of America Centennial field guide, v. 5, p. 247–256.

Moench, R. H., Boone, G. M., Bothner, W. A., Boudette, E. L., Hatch, N. L., Jr., Hussey, A. M., II, Marvinney, R. G., and Aleinikoff, J. N., 1995, Geologic map of the Sherbrooke-Lewiston area, Maine, New Hampshire, and Vermont, United States, and Quebec, Canada: United States Geological Survey Map I-1898 D, scale 1:250,000, and text, 56 p.

Nakamura, N., 1974, Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites: Geochimica et Cosmochimica Acta, v. 38, p. 757–775.

Naylor, R. S., and Boucot, A. J., 1965, Origin and distribution of rocks of Ludlow age (Late Silurian) in the northern Appalachians: American Journal of Science, v. 263, p. 153–169.

Neuman, R. B., 1967, Bedrock geology of the Shin Pond and Stacyville quadrangles, Penobscot County, Maine: U.S. Geological Survey Professional Paper 524-I, 37 p.

O'Brien, B. H., O'Brien, S. J., and Dunning, G. R., 1991, Silurian cover, late Precambrian-Early Ordovician basement, and the chronology of Silurian orogenesis in the Hermitage Flexure (Newfoundland Appalachians): American Journal of Science, v. 291, p. 760–799.

Osberg, P. H., 1974, Forward, *in* Osberg, P. H., editor, Guidebook for field trips in east-central Maine: Orono, University of Maine, New England Intercollegiate Geological Conference,

——— 1988, Geologic relations within the shale-wacke sequence in south-central Maine, *in* Tucker, R. D., and Marvinney, R. G., editors, Augusta, Studies in Maine Geology, v. 1: Augusta, Maine Geological Survey, p. 51–73.

Osberg, P. H., Tull, J. F., Robinson, P., Hon, R., and Butler, J. R., 1989, The Acadian orogen, *in* Hatcher, R. D., Thomas, W. A., and Viele, G. W., editors, The Appalachian-Ouachita Orogen in the United States: Geological Society of America, The Geology of North America, v. F-2, p. 179–232.

Pavlides, L., Boucot, A. J., and Skidmore, W. B., 1968, Stratigraphic evidence for the Taconic orogeny in the northern Appalachians, *in* Zen, E., White, W. S., Hadley, J. B., and Thompson, J. B., Jr., editors, Studies of Appalachian geology, northern and maritime: New York, Interscience Publishers, p. 61–82.

Pearce, J. A., 1982, Trace element characteristics of lavas from destructive plate boundaries, *in* Thorpe, R. S., editor, Andesites: Chichester, Wiley, p. 525–548.

Pincivy, A., Malo, M., Ruffet, G., Tremblay, A., and Sacks, P. E., 2003, Regional metamorphism of the Appalachian Humber Zone of Gaspé Peninsula; ^{40}Ar/ ^{39}Ar evidence for crustal thickening during the Taconian Orogeny: Canadian Journal of Earth Sciences, v. 40, p. 301–315.

Rankin, D. W., 1976, Appalachian salients and recesses: late Precambrian continental breakup and opening of the Iapetus ocean: Journal of Geophysical Research, v. 81, p. 5605–5619.

——— 1994, Continental margin of the eastern United States: past and present, *in* Speed, R. C., editor, Phanerozoic Evolution of North American Continent-Ocean Transitions: Boulder, Colorado, Geological Society of America, DNAG Continent-Ocean Transect Volume, p. 129–218.

——— 1996a, Bedrock geology of the Littleton, Vermont - New Hampshire 15-minute quadrangle northwest of the Ammonoosuc Fault, *in* van Baalen, M. R., editor, Guidebook to field trips in northern New Hampshire and adjacent regions of Maine and Vermont: Cambridge, Massachusetts, Harvard University, New England Intercollegiate Geological Conference, 88th annual meeting, p. 5–37.

——— 1996b, The Monroe Fault between Comerford Dam and North Concord, Vermont: a west-directed, premetamorphic thrust fault carrying a Silurian sheeted dike complex over rocks of the Connecticut Valley Trough, *in* van Baalen, M. R., editor, Guidebook to Field Trips in northern New Hampshire and adjacent regions of Maine and Vermont: Cambridge, Massachusetts, Harvard University, New England Intercollegiate Geological Conference, 88th annual meeting, p. 273–279.

——— 1998, The Littleton, VT-NH 15' quadrangle, 60 years later: No Piermont-Frontenac allochthon: Geological Society of America Abstracts with Programs, v. 30, n. 1, p. 67–68.

Rankin, D. W., and Tucker, D. H., 1999, Age and contact relations of the Lost Nation pluton, upper Connecticut Valley: implications for the Piermont-Frontenac allochthon: American Geophysical Union, EOS, Transactions, 1999 Spring Meeting Supplement, v. 80, n. 17, p. 5358.

——— 2000, Monroe fault truncated by Mesozoic (?) Connecticut Valley rift system at Bradford, VT: relationship to the Piermont allochthon: Geological Society of America Abstracts with Programs, v. 31, n. 1, p. A-67.

Ratcliffe, N. M., and Aleinikoff, J., 2000, Silurian age of the Braintree Complex, VT: bearing on the age of the Cram Hill and Shaw Mountain Formations: Geological Society of America Abstracts with Programs, v. 32, n. 1, p. 68.

Ratcliffe, N. M., Hames, W. E., and Stanley, R. S., 1998, Interpretation of ages of arc magmatism, metamorphism, and collisional tectonics in the Taconian orogen of western New England: American Journal of Science, v. 298, p. 791–797.

Reed, J. C., Jr., Wheeler, J. O., and Tucholke, B. E., 2004, Geologic map of North America: Decade of North American Geology: Boulder, Colorado, Geological Society of America Continental Scale Map 001, scale 1:5,000,000.

Richardson, L. A., ms, 1997, Lithology, stratigraphy and geochemistry of the Standing Pond Volcanics in northeastern Vermont: Burlington, University of Vermont, Masters thesis, 160 p.

Robinson, P., Tucker, R. D., Bradley, D., Berry, H. N., IV., and Osberg, P. H., 1998, Paleozoic orogens in New England, USA: GFF (Geological Society of Sweden), v. 120, p. 119–148.

Rollinson, H., 1993, Using geochemical data: evaluation, presentation, interpretation: New York, John Wiley and Sons, 352 p.

Rodgers, J., 1970, The tectonics of the Appalachians: New York, Interscience Publishers, 271 p.

——— 1971, The Taconic orogeny: Geological Society of America, v. 62, p. 1141–1178.

——— 1975, Appalachians salients and recesses: Geological Society of America Abstracts with Programs, v.7, n. 1, p. 111–112.

Roy, D. C., 1980, Tectonics and sedimentation in northeastern Maine and adjacent New Brunswick, *in* Roy, D. C., and Naylor, R. S., editors, Guidebook to the geology of northeastern Maine and neighboring New Brunswick: New England Intercollegiate Geological Conference, 72nd Annual Meeting, 1980, Presque Isle, Maine, p. 1–21.

——— 1989, The Depot Mountain Formation: Transition from syn- to post-Taconian basin along the Baie Verte-Brompton line in northwestern Maine, *in* Tucker, R. D., and Marvinney, R. G., editors, Studies in Maine Geology, v. 2, Structure and stratigraphy: Augusta, Maine Geological Survey, p. 85–99.

Roy, D. C., Pollock, S. G., and Hanson, L., 1991, Bedrock geology of the upper St. John River area, northwestern Maine: Augusta, Maine Geological Survey Open-File 91-8, scale 1:62,500.

Rumble, D., III, ms, 1969, Stratigraphic, structural, and petrologic studies in the Mt. Cube area, New Hampshire: Cambridge, Massachusetts, Harvard University, Ph. D. thesis, 120 p.

Sanford, B. V., and Grant, A. C., 1990, Bedrock geological mapping and basin studies in the Gulf of St. Lawrence: Geological Survey of Canada Current Research Paper 90-1B, 33–42 p.

Schwartz, W. D., Hon, R., and Roy, D. R., 1984, Trace element geochemistry of Silurian bimodal magmatism in northern Maine: Geological Society of America Abstracts with Programs, v. 16, p. 62.

Shervais, J. W., 1982, Ti-V plots and the petrogenesis of modern and ophiolitic lavas: Earth and Planetary Science Letters, v. 59, p. 101–118.

Stacey, J. S., and Kramers, J. D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage model: Earth and Planetary Science Letters, v. 26, p. 207–221.

Stanley, R. S., and Ratcliffe, N. M., 1985, Tectonic synthesis of the Taconian orogeny in western New England: Geological Society of America Bulletin, v. 96, p. 1227–1250.

Stewart, D. B., 1989, Crustal processes in Maine: American Mineralogist, v. 74, p. 698–714.

——— 1998, Geology of northern Penobscot Bay, Maine: United States Geological Survey Miscellaneous Investigations Series Map I-2551, scale 1:62,500.

Stewart, D. B., Wright, B. E., Unger, J. D., Phillips, J. D., and Hutchinson, D. R., 1993, Global Geoscience Transect 8: Quebec - Maine - Gulf of Maine Transect, southeastern Canada, northeastern United States of America: United States Geological Survey Miscellaneous Investigation Series Map I-2329, scale 1:1,000,000.

Stewart, D. B., Unger, J. D., and Hutchinson, D. R., 1995, Silurian tectonic history of Penobscot Bay region, Maine: Atlantic Geology, v. 31, p. 67–79.

Stockmal, G. S., Colman-Sadd, S. P., Keen, C. E., O'Brien, S. J., and Quinlan, G., 1987, Collision along an irregular margin; a regional plate tectonic interpretation of the Canadian Appalachians: Canadian Journal of Earth Sciences, v. 24, p. 1098–1107.

Stockmal, G. S., Colman-Sadd, S. P., Keen, C. E., Marillier, F., O'Brien, S. J., and Quinlan, G. M., 1990, Deep seismic structure and plate tectonic evolution of the Canadian Appalachians: Tectonics, v. 9, p. 45–62.

Thomas, W. A., 1977, Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin: American Journal of Science, v. 277, p. 1233–1278.

Thompson, J. B., Jr., and Norton, S. A., 1968, Paleozoic regional metamorphism in New England and adjacent areas, *in* Zen, E., White, W. S., Hadley, J. B., and Thompson, J. B., Jr., editors, Studies of Appalachian geology: northern and maritime: New York, Interscience Publishers, p. 319–327.

Thompson, J. B., Jr., Rosenfeld, J. L., Hepburn, J. C., and Trzcienski, W. E., 1997, How does New Hampshire connect to Vermont?, *in* Grover, T. W., Mango, H. N., and Hasenohr, E. J., editors, Guidebook for field trips in Vermont and adjacent New Hampshire and New York: Castleton, Vermont, Castleton State College, New England Intercollegiate Geological Conference, 89th Annual Meeting, p. C1-1 to C1-17.

Thompson, P., and Thompson, T., 2003, Prospect Rock thrust: western limit of the Taconian accretionary prism in the northern Green Mountain anticlinorium, Vermont: Canadian Journal of Earth Sciences, v. 40, p. 269–284.

Thompson, R. N., and Morrison, M. A., 1988, Asthenospheric and lower-lithospheric mantle contributions to continental extension magmatism: an example from the British Tertiary Province: Chemical Geology, v. 68, p. 1–15.

Timms, N. E., 2004, The Piermont Allochthon revisited and redefined at its type locality: Geological Society of America Bulletin, v. 116, p. 1392–1407.

Tremblay, A., and Pinet, N., 2005, Diachronous supracrustal extension in an intraplate setting and the origin of the Connecticut Valley-Gaspé and Merrimack troughs, northern Appalachians: Geological Magazine, v. 142, p. 7–22.

Tucker, R. D., and Robinson, P., 1990, Age and setting of the Bronson Hill magmatic arc: A re-evaluation based on U-Pb zircon ages in southern New England: Geological Society of America Bulletin, v. 102, p. 1404–1419.

Tucker, R. D., Osberg, P. H., and Berry, H. N., IV, 2001, The geology of a part of Acadia and the nature of the Acadian Orogeny across central and eastern Maine: American Journal of Science, v. 301, p. 205–260.

van der Voo, R., 1988, Paleozoic paleogeography of North America, Gondwana, and intervening displaced terranes; comparisons of paleomagnetism with paleoclimatology and biogeographical patterns: Geological Society of America Bulletin, v. 100, p. 311–324.

van Staal, C. R., 1994, Brunswick subduction complex in the Canadian Appalachians: record of the Late Ordovician to Late Silurian collision between Laurentia and the Gander margin of Avalon: Tectonics, v. 13, p. 946–962.

van Staal, C. R., and de Roo, J. A., 1995, Mid-Paleozoic tectonic evolution of the Appalachian Central mobile belt in northern New Brunswick, Canada; collision, extensional collapse and dextral transpression, *in* Hibbard, J. P., van Staal, C. R., and Cawood, P. A., editors, Current perspectives in the Appalachian-Caledonian Orogen: Toronto, Geological Association of Canada, p. 367–389.

van Staal, C. R., Dewey, J. F., Mac Niocaill, C., and McKerrow, W. S., 1998, The Cambrian-Silurian tectonic evolution of the northern Appalachians and British Caledonides: history of a complex, west and southwest Pacific- type segment of Iapetus, *in* Blundell, D. J., and Scott, A. C., editors, Lyell: the Past is the Key to the Present: Geological Society Special Publication 143, p. 199–242.

van Staal, C. R., Wilson, R. A., Rogers, N., Fyffe, L. R., Langton, J. P., McCutcheon, S. R., McNicoll, V., and Ravenhurst, C. E., 2003, Geology and tectonic history of the Bathurst Supergroup, Bathurst Mining Camp and its relationship to coeval rocks in southwestern New Brunswick and adjacent Maine - a synthesis, *in* Goodfellow, W. D., McCutcheon, S. R., and Peter, J. M., editors, Massive Sulfide Deposits of the Bathurst Mining Camp, New Brunswick and Northern Maine: Economic Geology Monograph, v. 11, p. 37–60.

West, D. P., Jr., Ludman, A., and Lux, D. R., 1992, Silurian age for the Pocomoonshine gabbro-diorite, southeastern Maine and its regional tectonic implications: American Journal of Science, v. 292, p. 253–273.

West, D. P., Jr., Beal, H. M., and Grover, T. W., 2003, Silurian deformation and metamorphism of Ordovician arc rocks of the Casco Bay Group, south-central Maine: Canadian Journal of Earth Sciences, v. 40, p. 887–905.

Whalen, J. B., and Currie, K. L., 1990, The Topsails Igneous Suite, western Newfoundland; fractionation and magma mixing in an "orogenic" A-type granite suite, *in* Stein, H. J., and Hannah, J. L., editors, Magmatic and hydrothermal processes in ore-bearing systems: Geological Society of America Special Paper, v. 246, p. 287–300.

White, W. S., and Billings, M. P., 1951, Geology of the Woodsville Quadrangle, Vermont-New Hampshire: Geological Society of America Bulletin, v. 62, p. 647–696.

Williams, H., 1978, Tectonic-Lithofacies Map of the Appalachian Orogen: St. John's, Newfoundland, Memorial University of Newfoundland Map No. 1A, scale 1:2,000,000.

——— 1995, Summary and overview, *in* Williams, H., editor, Geology of the Appalachian-Caledonian orogen in Canada and Greenland: Geological Survey of Canada, Geology of Canada, n. 6, p. 853–890.

Wilson, J. T., 1966, Did the Atlantic close and then reopen?: Nature, v. 211, p. 676–681.

Wilson, M., 1989, Igneous petrogenesis: A global tectonic approach: London, Boston, Unwin Hyman, 466 p.

Winchester, J. A., and Floyd, P. A., 1976, Geochemical magma type discrimination: Application to altered and metamorphosed igneous rocks: Earth and Planetary Science Letters, v. 28, p. 459–469.

Winter, J. D., 2001, An introduction to igneous and metamorphic petrology: Upper Saddle River, New Jersey, Prentice Hall, 697 p.

Zen, E., 1991, Phanerozoic denudation history of the southern New England Appalachians deduced from pressure data: American Journal of Science, v. 291, p. 401–424.