Evidence for a ridge subduction event in the Ordovician rocks of north-central Maine

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ABSTRACT

Modern and past ridge subduction events are characterized by the intrusion of mid-ocean-ridge basalt (MORB) magmas into an overlying accretionary prism. The field relationships and trace-element geochemistry of Ordovician mafic igneous rocks of the Weeksboro-Lunksoos and Munsungun anticlinoria of north-central Maine indicate that they resulted from such an event. The Bean Brook gabbro intrudes the Hurricane Mountain mélange and other related sedimentary strata of continental derivation. The gabbro and associated Dry Way volcanics have MORB trace-element chemistries, while the Bluffer Pond and Stacyville volcanics are more enriched (E-MORB), all of which indicate derivation from a mid-ocean ridge. On petrogenetic diagrams, mafic samples plot in MORB fields, or when Th is used as a discriminator, in arc fields along trends that originate from MORB fields and extend toward the composition of upper continental crust. These trends are consistent with the presence of silicic and metasedimentary xenoliths in the Dry Way volcanics and Bean Brook gabbro and indicate the magmas were not subduction products, but were contaminated by Th-rich upper continental crust.

The nearby Chain Lakes Massif likely represents the basement to the "Chain Lakes microcontinent," and the geographic relationship and ages of the massif, Hurricane Mountain mélange, and Dry Way–Bean Brook magmatic rocks indicate northwest-directed subduction (modern coordinates) on the southeastern margin of the Chain Lakes microcontinent, within the Early to Middle Ordovician Taconic ocean. Subduction at this boundary probably terminated because of the ridge subduction, analogous to Neogene California.

Keywords: Bean Brook gabbro, Chain Lakes Massif, ridge subduction, basalt geochemistry, Taconic ocean, Dunnage zone.

INTRODUCTION

Recent studies along the Alaskan Tertiary margin have described the effects of active mid-ocean-ridge subduction (e.g., Sisson et al., 2003), and while there are several modern and Mesozoic examples, few from the more ancient past have been identified (see Bradley et al., 2003). In this paper, we present evidence for a ridge subduction event recorded in the Early Ordovician Appalachians of northern Maine.

Over the past decade, the simple model of a largely featureless Taconic ocean (ca. 554 to ca. 448 Ma; Kumarapelli et al., 1989; Tucker and Robinson, 1990) undergoing closure along two or three subduction zones has been replaced by a more complicated Western Pacific–style model that envisions multiple (including some coeval) island and continental arcs, backarc basins, continental fragments, and collisions between these elements as the ocean closed (van Staal, 1994; van Staal et al., 1998; Karabinos et al., 1998; Robinson et al., 1998). Spreading ridge-trench interactions, including ridge subduction, should not be rare events in such systems, but have not been widely recognized in the history of the northern Appalachians. We propose that the subduction of parts of an actively spreading ridge best explains regionally significant mid-Ordovician mafic magmatism of the north-central Maine Appalachians.

This paper describes the geology and geochemistry of the Ordovician Bean Brook gabbro and equivalent Dry Way volcanics in the Chesuncook Dome section of the Weeksboro-Lunksoos anticlinorium, northern Maine (Fig. 1). Their mid-ocean-ridge basalt (MORB) geochemical characteristics and field relationships with mélange, flysch, and continental-margin sedimentary rocks are consistent with emplacement in an accretionary prism during the subduction of an active spreading ridge. A similar case is made for basalts in the nearby Munsungun anticlinorium, the Shin Pond and Stacyville Quadrangles of the Weeksboro-Lunksoos anticlinorium, and possibly for the Lobster Mountain anticlinorium. This interpretation of the Late Cambrian(?) to Middle Ordovician rocks in the three anticlinoria of northern Maine has significant implications for the closure history of the Taconic ocean, and represents one of the few cases of ancient ridge subduction events thus far identified.

REGIONAL CORRELATIONS, PALEOPOSITION, AND PREVIOUS INTERPRETATIONS OF TECTONIC SETTING

Cambrian(?) to Ordovician volcanic rocks occur in several outliers in northern Maine, including the Weeksboro-Lunksoos, Munsungun, and Lobster Mountain anticlinoria (Fig. 1). Stratigraphic sections from the outliers containing Ordovician volcanic rocks and gabbro are described below and summarized in Figure 2. The anticlinoria crop out from beneath a widespread carpet of Seboomook flysch, which was deformed in the Devonian Acadian orogeny. Because they have been lightly studied (with the exception of the Lobster Mountain anticlinorium) and lack direct connection with other pre-Devonian rocks in New England and Canada, our understanding of their relationship to other tectonic terranes in the northern Appalachians is poor, despite the low metamorphic grade of the rocks. They are approximately along-strike with the Bronson Hill anticlinorium of southern New England (Hall, 1970; Robinson et al., 1998), with which they have been tentatively correlated, and, to the northeast, with the Tetagouche and Fournier Groups of New Brunswick (Winchester and van Staal, 1994).

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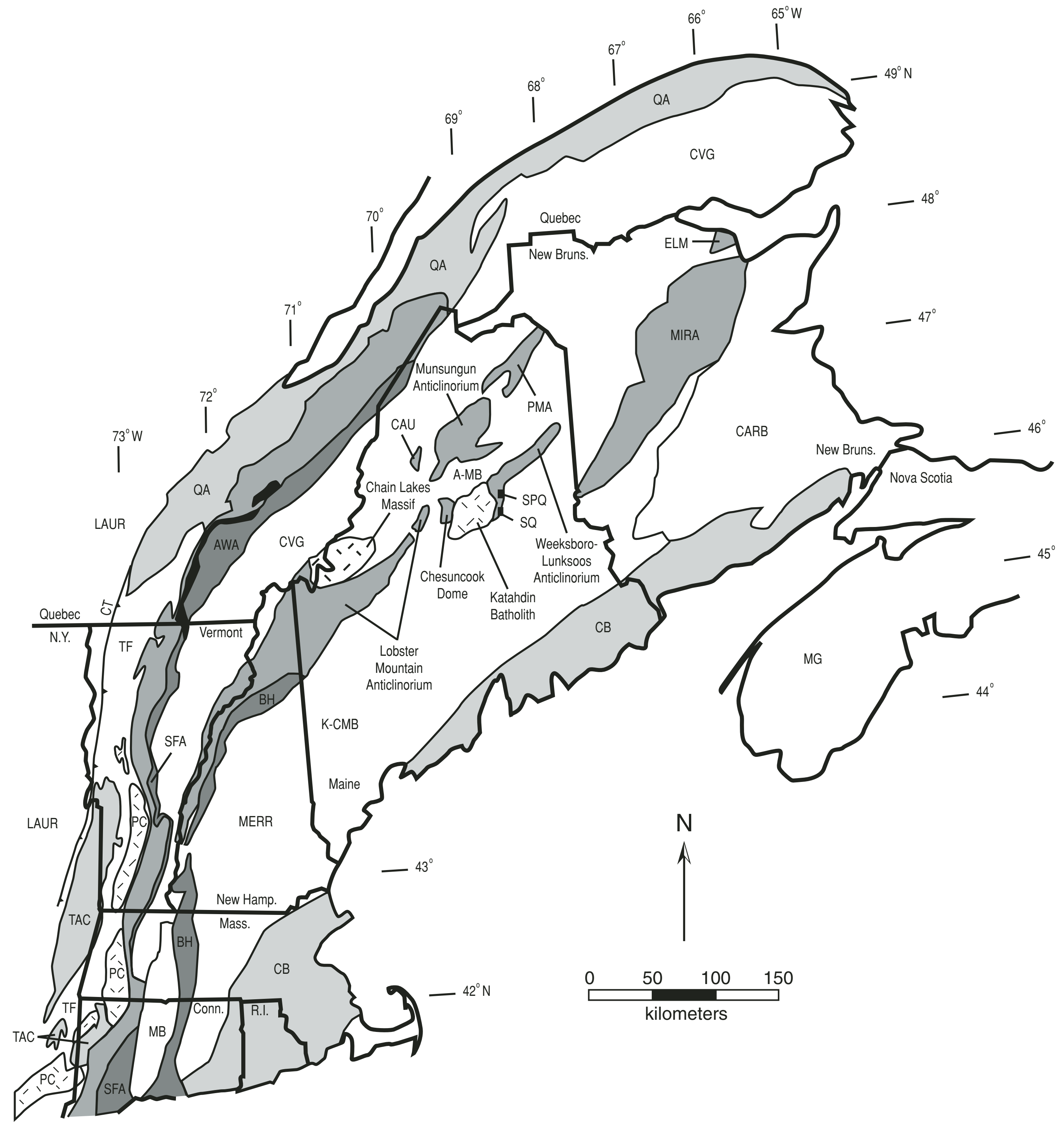


Figure 1. Generalized geology of the northern Appalachians. Pre-Devonian units are shaded. LAUR—autochthonous Laurentian margin, QA—Quebec allochthons, TAC—Taconic allochthons, TF—transported Laurentian margin and basin deposits, PC—Precambrian massifs, SFA-AWA—Shelburne Falls arc, Ascot-Weedon arc, and related oceanic rocks, including ophiolitic fragments, MB—Mesozoic basin, CVG—Connecticut Valley Gaspé synclinorium, BH—Bronson Hill arc, MERR—Merrimack synclinorium, CAU—Caucomgomoc inlier, A-MB—Aroostook-Matapedia belt, SPQ—Shin Pond quadrangle, SQ—Stacyville quadrangle, PMA—Pennington Mtn. anticlinorium, MIRA—Miramichi Highlands, K-CMB—Kearsarge-Central Maine belt, ELM—Elmtree-Belledune inlier, CARB—Carboniferous cover rocks, CB—Coastal belt, MEG—Meguma terrane (adapted from Williams, 1978; Osberg et al., 1985; and Robinson et al., 1998).

Chesuncook Dome of the Weeksboro-Lunksoos Anticlinorium

The Weeksboro-Lunksoos anticlinorium is cut into two discrete sections by the early Devonian Katahdin Granite (Fig. 1). The Chesuncook Dome occurs southwest of the granite, while correlative rocks, including those in the Stacyville and Shin Pond Quadrangles, are found to the northeast. The Chesuncook Dome rocks were first mapped by Griscom (1976), and later by Jarhling (1981; cited in Osberg et al., 1985; Boone and Boudette, 1989; Boone et al., 1989), and are summarized in Figure 2. The oldest unit consists of ~3000–4000 m of highly deformed sedimentary rocks mapped as slate interbedded with varying amounts of graded beds of coarser metasiltstones and quartzite with rare tuffs (Chesuncook Dam Formation; not shown in Fig. 2). These are overlain by the Hurricane Mountain and Dead River Formations; the latter grades laterally into the Sawmill Formation, a unit of quartzites and metasubgraywackes with rare conglomerates. The Sawmill Formation is, in turn, overlain by the Southeast Cove Formation, a succession of siltstone, slate, and quartzite (Jarhling, 1981, referenced in Boone and Boudette, 1989). No fossils have been found in these units, but are all intruded by the Bean Brook gabbro (see below), which Faul et al. (1963) dated at 473 Ma using K/Ar (biotite) (no error quoted; age recalculated here according to Steiger and Jäger, 1977). Samples of the Bean Brook gabbro were processed for zircons for a U/Pb igneous age, but no zircons were found. The sedimentary units have been assigned a Cambrian age (Griscom, 1976; Osberg et al., 1985), although part, or all, may be as old as Precambrian or as young as Early to mid-Ordovician.

The Dry Way volcanics consist of pillowed mafic lava and dolerite with minor chert metamorphosed to greenstones. The contact between the volcanic and deformed Cambrian(?) sedimentary rocks is faulted, but was proposed by Griscom (1976) to have been an unconformity based on: (1) the lack of penetrative deformation in the volcanic rocks, compared with strong

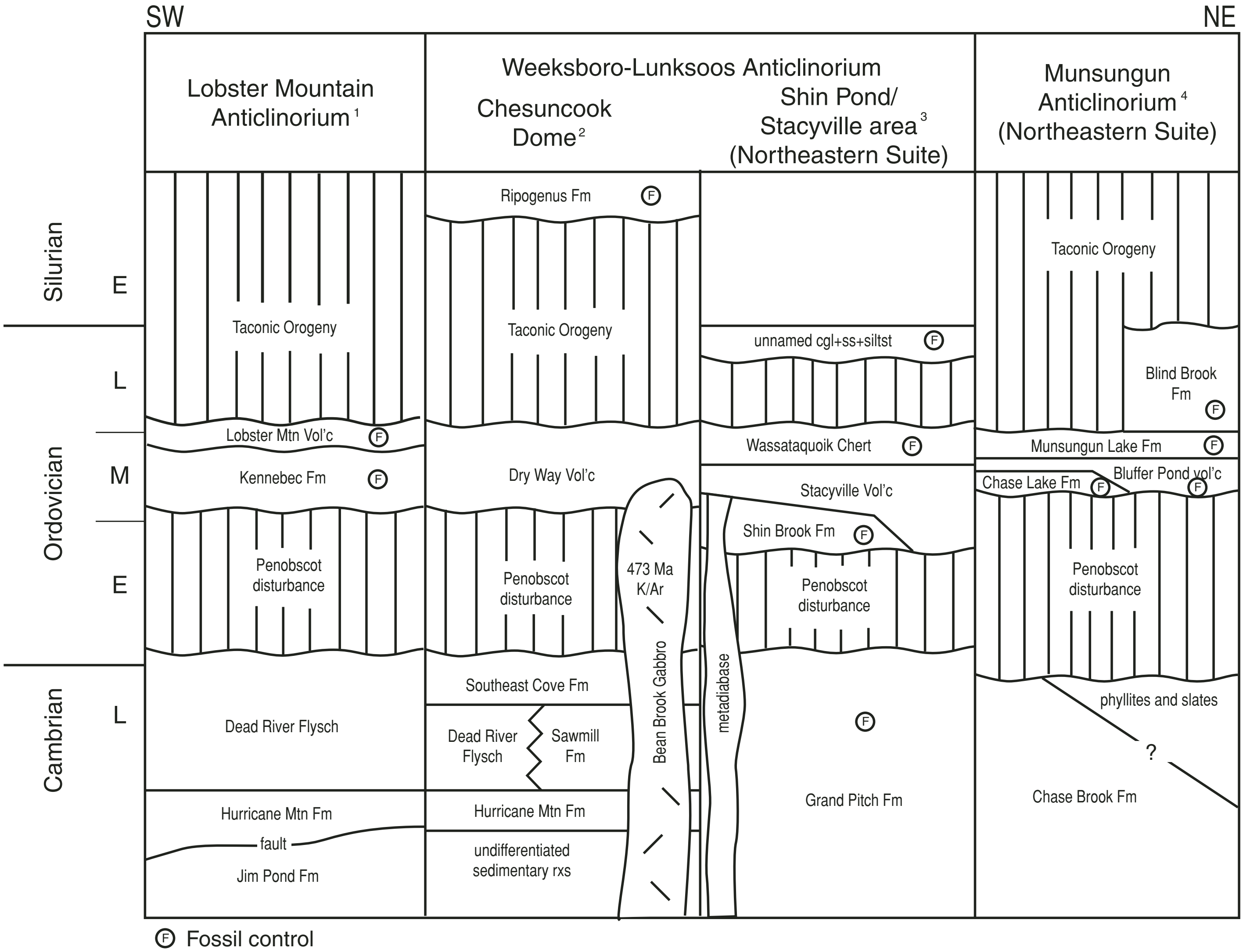


Figure 2. Correlation chart of Silurian and older rocks of north-central Maine. Compiled from: 1—Boone and Boudette (1989), Boone et al. (1989), Boucot (1969), and Simmons Major (1988); 2—this study, Griscom (1976), Jarhling (1981, cited in Boone and Boudette, 1989), and Osberg et al. (1985); 3—Neuman (1967); 4—Hall (1970).

deformation in the Cambrian(?) aged metasedimentary rocks, and (2) the similar structural discontinuities (Penobscot) seen beneath the correlative Stacyville volcanics in the Stacyville and Shin Brook Quadrangles, and the Bluffer Pond Formation in the Munsungun Lake anticlinorium, (Neuman, 1967; Hall, 1970; Fig. 1). Below the Ripogenus dam (Fig. 3), the top of the Dry Way volcanics is marked by an angular unconformity considered to be Taconian in origin (Griscom, 1976; Kusky et al., 1994). It is overlain by the brachiopod-bearing, Llandoverian to Ludlovian (Silurian) Ripogenus Formation, the base of which is conglomeratic and contains abundant clasts of the underlying volcanics.

The age of the Dry Way volcanics is only constrained by the overlying Ripogenus Formation. Possible equivalents elsewhere that have more closely defined ages are Kennebec Formation (Llanvirn to Llandeilo) and Lobster Mountain volcanics (Ashgill) in the Lobster Mountain anticlinorium, the Stacyville volcanics (Middle Ordovician) in the Stacyville and Shin Pond Quadrangles, and the Bluffer Pond Formation (early Caradocian) in the Munsungun anticlinorium. Thus, emplacement of the Dry Way volcanics may have occurred in the range from early Middle to early Late Ordovician. The overlying unconformity, widely considered to be of Taconic origin, is no older than late Middle Ordovician based on similar relationships in the Stacyville and Shin Pond Quadrangles of the Weeksboro-Lunksoos anticlinorium and Munsungun anticlinorium (see Fig. 2).

Griscom (1976) considered the Dry Way volcanics to be the extrusive equivalent to the Bean Brook gabbro, a large intrusive body ~14 km long, based on the presence of dikes similar to the gabbro intruding the volcanics that decrease substantially in abundance away from their contact. This conclusion is supported by the geochemical characteristics presented in later sections of this paper. The main body of gabbro is located south-southeast of Ripogenus Lake, but occurrences of gabbro are also found along the shore of Chesuncook and Ripogenus Lake (CL-02–21 and CL-04–21, Fig. 3) intruding the Sawmill Formation, as well as isolated dikes and plugs in the other sedimentary units (Hurricane Mountain, Dead River, Southeast Cove) to the west. At the macroscopic scale, the contact between gabbro and country rock is gradual. Outcrops consisting entirely of coarse-grained gabbro occupy large areas on the eastern side (near its contact with the Katahdin Granite), but to the west, massive coarse- and fine-grained gabbros are intercalated with increasingly abundant fragments of wall rock; near the mapped contact, these grade into outcrops composed of wall rock with irregular-shaped gabbroic and doleritic dikes and veins in decreasing abundance westward over several hundred meters. At mesoscopic scale, intrusions often display chill margins along contacts with country rock and sometimes grade, within several centimeters of intrusive contacts, from a dark-colored, fine-grained, sometimes doleritic, texture to lighter-colored, medium-grained gabbro. Some outcrops display both fine-grained and medium-grained varieties, in some cases gradational, others in sharp, crosscutting contact. Some gabbro outcrops contain basaltic dikes, which also intrude the host metasedimentary rocks. Deformational features (foliations, folds, and some fractures) present in the sedimentary country rock are not seen in the gabbro or dikes and are truncated along their contacts (Fig. 4). Most outcrops of igneous rock contain fractures and calcite and/or quartz veins, while their contacts with metasedimentary rocks are commonly modified by small faults.

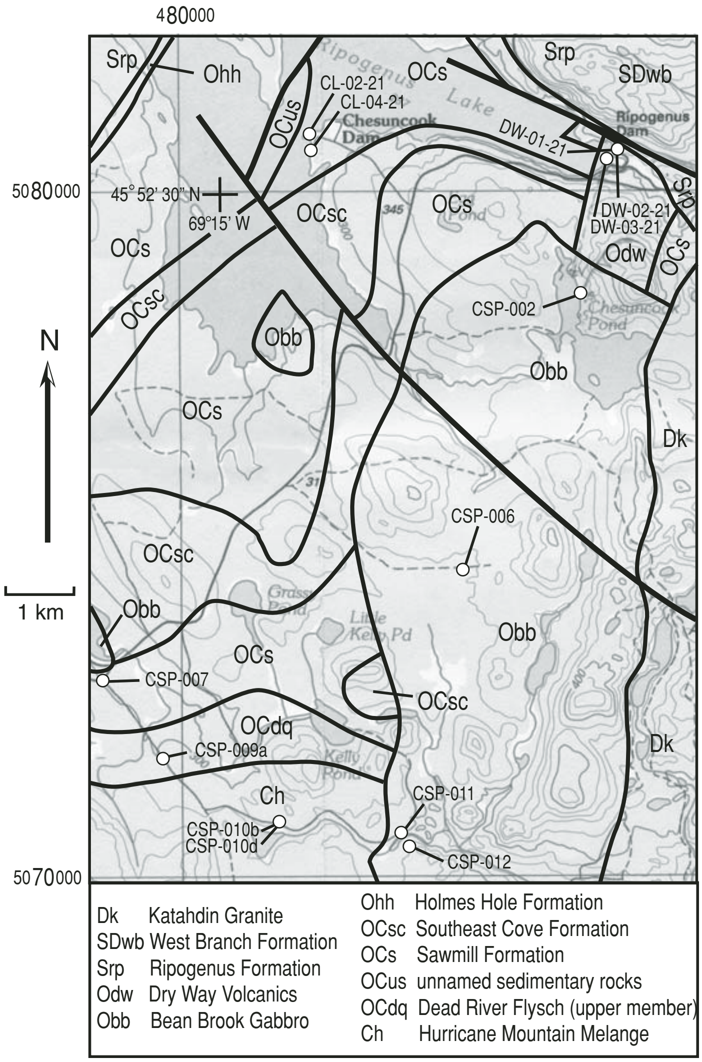


Figure 3. Geologic map of part of the Chesuncook Dome with sample locations (modified from Osberg et al., 1985). Chesuncook Dam Formation, discussed in the text, is not shown.

Correlative Rocks in the Shin Pond and Stacyville Quadrangles of the Weeksboro-Lunksoos Anticlinorium and the Southern Munsungun Anticlinorium

Griscom (1976) correlated the rocks of the Chesuncook Dome with those found in the Stacyville and Shin Pond Quadrangles of the Weeksboro-Lunksoos anticlinorium (described by Neuman, 1967) and in the southern Munsungun anticlinorium (described by Hall, 1970; see Fig. 2). Deformed rocks similar to the sequence beneath the Dry Way volcanics include the Grand Pitch Formation (contains *Oldhamia* *smithi,* Ruedeman) and Chase Brook Formations. The "Penobscot Disturbance," a term introduced by Neuman (1967), was proposed to explain the angular unconformity seen at the top of the Grand Pitch and Chase Brook Formations. Griscom (1976) inferred from this that a similar unconformity once separated the Dry Way volcanics from the deformed, probable Cambrian sedimentary sequence in the Chesuncook Dome. Among the fossil-bearing sedimentary and tuffaceous rocks overlying the Penobscot unconformity are a series of unnamed basaltic and andesitic lava flows (informally termed the "Stacyville Volcanics" by Wellensiek et al., 1990, and its usage is retained in this paper) in the Stacyville Quadrangle (Neuman, 1967) and andesites, dolerites, pillowed basalts, and tuffs of the Bluffer Pond Formation in the Munsungun anticlinorium (Hall, 1970), which Griscom (1976) correlated with the Dry Way volcanics. These volcanic units are overlain by the fossil-bearing Middle Ordovician Wassataquoik Chert in the Shin Pond Quadrangle, and the Caradocian (graptolites of Berry, 1960, cited in Hall, 1970) Munsungun Lake Formation and the Caradocian to Ashgill Blind Brook Formation in the Munsungun anticlinorium, all of which are cut by the Taconic unconformity (Neuman, 1967; Hall, 1970).

Lobster Mountain Anticlinorium

Of the rocks considered in this paper, those in the Lobster Mountain anticlinorium (Boundary Mountain terrane of Boone and Boudette, 1989) have received the most study (Coish and Rogers, 1987; Boone and Boudette, 1989; Boone et al., 1989; Cheatham et al., 1989; Trzcienski et al., 1992; Kusky et al., 1997). The oldest unit in the anticlinorium is the Precambrian Chain Lakes Massif (Fig. 1), a distinctive and variable granofels and gneiss terrane, polymetamorphosed, and long considered allochthonous (e.g., Zen, 1983). Differences in lithology, age, and metamorphic history based on isotopic data suggest it is largely unrelated to Grenvillian or Avalonian basement (see discussion in Cheatham et al., 1989). In addition, Spencer et al. (1989) concluded, based on results of the Quebec-Maine seismic survey, that Grenville crust extends as a wedge beneath the massif separated by a major décollement of Taconian origin. They also suggested that Chain Lakes crust likely underlies a significant part of the Connecticut Valley–Gaspé synclinorium.

The southeast flank of the Chain Lakes Massif is in fault contact with the southeast-younging Boil Mountain ophiolite and volcanic Jim Pond Formation (Boone and Boudette, 1989), which together comprise the "Boil Mountain ophiolitic complex" of Coish and Rogers (1987; Fig. 1). Isotopic ages for ophiolite genesis have been reported and include Cambrian ages of 500 ± 10 Ma (U-Pb zircon; Aleinikoff and Moench, 1985), 520 ± 12 Ma (U-Pb zircon; Eisenberg, 1981), and a minimum Arenigian age 477 ± 1 Ma (U-Pb zircon; Kusky et al., 1997). These ages should also represent a maximum age of emplacement, but this is controversial (Kusky et al., 1997). Boone and Boudette (1989) used the Cambrian ages to distinguish the ophiolite emplacement event as associated with the Penobscot disturbance, distinct from the Taconian orogeny. Although Kusky et al. (1997) reported a minimum age approximately contemporaneous with the Taconic orogeny, they conceded that the ophiolite might have been in place prior to intrusion of the tonalites from which their zircons were derived.

The Hurricane Mountain Formation is located near the southeast flank of the Chain Lakes Massif, outboard of, and in fault contact with, the Boil Mountain ophiolite (Fig. 1). It has been interpreted as a tectonic mélange associated with subduction related to the Penobscot disturbance (Boone and Boudette, 1989; Boone et al., 1989). Boone and Boudette (1989) correlated the mélange with the inferred younger Chase Brook Formation in the Munsungun anticlinorium, and the difference in ages suggested to them a possible diachroneity of mélange formation. Furthermore, in the Weeksboro-Lunksoos anticlinorium, Boone et al. (1989) noted similarities between the Grand Pitch and Hurricane Mountain Formations, which they tentatively correlated.

The Dead River Formation conformably overlies the Hurricane Mountain Formation and is a volcanogenic flysch that Boone and Boudette (1989) interpreted as Penobscot-associated forearc basin deposits. At the northeastern end of the Lobster Mountain anticlinorium, bordering Moosehead Lake, the volcanogenic Kennebec Formation and Lobster Mountain volcanics (Boucot, 1969; Simmons-Major, 1988) unconformably overlie the Dead River Formation and contain fossil assemblages of Llanvirn to Llandeilo, and Ashgill ages, respectively.

Paleoposition and Previous Interpretations of Tectonic Setting

Conflicting interpretations of paleoposition have been proposed for the Cambrian(?) to Ordovician sections in north-central Maine. In

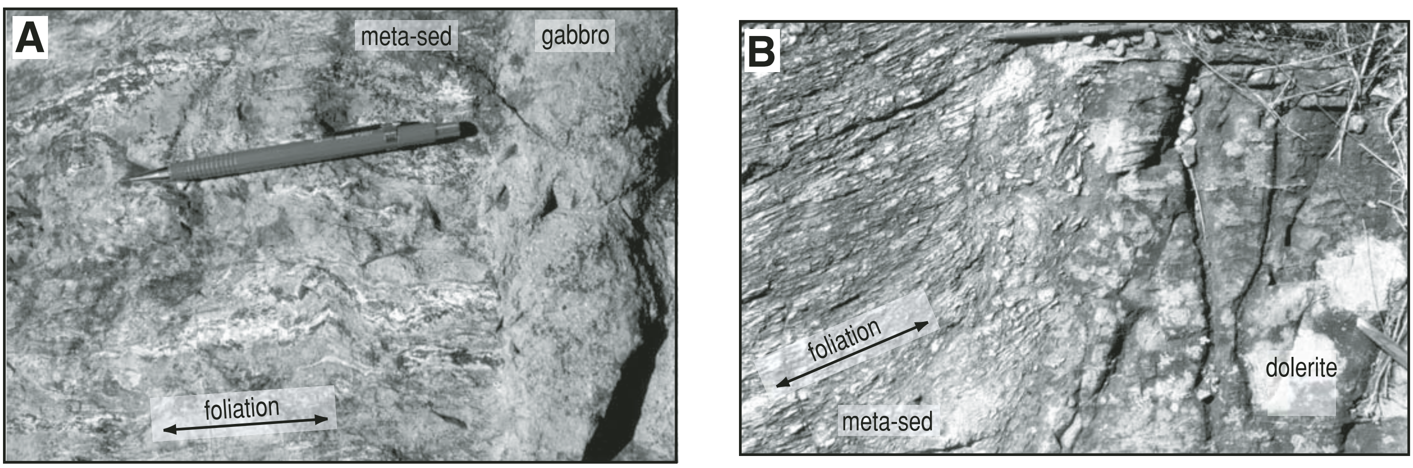


Figure 4. Field relations of Bean Brook gabbro and dolerite and Cambrian(?) sedimentary rocks. (A) Gabbro (CSP-010b) and Hurricane Mountain Formation. (B) Dolerite (CSP-010d) and Hurricane Mountain Formation.

the Weeksboro-Lunksoos anticlinorium, sedimentary rocks of the Early to Middle Ordovician Shin Pond Formation contain a shelly fossil assemblage of Celtic affinity, indicative of high southern latitude depositional environments significantly south of the paleo-Laurentian margin (Neuman, 1984). In contrast, paleomagnetic data from the overlying Stacyville volcanics and the Bluffer Pond Formation in the Munsungun anticlinorium indicate a low-latitude position near the Laurentian margin (Wellensiek et al., 1990; Potts et al., 1993).

Tectonic settings inferred from the geochemistry of the volcanic rocks are likewise difficult to reconcile. Early studies by Hynes (1976, 1981) concluded that the Bluffer Pond Formation likely extruded in an oceanic within-plate setting, while the Stacyville volcanics were associated with an island arc. In contrast, Winchester and van Staal (1994) inferred a rifted, continental within-plate setting for both the Bluffer Pond Formation and Stacyville volcanic rocks as well as for the Dry Way volcanics of the Chesuncook Dome, although van Staal et al. (1998, p. 226) later retracted this conclusion in favor of a possible accreted seamount or ridge subduction origin for the rocks of the Munsungun anticlinorium. Winchester and van Staal (1994) noted strong Th enrichment and a negative Nb anomaly on their MORB-normalized trace-element diagram and suggested the basalts were contaminated by Th-rich continental crust. Additionally, they analyzed volcanic rocks from the Munsungun Lake Formation and concluded that they had formed in a backarc setting based on mixed island-arc and MORB characteristics.

In the Lobster Mountain anticlinorium, Boone and Boudette (1989) and Boone et al. (1989) proposed that a southeast-dipping subduction zone was responsible for emplacement of the Boil Mountain ophiolite and formation of the Hurricane Mountain mélange and Dead River forearc deposits during the Penobscot disturbance. The polarity of the subduction was based on the similarity in spatial relationships of the deposits (Boone and Boudette, 1989; Fig. 1) relative to those of the Taconic orogeny in Quebec (St. Daniel Formation and Magog Group), which is widely considered to have been an easterly dipping subduction system (e.g., Pinet and Tremblay, 1995); direct measurement of structures for analysis in the area is complicated by poor outcrop and younger Acadian folding (Boone et al., 1989).

Winchester and van Staal (1994) correlated the volcanic rocks of the Bluffer Pond Formation–Stacyville volcanics and the Munsungun Lake Formation, respectively, with the Tetagouche and Fournier Groups of New Brunswick, where a rifted continental-arc setting is inferred, although van Staal et al. (1998) later discounted this correlation based on the paleomagnetic data of Potts et al. (1993, 1995).

In the absence of direct evidence to the contrary, we consider the southeast position of the Hurricane Mountain mélange, relative to the Chain Lakes Massif, to indicate that northwest-directed Andean-style subduction (modern coordinates) beneath the massif, and obduction of the Boil Mountain ophiolite onto the southeast flank of the Chain Lakes Massif, occurred in the larger Taconic ocean, outboard from the pre-Taconic Laurentian margin.

PETROGRAPHY

Detailed petrography of the Dry Way volcanics and Bean Brook gabbro is described in Griscom (1976), but a brief description of the samples used for geochemistry is given here.

The Dry Way volcanics are basalts and dolerite, and the Bean Brook gabbro ranges from dark-colored dolerite to medium-dark-colored, fine-to-medium-grained gabbro, to feldspathic, light-colored, medium-grained gabbro. Despite the fact that the rocks have been exposed to lower greenschist–grade metamorphism, some samples display preserved igneous textures. These include holocrystalline (gabbros) to hypocrystalline (dolerite and volcanic rocks) euhedral to subhedral, inequigranular to equigranular, intergranular, and occasionally subophitic textures. Where sufficient igneous minerals are present, the texture is sometimes porphyritic, and plagioclase forms the larger crystal sizes.

Most coarse-grained samples show original albite-twinned plagioclase crystal outlines (although variably saussuritized); the mafic minerals are typically partially to fully recrystallized to chlorite dominantly, but also to other minerals, including epidote, actinolite, calcite, and sphene. Rare igneous brown hornblende is partially replaced by actinolite and chlorite. Original pyroxenes (augite, per Griscom, 1976) are poorly preserved, but are observed in some samples; a few samples preserve some original, partially altered olivine. Other relict igneous minerals include skeletal opaques and trace quartz.

GEOCHEMISTRY

We have made new geochemical analyses (Table 1) using X-ray fluorescence (XRF) and inductively coupled plasma–mass spectrometry (ICP-MS) methods of three Dry Way basalts and ten Bean Brook gabbros and dolerite in the Chesuncook Dome (Fig. 3). We also included in our study two published analyses of the Dry Way volcanics by Fitzgerald (1991), and 14 additional analyses (selected from the complete data set kindly provided by John Winchester), which are condensed in Winchester and van Staal (1994). The latter include samples from the Munsungun (Bluffer Pond and Munsungun Lake Formations) and Lobster Mountain anticlinoria (Lobster Mountain volcanics), Chesuncook Dome (Dry Way volcanics), and Shin Pond and Stacyville Quadrangles (Stacyville volcanics). Due to the similarity of their chemistries, the Dry Way volcanics and Bean Brook gabbros are collectively referred to below as the Chesuncook Dome suite, and the Bluffer Pond basalts and Stacyville volcanics are referred to as the Northeastern suite. The Lobster Mountain volcanics and Munsungun Lake Formation basalts are shown in plots, but due to their small sample number (two samples of each), significant interpretations are not made.

The criteria used to select or exclude analyses from the large data set (105 analyses[1]) summarized in Winchester and van Staal (1994) were: (1) location, because some analyses (e.g., Haymock Lake) strongly resemble those of the nearby Devonian Spider Lake volcanics, and map locations suggest the younger basalts may have been inadvertently sampled; (2) only complete or nearly complete analyses, relative to the elements in our data set were selected; and (3) analyses that we judged showed significant anomalies in several elemental concentrations, likely caused by secondary alteration, were not included. We think that these are independently justifiable selection criteria and that the conclusions based on the select data set are representative of the magmatic conditions and tectonic setting of this area during the Ordovician.

All samples were chosen to minimize alteration: weathered surfaces were discarded, only sample interiors were used, and chilled margins were sampled when possible. Rock chips were handpicked at the University of Albany to avoid secondary veins and inclusions. The powders were ground and ICP-MS and XRF analyses conducted at Washington State University's GeoAnalytical Laboratory (WSU). Our samples were analyzed in two separate batches, five months apart; both batches included samples of Palisades Sill standard PAL-889. The resulting analyses of the standard were compared to a previous XRF analysis from the University of Massachusetts (UMass) with the following

[1]GSA Data Repository item 2006144, complete geochemical data file obtained from John Winchester; the data were originally presented in Winchester and van Staal (1994) and also used here, is available on the Web at http://www.geosociety.org/pubs/ft2006.htm. Requests may also be sent to editing@geosociety.org.

TABLE 1. GEOCHEMICAL DATA OF SAMPLES OBTAINED FOR THIS STUDY.

Sample	DW 01–21	DW 02–21	DW 03–21	CSP 002	CSP 006	CSP 007	CSP 009a	CSP 010b	CSP 010d	CSP 011	CSP 012	CL 02–21	CL 04–21
Lat. (45°N)	52′52″	52′52″	52′47″	51′23″	49′23″	48′39″	48′00″	47′29″	47′29″	47′20″	47′11″	53′0″	52′50″
Long. (69°W)	10′33″	10′31″	10′40″	11′02″	12′26″	16′20″	15′37″	14′15″	14′15″	13′08″	13′01″	14′02″	14′03″
LOI (%)	1.98	1.80	3.47	2.16	5.72	2.11	2.13	1.19	0.53	0.70	1.18	4.05	9.60
Major elements													
XRF (wt%)													
SiO_2	50.11	55.45	49.59	54.47	51.65	50.97	51.36	52.03	51.72	50.32	50.80	52.90	51.10
Al_2O_3	16.36	15.14	15.72	15.82	14.53	14.93	14.21	15.86	13.97	15.81	14.57	15.98	14.96
TiO_2	1.34	1.46	1.67	1.09	1.06	2.15	2.44	1.21	1.97	1.22	2.21	1.42	0.91
FeO†	9.69	9.86	12.87	11.11	10.51	12.96	14.48	10.51	13.65	10.28	14.22	10.30	10.22
MnO	0.16	0.25	0.22	0.20	0.23	0.26‡	0.26‡	0.22	0.24	0.19	0.26‡	0.21	0.21
CaO	12.25	7.95	8.92	7.63	8.22	8.29	7.96	9.22	9.75	12.28	7.76	9.38	8.76
MgO	7.81	5.91	7.07	5.16	11.05	5.97	5.09	6.96	5.63	7.24	5.18	6.26	10.67
K_2O	0.20	0.44	0.44	1.41	0.53	0.66	0.24	0.91	0.35	0.33	0.59	0.19	1.80
Na_2O	1.95	3.36	3.34	2.92	2.01	3.59	3.72	2.95	2.54	2.22	4.19	3.20	1.22
P_2O_5	0.12	0.18	0.15	0.18	0.22	0.23	0.23	0.11	0.17	0.10	0.23	0.15	0.15
Trace elements													
XRF (ppm)													
Ni	83	45	54	17	200	38	13	39	27	53	19	35	146
Cr	282	134	163	36	640	86	27	103	61	198	34	114	529
V	275	244	331	292	215	410	500‡	281	419	291	484	293	245
Ga	17	18	21	19	16	23	20	18	23	18	19	20	15
Cu	82	51	75	43	50	47	42	30	89	73	33	45	61
Zn	64	83	91	86	95	109	111	67	111	74	92	79	66
Zr	90	138	110	117	103	136	124	77	117	70	106	92	87
ICP-MS (ppm)													
La	4.79	10.77	6.25	19.55	20.95	8.21	7.60	6.25	5.82	3.48	6.91	7.43	17.80
Ce	12.16	24.20	15.57	39.02	45.21	20.67	19.13	13.55	15.14	8.78	17.11	16.95	33.85
Pr	1.79	3.28	2.25	4.60	5.66	3.08	2.86	1.85	2.27	1.36	2.53	2.33	3.93
Nd	9.20	15.62	11.58	19.37	24.78	15.97	14.99	9.00	12.29	7.41	13.25	11.33	15.95
Sm	3.26	5.05	4.17	4.80	5.72	5.58	5.35	3.01	4.55	2.87	4.71	3.56	3.84
Eu	1.23	1.59	1.66	1.29	1.47	1.93	1.88	1.04	1.62	1.02	1.68	1.33	1.09
Gd	4.27	6.18	5.45	4.41	4.87	6.98	6.56	3.69	6.01	3.73	5.95	4.53	3.54
Tb	0.82	1.14	1.03	0.73	0.71	1.28	1.21	0.69	1.15	0.74	1.08	0.81	0.55
Dy	5.30	7.40	6.65	4.52	3.85	8.25	7.89	4.50	7.52	4.92	7.05	5.22	3.29
Ho	1.12	1.57	1.42	0.94	0.69	1.77	1.66	0.96	1.65	1.07	1.50	1.10	0.66
Er	3.10	4.45	3.99	2.55	1.79	4.76	4.60	2.59	4.55	2.91	4.13	2.99	1.74
Tm	0.44	0.64	0.59	0.38	0.24	0.71	0.67	0.38	0.66	0.42	0.60	0.43	0.24
Yb	2.76	4.02	3.62	2.36	1.48	4.44	4.13	2.43	4.23	2.70	3.75	2.69	1.55
Lu	0.43	0.61	0.56	0.37	0.23	0.69	0.63	0.37	0.66	0.42	0.58	0.41	0.23
Ba	33.00	73.00	110.00	304.66	99.47	93.35	46.88	115.38	34.20	35.53	98.26	67.00	534.00
Th	0.79	2.37	1.04	4.91	5.19	1.12	1.08	1.17	0.85	0.38	0.99	1.33	4.48
Nb	2.78	5.42	3.60	5.27	7.94	2.23	2.10	3.17	3.31	1.86	2.07	3.81	2.52
Y	29.34	41.50	37.86	24.97	18.66	46.60	43.50	24.88	43.59	27.82	39.00	28.16	16.98
Hf	2.39	3.87	3.09	2.98	2.67	3.66	3.37	2.15	3.26	1.96	2.81	2.45	2.10
Ta	0.20	0.38	0.26	0.36	0.56	0.15	0.14	0.22	0.25	0.13	0.15	0.27	0.15
U	0.20	0.68	0.26	0.96	1.03	0.24	0.23	0.29	0.24	0.12	0.20	0.30	0.76
Pb	1.14	3.61	0.76	4.64	6.09	3.26	4.72	2.38	1.51	1.66	4.76	7.83	4.23
Rb	5.70	12.90	13.30	32.62	25.67	13.76	5.34	24.16	5.34	3.97	11.48	4.30	66.20
Cs	1.05	1.23	0.63	2.42	1.73	1.03	0.28	1.84	0.23	0.33	1.13	0.79	6.09
Sr	164.00	184.00	231.00	321.10	149.77	161.60	180.21	165.10	120.25	113.04	173.95	265.00	114.00
Sc	45.80	39.90	49.60	37.94	35.08	43.87	47.53	46.11	46.55	48.93	46.22	41.00	42.30

Notes: Symbol designations that begin with "DW" are Dry Way volcanics, "CSP" are Bean Brook gabbros, and "CL" are Bean Brook gabbros from the shores of Chesuncook Lake, informally known as "Boom House Gabbro." XRF—X-ray fluorescence; ISP-MS—inductively coupled plasma–mass spectrometry; LOI—loss on ignition.

†FeO is total iron.

‡Value greater than 120% of highest standard.

percent variations (= [WSU – UMass]/UMass × 100; batch 2 in parentheses): TiO_2: 0.5% (0.5%), Cr: 0.6% (0.8%), V: 2.6% (3.0%), and Zr: 6.5% (6.5%). Similarly, two ICP-MS analyses of PAL-889 were compared to an Instrumental Neutron Activation Analysis (INAA) analysis from Cornell University, with the following percent variations: La: 0.5% (5.0%), Ce: 8.3% (9.8%), Nd: 6.8% (7.3%), Sm: 2.5% (1.5%), Eu: 10.5% (5.6%), Tb: 3.5% (0.2%), Yb: 6.3% (5.7%), Lu: 3.2% (1.4%), Ba: 4.8% (5.7%), Th: 0.4% (3.2%), Hf: 0.1% (1.2%), Ta: 3.7% (6.0%), U: 8.9% (10.2%), Cs: 10.4% (11.8%), and Sr: 3.7% (7.9%).

Although deformation is not strong in these rocks, all have been affected by lower greenschist–facies hydrothermal and regional metamorphism. In order to avoid problems of element mobility during metamorphism (e.g., Pearce 1996), our inferences on the tectonic origin of the volcanic rocks are derived only from relatively immobile trace-element and rare earth element data. All of the rocks for which new analyses are presented here are subalkaline to tholeiitic basalts, dolerites, or gabbros. They fall in the subalkaline basalt field of the Zr/Ti versus Nb/Y diagram of Winchester and Floyd (1977), have SiO_2 concentrations that range from 49.59% to 55.45% (one outlying sample from Winchester, WS-550, has 46.74% SiO_2), and have low alkali element concentrations ($Na_2O + K_2O < 5.5\%$).

To prevent the inclusion of samples of gabbros or dolerite with significant cumulate modification, we screened for petrographic cumulate textures, rejected samples that showed positive Eu anomalies on chondrite-normalized diagrams, and also rejected those having anomalously high concentrations of any of the following elements that are compatible in cumulate crystals, according to the criteria of Pearce (1996): $Al_2O_3 > 20\%$ (feldspar cumulates); Sc > 50 ppm (clinopyroxene cumulates); and Ni > 200 ppm (olivine cumulates). From our original data set, which included 14 gabbro and dolerite samples, four were rejected for anomalously high concentrations of at least one of these elements, and each of these rejected samples also displayed a positive Eu anomaly.

In the gabbro, metasedimentary xenoliths are commonly observed at the outcrop scale, and Griscom (1976) also reported pelitic xenoliths. Similarly, the effects of assimilation of preexisting country rock are seen in the tectonic discrimination diagrams used below. In the appropriate diagrams, the average composition of Th-rich upper continental crust is plotted, and the sample distributions roughly define trends toward this composition. Specific compositional data for crustal rocks of pre-Ordovician north-central Maine are lacking, so we used the average upper continental crustal composition of McLennan (2001). For two of the tectonic discrimination diagrams used below (Th-Hf-Nb, Th/Yb-Ta/Yb), these trends are nearly equivalent to the suprasubduction zone vector, due to the use of Th as a discriminator of arc environments. This produces a significant potential for misidentification of tectonic environment, and is discussed below.

Normalized Rare Earth and Trace-Element Diagrams

Rare earth element (REE) concentrations of the Chesuncook Dome suite are shown on the chondrite-normalized diagram (Fig. 5A), and selected trace elements are shown on the MORB-normalized diagram (Fig. 5B). On the chondrite-normalized diagram, the pattern of REEs is nearly flat, but slightly enriched in the incompatible light rare earth elements (LREEs), which is typical of E-MORB. Three of the gabbros (CSP-002, CSP-006, and CL-04-21) are significantly enriched in the LREEs and show a negative slope. In contrast, while most elements on the MORB-normalized diagram show little to no enrichment relative to MORB, Th and Ce are enriched, and a Ta-Nb negative anomaly is present (relative to Th and Ce); these characteristics are commonly associated with basalts from suprasubduction zone settings. The pattern of enrichment of these two elements shows a spectrum of concentrations, which suggests that the enrichment factor is variable in these samples.

REE patterns of the Bluffer Pond Formation and Stacyville volcanics of the Northeastern suite show strong correlation (Fig. 5C). REEs are moderately enriched relative to chondrite and show a slight negative slope, also characteristic of E-MORB, although more enriched than the Chesuncook Dome suite. On the MORB-normalized diagram (Fig. 5D), a similar pattern is evident, except that Th is strongly enriched and Ta shows less enrichment relative to Nb and Ce, resulting in a small Ta negative anomaly. The Zr/Y ratio of the Munsungun and Stacyville basalts (4.2) is greater than that of the Chesuncook Dome suite (3.2), which has a flatter, MORB-like pattern.

REE patterns for the Munsungun Lake Formation and the Lobster Mountain volcanics (Fig. 5E) differ from one another but resemble the suites from the Chesuncook Dome and Northeastern suites, respectively (Figs. 5A and 5C), although the small number of analyses makes any correlation tentative. The Lobster Mountain volcanics show some scatter, but are both enriched in LREEs with a negative slope. On the MORB-normalized diagram for the Lobster Mountain volcanics (Fig. 5F), the patterns are "spiky" in appearance and show moderate Th enrichment and a Ta-Nb negative anomaly, all characteristic of arc environments. The Munsungun Lake Formation basalts are only slightly enriched relative to chondrite with a slight positive slope, typical of normal (N) MORB (Fig. 5F).

Ti-Zr-Y Diagram

The Ti-Zr-Y diagram (Fig. 6A) of Pearce and Cann (1973) is used to discriminate basalts having within-plate characteristics from those of mid-ocean-ridge and volcanic arc settings. We used this to test Winchester and van Staal's (1994) original conclusion that the basalts from the Chesuncook Dome suite formed in a within-plate setting. Samples from the Chesuncook Dome plot almost exclusively in the combined low-K–tholeiite, ocean floor basalt, and calc-alkaline basalt field. The three anomalously enriched gabbros, noted above plot near or over the boundary with fields for within-plate basalts and calc-alkaline basalts, roughly along a vector toward an upper-crustal composition (UC).

Samples from the Northeastern suite also plot in field B, with one exception, which plots in the within-plate field. Overall, these data straddle the boundary with the within-plate field as a result of the higher concentration of Ti and Zr relative to the more compatible Y, and reflect the negative slopes seen in the chondrite-normalized diagram (Fig. 5C).

Th-Hf-Ta Diagram

The Th-Hf-Ta diagram of Wood (1980), based on Wood et al. (1979), is often used to identify volcanic arc environments and is also useful to discriminate between mantle sources. Wood (1980) warned that it cannot discriminate between E-MORB and continental within-plate tholeiites, a consideration of potential importance given the within-plate setting proposed by Winchester and van Staal (1994) and E-MORB character of the rocks thus far described.

The Chesuncook Dome suite plots (Fig. 6B) almost fully within the volcanic arc fields, falling in a trend that originates near the N-MORB field, crosses both island-arc tholeiite and calc-alkaline basalt arc fields, and terminates near the composition of upper continental crust. The two samples from Fitzgerald (1991) show anomalous concentrations of Ta (0.5 ppm and "not detected" for the two samples) with respect to the other Dry Way volcanic samples, and we place no significance on their position in this plot.

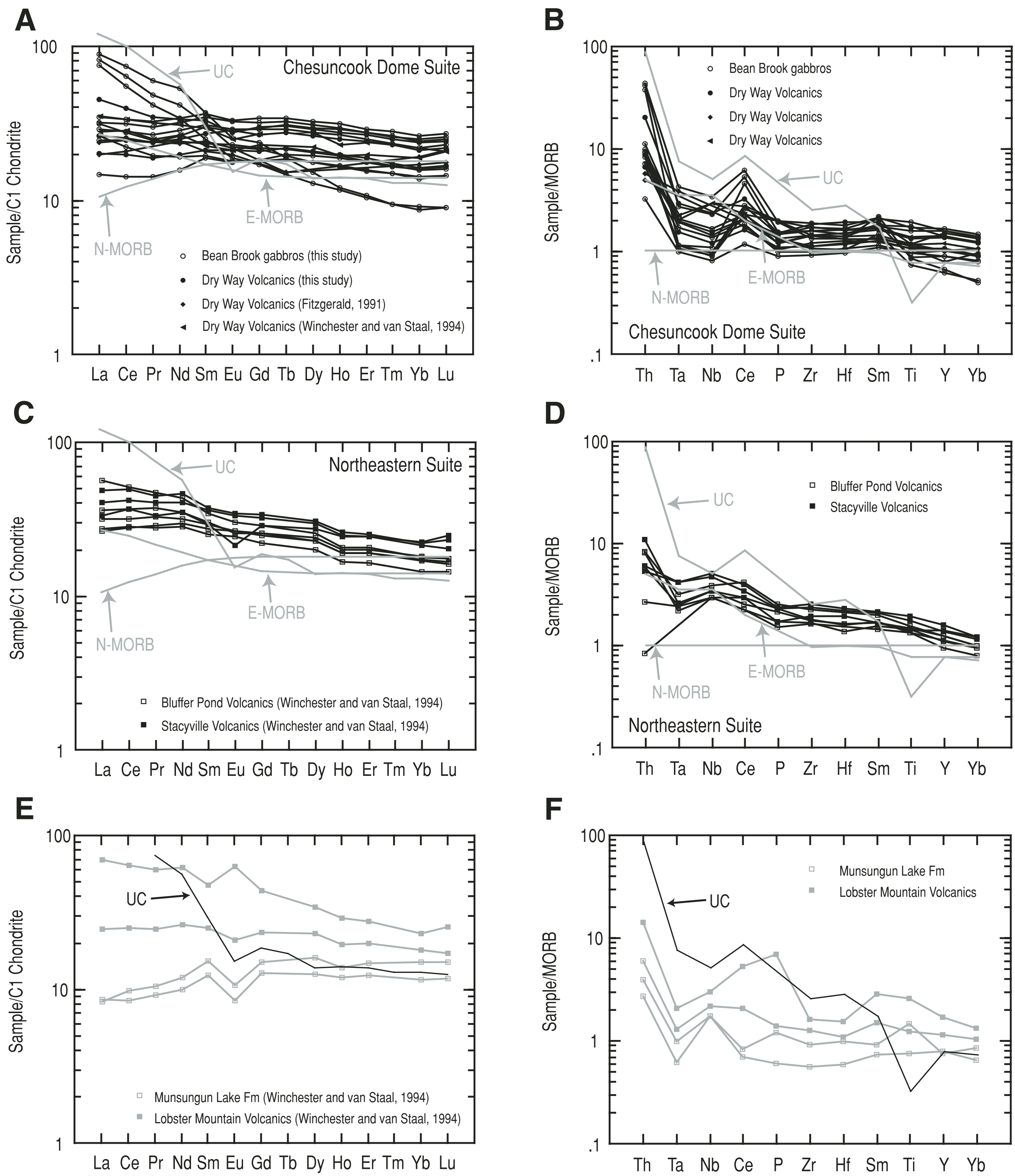
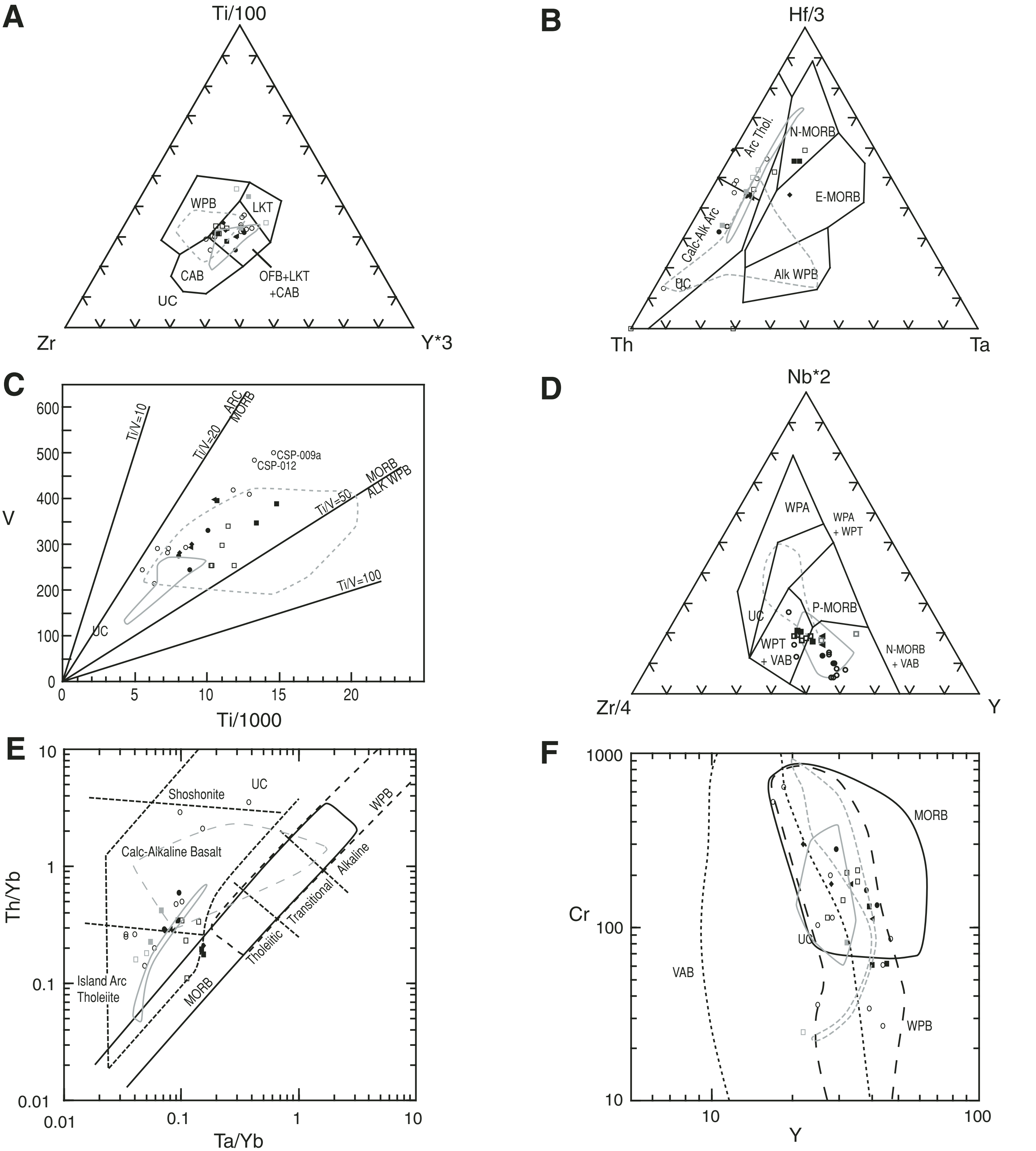


Figure 5. C1-chondrite (rare earth element [REE])–normalized and mid-ocean-ridge basalt (MORB; trace element)–normalized diagrams. UC—upper continental crust composition, from McLennan (2001), N-MORB—normal, depleted mantle–derived mid-ocean-ridge basalt composition from Sun and McDonough (1989), E-MORB—enriched mid-ocean-ridge basalt from Sun and McDonough (1989). Normalization values are from Sun and McDonough (1989).



Chesuncook Dome Suite:

- ○ Bean Brook gabbros (this study)
- • Dry Way Volcanics (this study)
- ◆ Dry Way Volcanics (Fitzgerald, 1991)
- ◂ Dry Way Volcanics (Winchester and van Staal, 1994)

Northeastern Suite:

- □ Bluffer Pond Volcanics (Winchester and van Staal, 1994)
- ■ Stacyville Volcanics (Winchester and van Staal, 1994)
- □ Munsungun Lake Fm (Winchester and van Staal, 1994)
- ■ Lobster Mountain Volcanics (Winchester and van Staal, 1994)

Figure 6. Tectonic discrimination diagrams. UC—upper continental crust composition from McLennan (2001). Gray solid line—field for Chile margin and Chile ridge basalts (see Fig. 7 caption for sample numbers). Gray dashed line—field for within-plate basalts (see Fig. 7 caption for locations and sample numbers). (A) Ti-Zr-Y diagram of Pearce and Cann (1973), WPB—within-plate basalts (oceanic and continental), OFB—ocean floor basalts, LKT—low-K tholeiites, CAB—calc-alkaline basalts. (B) Th-Hf-Ta diagram of Wood (1980), Calc-Alk Arc—calc-alkaline volcanic arc basalt, Arc Thol.— volcanic arc tholeiite, N-MORB—normal, depleted-mantle mid-ocean-ridge basalt, E-MORB—enriched mid-ocean-ridge basalt, Alk WPB—alkaline within-plate basalt. (C) Ti-V diagram of Shervais (1982), ARC—volcanic arc basalt, MORB—mid-ocean-ridge basalt, ALK WPB—alkaline within-plate basalt. (D) Nb-Zr-Y diagram of Meschede (1986), WPA—within-plate alkaline basalts, WPT—within-plate tholeiites, P-MORB—plume-influenced mid-ocean-ridge basalt, N-MORB—normal, mid-ocean-ridge basalt, VAB—volcanic arc basalt. (E) Th/Yb-Ta/Yb diagram of Pearce (1982), MORB—mid-ocean-ridge basalt, WPB—within-plate basalt. (F) Cr-Y diagram of Pearce (1982), VAB—volcanic arc basalt, MORB—mid-ocean-ridge basalt, WPB—within-plate basalt.

The Northeastern suite also defines a trend toward the Th apex but originates from a more Ta-rich point within the N-MORB field, near the N-MORB–E-MORB transition zone, and only extends into the island-arc tholeiite field.

Ti-V Diagram

The Ti-V diagram (Fig. 6C) of Shervais (1982) is used to distinguish volcanic arc basalts from within-plate and MORB and is included here to test the apparent volcanic arc character on the MORB-normalized diagram (Fig. 5B). Due to variations in the partition coefficient of V under varying oxygen fugacities, basalts with Ti/V ratios below 20 are typical of fluid-rich volcanic arc basalts, while samples with Ti/V ratios of 20–50 are characteristic of continental flood basalts and MORB. "Dry" alkaline basalts from within-plate settings have Ti/V ratios greater than 50. Magnetite and/or hornblende fractionation can reduce the V concentration in the remaining melt, rendering the tectonic discrimination of the Ti-V diagram inaccurate for rocks derived from such melts (Shervais, 1982). Titanium was plotted (not shown) against Zr to identify possible fractionation trends in the Chesuncook Dome and Northeastern suites. Zirconium is incompatible in basaltic melts and is progressively enriched in evolved magmas during magnetite and hornblende fractionation. Most of the rocks in both suites plot along a positive slope, indicating that the melts were not subject to V-reducing fractionation. However, the gabbros display a more complex distribution; samples CSP-009a and CSP-012 have high Ti/Zr ratios, suggesting they experienced significant V-reducing fractionation, so these two samples should not be used to draw conclusions of significance from Figure 6C. Anomalous Ti enrichment due to crustal contamination is not considered to be a factor here based on the much lower Ti/Zr ratio of continental crust relative to our samples.

All of the Chesuncook Dome suite samples have Ti/V ratios between 20 and 50, indicative of non-calc-alkaline, subalkaline basalts. They have low overall Ti and V concentrations typical of MORB tholeiites.

The Northeastern suite samples also have Ti/V ratios between 20 and 50 but are more Ti-rich relative to V, which is consistent with their more enriched nature. Of the two groups within the suite, the Stacyville volcanics have higher overall V concentrations, such that the two groups plot separately within the larger Ti/V ratio-defined fields.

Nb-Zr-Y Diagram

The Nb-Zr-Y diagram of Meschede (1986) is used to discriminate within-plate alkaline basalts, within-plate tholeiites, N-MORB, and plume-influenced MORB (P-MORB, also E-MORB). Volcanic arc basalts are not discriminated from non-arc environments on this diagram, plotting in the within-plate tholeiite and N-MORB fields.

The Chesuncook Dome suite plots wholly within the N-MORB field, except for the three anomalous gabbros (CSP-002, CSP-006, CL-04-21), which plot in the within-plate tholeiite field, in the direction of the composition of upper continental crust, which is consistent with trends seen in the other diagrams. The Northeastern suite clusters near the N-MORB and within-plate tholeiite field boundary, and most of the individual values plot in the within-plate basalt field, consistent with the elevated Nb and Zr concentrations relative to Y seen in Figure 5D. Collectively, the two suites plot along a vector toward the concentration of upper continental crust.

Th/Yb-Ta/Yb Diagram

The Th/Yb-Ta/Yb diagram of Pearce (1982) can be used to identify basalts from volcanic arcs and to indicate the magma source. The preferential enrichment of Th relative to Ta in subduction-related fluids results in samples that plot above the "mantle array" along a vector nearly parallel to the Th/Yb axis. Assimilation of country rock by magmas passing through upper continental crust also results in similar Th enrichment, and samples plot along a vector subparallel to the arc vector but show slight concomitant Ta enrichment.

Samples from the Chesuncook Dome suite all plot (Fig. 6E) off the mantle array in the island-arc tholeiite, calc-alkaline, and shoshonite fields (with the exception of one sample from Fitzgerald, which also shows an anomalous Ta concentration in Fig. 6B). The trend of this distribution appears to be toward an upper crustal composition, although it is inconclusive given the subparallel arc and crustal contamination trends. Additionally, the distribution of samples originates from an N-MORB mantle source, consistent with the Th-Ha-Ta diagram (Fig. 6B). The three samples most enriched in Th (CSP-002, CSP-006, CL-04-21), plot in the shoshonitic or Th-rich (upper) part of the calc-alkaline field and correspond to the anomalous samples noted on previous diagrams.

The Northeastern suite samples, for the most part, also plot off of the mantle array. However, the orientation of their trend appears to be closer to the arc vector, although it is poorly defined. The point from which the trend appears to originate falls within the N-MORB field but from a more enriched position than the Chesuncook Dome suite, which is also consistent with previous diagrams.

Cr-Y Diagram

The Cr-Y diagram of Pearce (1982) is used to discriminate between volcanic arc basalts and MORB or within-plate basalts. This diagram is useful since it does not rely on Th as a discrimination variable, whereas in Th-dependent diagrams, volcanic arc and upper continental crustal contamination vectors are nearly parallel. Instead, this diagram relies on Y, which is enriched in MORB and within-plate basalts relative to volcanic arc basalts. The Y concentration in upper continental crust is slightly depleted relative to MORB, but not to the extent found in volcanic arc basalts.

The Chesuncook Dome suite plots (Fig. 6F) mostly in the MORB and within-plate fields, although some of the gabbros plot solely in the within-plate field, and one sample plots in the volcanic arc field. Unlike the Th/Yb-Ta/Yb and Th-Hf-Nb diagrams, this suggests that subduction-zone processes were not present in the formation of these samples, although it does not permit a confident discrimination of the MORB versus within-plate character of this suite.

The Northeastern suite plots in a similar manner to the Chesuncook Dome suite, in the MORB and within-plate fields. This also is consistent with previous diagrams, since the field of basalts derived from normal depleted mantle overlaps with the more enriched basalts from within-plate settings.

DISCUSSION

The geochemical diagrams indicate the following: (1) the Chesuncook Dome suite likely was derived from a mid-ocean-ridge source, possibly plume influenced; (2) the Northeastern suite was derived from a more enriched mid-ocean-ridge source, likely plume influenced; and (3) we agree with Winchester and van Staal (1994) that the apparent suprasubduction zone character of the suites is a result of Th enrichment through the assimilation of country rock composed of upper continental crust.

In the chondrite-normalized diagrams (Figs. 5A and 5C), both the Chesuncook Dome and Northeastern suites exhibit a mixed E-MORB signature, although the Northeastern suite is more enriched, particularly in the LREEs. However, it is not as enriched as would be expected for deeper, mantle-derived within-plate basalts. In each of the tectonic discrimination diagrams, the Chesuncook Dome suite either plots in the N-MORB field, or defines a trend that originates at or near the N-MORB field and extends toward the composition of upper continental crust. This appears to be strong evidence of derivation from a mid-ocean-ridge source where partial melts from depleted mantle may have mixed with plume-related melts, and then further modified by upper continental crust. Similarly, plots of the Northeastern suite define trends toward an upper crustal composition, but originate from near the E-MORB–N-MORB boundary. This suggests a slightly more enriched mantle source, but is still consistent with a MORB source, and supports the correlation by previous workers of Northeastern suite basalts (Bluffer Pond Formation and Stacyville volcanics) and their associated sedimentary rocks with those of the Chesuncook Dome.

The trends in the Th-based discrimination and MORB-normalized diagrams initially suggest that the two suites have a volcanic arc compositional affinity. The Th-Hf-Nb and Th/Yb-Ta/Yb diagrams (Figs. 6B and 6E) are both used to identify volcanic arc environments based on the preferential enrichment of Th in arc volcanics. However, upper continental crust is highly enriched in Th, and magmas that have assimilated variable amounts of crustal material can be expected to plot along a mixing line between the fields defined by their mantle source composition and the composition of the incorporated material, and to mimic arc-derived igneous rocks. Thorium concentrations in upper continental crust (10.70 ppm; McLennan, 2001) are ~90 times that of depleted N-MORB (0.12 ppm; Sun and McDonough, 1989) and 18 times that of E-MORB (0.60 ppm; Sun and McDonough, 1989; Figs. 5A–D). With the exception of three anomalous samples (CSP-002, CSP-006, CL-04-21), Th concentrations in the Chesuncook Dome and Northeastern suites are ~10 times MORB or less, requiring mixing of up to 10.2% of a bulk melt of continental crust with 89.8% N-MORB magma, or up to 5.9% bulk melt of continental crust with 94.1% E-MORB magma (after Best and Christiansen, 2000, p. 327–328). Three of the samples (CSP-002, CSP-006, CL-04-21) plot in anomalous positions on most of the discrimination diagrams, and in some cases cluster around the composition of upper continental crust, and we infer that these samples have likely undergone greater assimilation and contamination than the other samples analyzed. The greater behavioral complexity of partitioning of Th during the partial melting of continental crust is beyond the scope of this article and is not addressed.

The Ti-V and Cr-Y diagrams do not rely on Th as a discriminator of arc environments and are useful to discriminate between arc environments, and mid-ocean-ridge or within-plate environments that include basalts contaminated by crustal material. Upper continental crust has low overall Ti and V concentrations, with a Ti/V ratio slightly above 20, and plots in the ocean floor basalt field. Basalts of non-arc origin contaminated by such crust would not be expected to define a mixing line that crosses into the arc field. The Cr-Y diagram is less discriminatory since average upper continental crust plots in the overlap region between within-plate, mid-ocean-ridge, and volcanic arc fields. However, many of the samples plot fully within the mid-ocean-ridge field, and in the mid-ocean-ridge and within-plate field overlap, indicating that those in the overlap region also did not originate in an arc environment.

Winchester and van Staal's (1994) interpretation of a continental within-plate environment is partly supported by the data from the Northeastern suite, but the basalts from the Chesuncook Dome clearly appear to be derived from a mantle source that is typical of mid-ocean ridges (Figs. 5 and 6A). Published geochemical analyses from well-established continental within-plate environments (Columbia River, Paraná, Tibbit Hill) were chosen for comparison with the Northeastern suite and are shown in chondrite-normalized diagrams (Fig. 7A). The Columbia River and Paraná basalts are plume-related, while the Tibbit Hill volcanics of southern Quebec are rift volcanics associated with breakup of the Grenville Supercontinent during the late Precambrian. Each of the three, well-established, within-plate environments shows stronger enrichment of REEs, especially LREEs, than the Northeastern suite, which indicates that a continental within-plate environment for the Northeastern suite is unlikely.

The geochemical character and rock associations presented here are similar to those reported from the Taitao Peninsula, where the Chile Ridge is currently subducting beneath the South American continent (Forsythe et al., 1986; La Gabrielle et al., 1994; Klein and Karsten, 1995; Le Moigne et al., 1996), the intrusive Maryuma and extrusive Shiina suites of the Muroto Peninsula of southwest Japan (Hibbard and Karig, 1990), and the more felsic rocks of the Sanak-Baranof belt of southern Alaska (Bradley et al., 2003). Basalts with similar chondrite- and MORB-normalized patterns have also been reported from the southern San Joaquin Basin and Santa Maria Province, southern California, and are interpreted to have formed from magmas derived from depleted upper mantle associated with the Eastern Pacific Rise interacting with continental crust of North America (Sharma et al., 1991; Cole and Basu, 1992, respectively). Geochemical data from basalts from the Taitao Peninsula and segments 1 and 3 of the Chile Ridge show a strong similarity to selected analyses from the Chesuncook Dome and Northeastern suites, respectively (Fig. 7B).

PROPOSED TECTONIC ENVIRONMENT

The geochemistry indicates that the Chesuncook Dome suite was derived from depleted and/or enriched upper mantle typical of mid-ocean-ridge systems, but the field relations are inconsistent with typical mid-ocean-ridge settings, or even backarc basins, where continental contamination might occur during the early stages of opening. Sheeted dikes, layered cumulates, or ultramafic rocks are not observed or reported in the Chesuncook Dome or from the correlative rock units in the other anticlinoria.

The geochemistry of the suite suggests contamination by upper continental crustal material, and the gabbros can be seen locally to contain silicic metasedimentary xenoliths. The Bean Brook gabbro intrudes deformed sedimentary rocks derived from a continental margin (Chesuncook Dam, Sawmill, and Southeast Cove Formations), mélange (Hurricane Mountain Formation), and flysch (Dead River Formation). Broadly similar sedimentary packages (sandstones, turbitic sandstones and shales, limestones, conglomerate, tuffs) have been reported from the Kodiak Formation in the Alaskan accretionary prism (Sample and Reid, 2003) and Chugach terrane, Alaska (Trop et al., 2003). Although direct geologic relationships are lacking, the country rocks are spatially associated with the Chain Lakes Massif, which is interpreted to be a continental crustal fragment (Boone and Boudette, 1989).

We propose that the combination of mid-ocean-ridge compositions of the Dry Way volcanics and Bean Brook gabbro, and their association with continentally derived sedimentary rocks deposited along an active margin, indicate that the Chesuncook Dome and Northeastern suite formed during a ridge subduction event. Although large, unidentified faults may exist, the areal position of the Chain Lakes Massif, Boil Mountain ophiolite, Hurricane Mountain Formation, and mafic igneous suites suggests northwestward-directed (modern coordinates) subduction of an active ridge beneath an accretionary prism located on the southeast margin of the Chain Lakes Massif during the Early to mid-Ordovician (Fig. 8). Magmas from the subducted ridge intruded the accretionary prism, flysch, and continental margin sediments, emplacing the Bean Brook gabbro, Dry Way, Bluffer Pond, and Stacyville volcanics. The upper volcanic unit of the Boil Mountain ophiolite has a MORB geochemical character (Coish and Rogers, 1987) and may also be related to this event.

The ridge subduction hypothesis has significant implications for evolving plate tectonic models of the pre-Acadian oceanic basin east of Laurentia. The idea requires a northwest-dipping subduction zone beneath the Chain Lakes Massif, which may have been partly intra-oceanic depending on the paleo-areal extent of the massif. Integrating this model with existing published models of pre-Acadian oceanic closure is in part dependent on the confidence placed in the 473 Ma K/Ar date for the Bean Brook gabbro. Correlation with the fossil-bearing units of the region indicates a Middle Ordovician, possibly early Upper Ordovician age for the Dry Way volcanics and an age no older than late Middle Ordovician for the overlying unconformity. That the unconformity at the top of the Dry Way volcanics is considered to be Taconian in origin suggests relative proximity with the Laurentian margin at the time of ridge subduction, although the Lower Ordovician Shin Brook Formation contains a Celtic shelly fauna assemblage (Neuman, 1984). The Taconic unconformity, combined with a lack of penetrative deformation in the Dry Way volcanics and Bean Brook gabbro, suggests that the region was part of the Taconian upper plate. This is consistent with evidence from the Quebec-Maine seismic-reflection survey, which showed that the Chain Lakes Massif was thrust over the Laurentian margin along a major décollement (Spencer, et al., 1989). According to this model, the emplacement of the

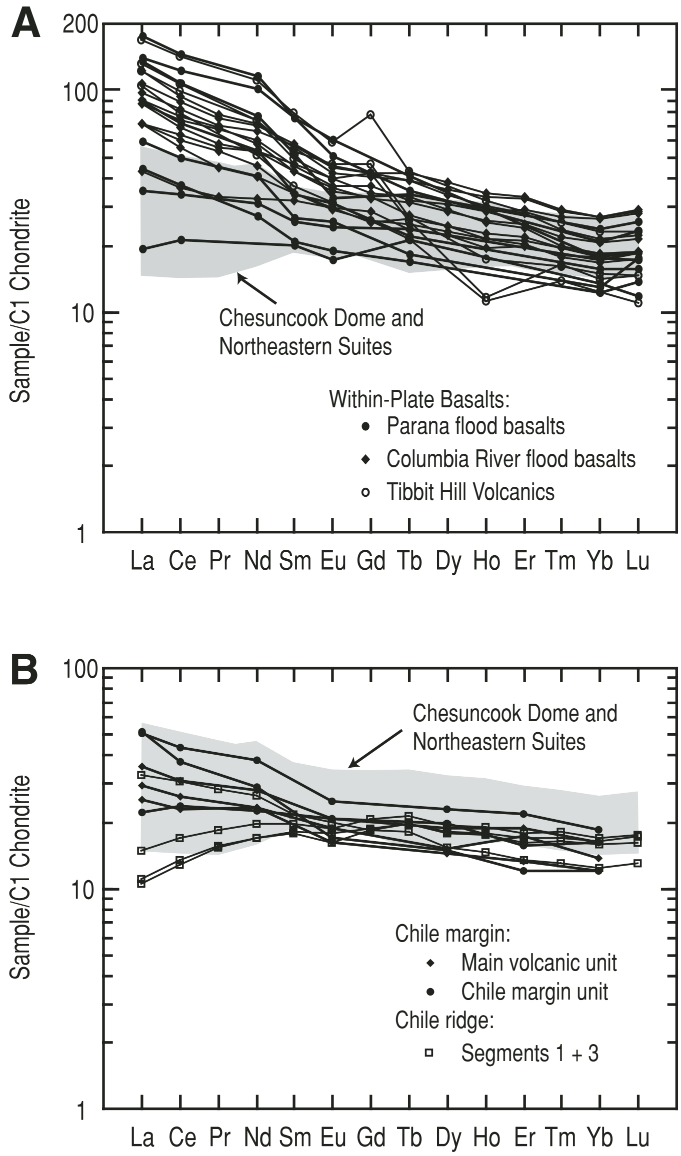


Figure 7. C1-chondite-normalized rare earth element (REE) diagrams. Normalization values are from Sun and McDonough (1989). (A) Within-plate basalts: Paraná flood basalts from Peate (1997): B448, DSM-06, DUP-30, DUP-38, B980, PAR-06, CB-1110, DUP-35. Columbia River flood basalts from Hooper and Hawkesworth (1993): DB-2, I-33, DB-10, MLC-10, PHGR-02, PHGR-03, PHGR-09, PHGR-48, PHGR-51, PHGR-56, PHGR-59. Tibbit Hill Volcanics from Colpron (1990): 60-A-86, 1551-A-87, 1652-B-87, 1603-B-87. (B) Basalts from the Chile ridge–trench interaction: Chile margin basalts from Le Moigne et al. (1996): T8 g2, T15b, T16b, T26e, T20e, T28b. Chile ridge segments from Klein and Karsten (1995): D14-9, D20-1, D42-4, D53-2. The gray field encompasses the REE composition of the Chesuncook Dome and Northeastern suites. The three anomalous gabbros (CL-04-21, CSP-002, CSP-006) are excluded.

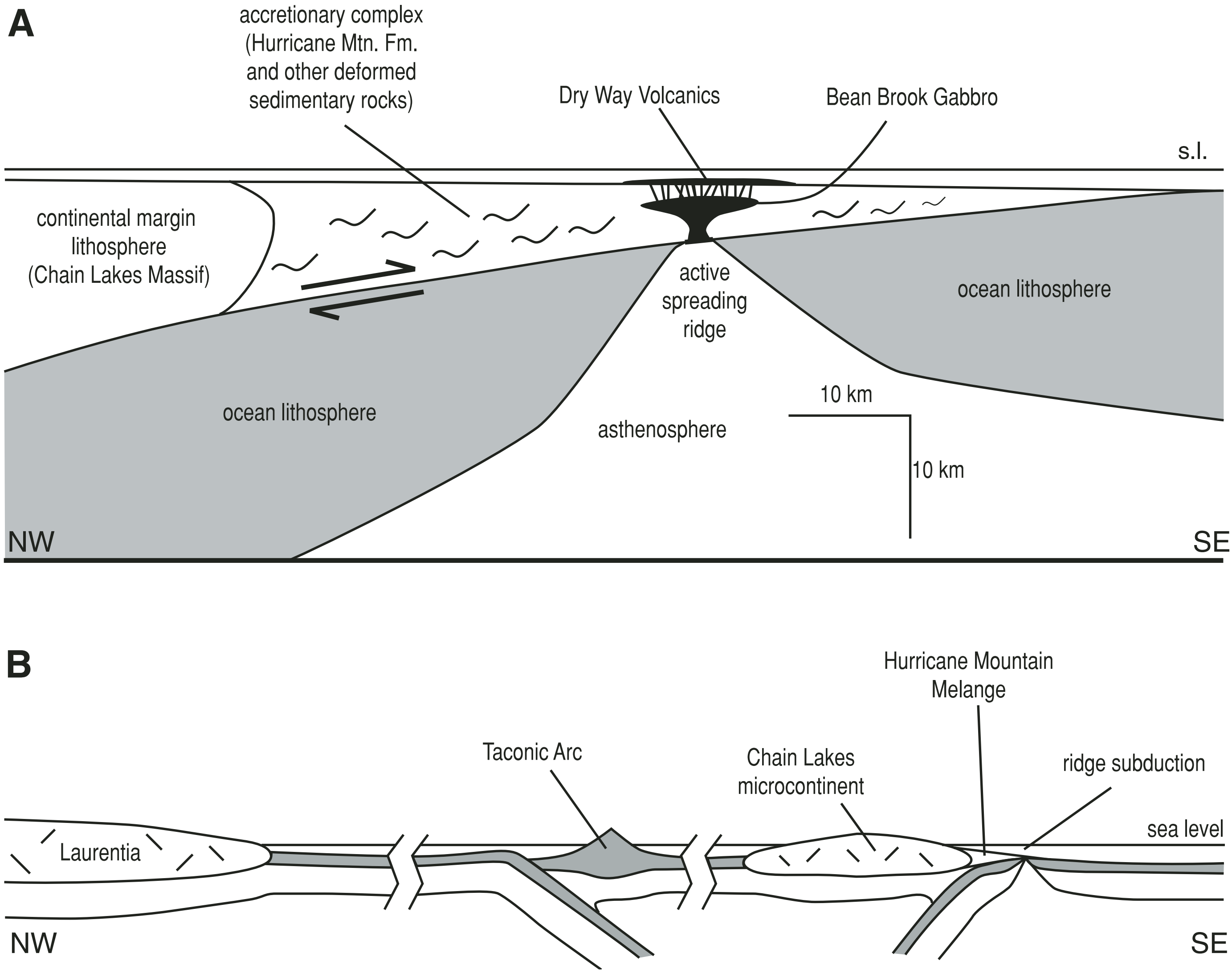


Figure 8. Schematic cartoons of the Early to Middle Ordovician Taconic ocean illustrating: (A) Ridge subduction beneath Chain Lakes Massif (s.l.—sea level), and (B) relationship of Chain Lakes microcontinent to pre-Taconic Laurentian margin and Taconic arc.

Dry Way volcanics and Bean Brook gabbro over a west-dipping subduction zone occurred along the margin of the "Chain Lakes microcontinent" within the Taconic ocean and terminated prior to the Taconic collision on the Laurentian margin, during Middle Ordovician time (Fig. 8).

We think this model also applies to the Exploits zone in the Notre Dame Bay region of Newfoundland, where the Lawrence Head volcanics are associated with rocks likely deposited in a forearc basin related to the accretionary complex of the Dunnage mélange (Kidd et al., 1977), and perhaps to the Elmtree-Belledune inlier of New Brunswick. Preliminary geochemical analyses of volcanic rocks from Newfoundland show that they plot across E-MORB and within-plate fields of petrogenetic diagrams and display similar patterns to the Northeast suite on chondrite- and MORB-normalized diagrams. In the Elmtree-Belledune inlier, basalts with MORB characteristics are associated with only slightly younger mélange (Winchester et al., 1992).

The relative timing of events in the Chesuncook Dome requires a cessation of west-directed subduction prior to the Taconic orogeny. The west coast of North America contains modern examples of oblique ridge subduction (Gorda Ridge and East Pacific Rise) where the leading oceanic plates (Juan de Fuca and Cocos) are subducting beneath continental crust. Following ridge subduction, the relative plate velocities between the upper plate (North America) and trailing oceanic plate (Pacific) convert the plate boundary to transform motion (San Andreas and Queen Charlotte Islands faults), resulting in a cessation of subduction. The lack of strong deformation in the Chesuncook Dome suite and the absence of an associated volcanic arc (unless the Bronson Hill arc is considered a candidate, although its age makes it a poor one) suggest that the ridge was near parallel to the trench and that there was no significant convergent plate motion between the Chain Lakes Massif and the trailing oceanic plate immediately following ridge subduction.

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