MESOZOIC GEOLOGY OF GRAND MANAN

by
J. Gregory McHone, Graduate Liberal Studies Program,
Wesleyan University, Middletown, CT 06459-0519 (jmchone@wesleyan.edu)

INTRODUCTION

Since 1988, Nancy McHone and I have made five brief visits to Grand Manan Island. From the first, it has been apparent to us that the spectacular exposures of basalts on Grand Manan deserve much more attention. Our examinations of the Mesozoic rocks and structures as described in this paper are essentially reconnaissance, but we intend to conduct more serious mapping sessions during the next several years.

The stratigraphic relationships of tholeiite layers that comprise the North Mountain Basalt of the Fundy Basin are well shown on Grand Manan, and they can be compared with the basaltic stratigraphy across the bay near Digby (Papezik and others, 1988) and in the deep Chinampas well log to the north (Papezik and Greenough, 1987). The interesting structures running through and between basalt units can tell us much about the tectonic events near the Tr-J boundary in this region, during which the modern geometry of the basin was established (Wade and others, 1996; Olsen, 1997). It might also be possible to demonstrate some genetic connections between likely source dikes in the region relative to various surface flows, including their eruption sequence within the North Mountain Basalts.

Setting

Grand Manan Island is in the southwestern corner of the Bay of Fundy (Fig. 1). The island is about 25 km long by 12 km wide, not including smaller islands of the "Grand Manan Archipelago" along its eastern side. The Mesozoic basin that also defines the Bay of Fundy is actually composed of several sub-basins, which are divided by necks and high sections of the metamorphic basement rocks (Wade and others, 1996). One of these highs is a horst-like north-south fault block that includes the eastern third of Grand Manan Island, leaving the basalts of the western two-thirds of the island "perched" above water along the edge of the Grand Manan sub-basin to the west (Fig. 1). This sub-basin extends under the channel for about 30 km westward to the main Fundy Basin border fault, and it continues to the southwest for 60 km or more along the Maine coastline. Structures and strata of the Grand Manan sub-basin are not well recorded to the north (Wade and others, 1996).

The horst along eastern Grand Manan is mostly under water and narrows to about 5 km wide near the northeast end of the island, with the western fault of the horst exposed on Grand Manan as the Red Point Fault. The Grand Manan Fault along the eastern side of the horst block has truncated the deepest portion of the Mesozoic Fundy Basin strata, which total about 9 km in thickness (Fig. 1; Wade and others, 1996). The border faults of the Grand Manan horst extend to the north to intersect the main western border fault of the Fundy Basin, and they clearly offset the Early Jurassic basalt and probably all of the Mesozoic pre- and post-basalt sediments of the basin (Wade and others, 1996). Therefore, the Mesozoic basalts and sediments of Grand Manan and its sub-basin were originally continuous with the main basin to the east. The exposures of basalts, sediments, and faults on the island reveal the Mesozoic history of this part of the Fundy Basin, and also of the nearby regions of Maine and New Brunswick.

Previous Work

According to Gunter (1967), the earliest geological description of Grand Manan was made by Dr. Abraham Gesner, Provincial Geologist, who visited in 1839. Gesner recognized that the eastern side of the island is of older meta-sedimentary rock, while the western half displays younger post-metamorphic volcanic rock, with a separation along the Red Point Fault. Allaby (1984) states that copper was mined in the 1870s in basalt near Sloop Cove on the western shore (copper mineral stains are common throughout the basalts). Powers (1916) included Grand Manan among his observations of the Mesozoic geology of the Fundy Basin. Alcock's (1948) map of the island has been the main basis for later maps, until a recent compilation and some new dates for the Paleozoic metamorphic section were provided by McLeod and others (1998). The Mesozoic section was also mapped and drilled in the early 1960s by geologists of the Keevil Mining Group, Ltd., who were prospecting for copper. Students and faculty of the University of New Brunswick conducted geology field camps and research projects on the island in the mid-1960s

(Helmstaedt and others, 1966; Gunter, 1967; Pringle and others, 1973), producing materials and a map presently on exhibit at the Grand Manan Museum. Their work forms the basis for geologic descriptions by Allaby (1984).

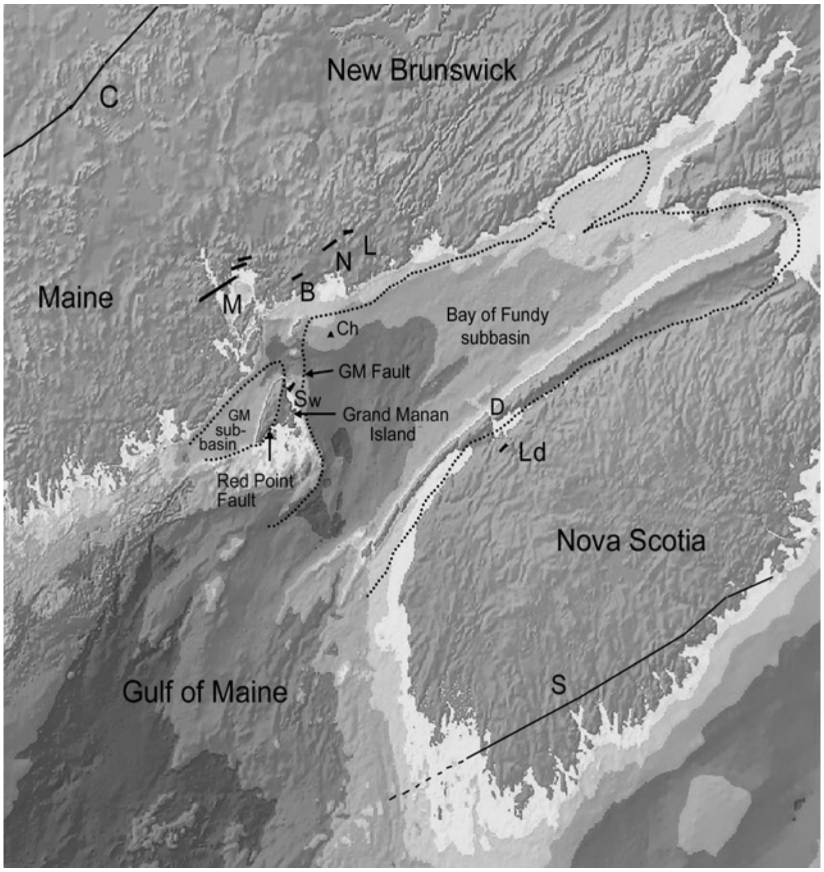

Figure 1. Relief map of the Bay of Fundy region, showing Early Jurassic dikes (solid lines) and the Fundy sub-basins (dotted lines). Letter codes: C=Caraquet dike; M=Ministers Island dike; B=Buckman's Creek dike; N=New River dike; L=Lepreau River dike; Sw=Swallowtail Head dike; Ch=Chinampas well site; D=Digby, NS; Ld= Lansdowne dike; S=Shelburne dike. The digital bathymetric base map is by Ed Roworth and Rich Signell, of the Gulf of Maine Information System Project.

Studies of the Mesozoic rocks and structures of Atlantic Canada accelerated in the 1980s, including much new work on the North Mountain Basalt that covers most of the Fundy Basin, and also studies of associated large tholeiite dikes outside of the basin (see references at the end of this paper). However, few geologists have included the Mesozoic features of Grand Manan in their studies, except for some geochemical data recently listed by Pe-Piper and Piper (1999). In the fall of 2000, Jelle de Boer and his students drilled oriented plugs at several locations in the basalts and dikes on the island, as part of a project to describe the paleomagnetic fabric (AMS, or anisotropy of magnetic susceptibility) of the Mesozoic magmas. They have determined an AMS fabric consistent with NE-SW flow directions for at least the lower part of the basalt, and with vertical flow in the Swallowtail Head dike (J. de Boer, pers. comm.).

Malcolm McLeod, Leslie Fyffe, Richard Grant, and Sandra Barr are conducting new studies of the metamorphic rocks of the island and adjacent New Brunswick (see preceding field guides). They have also encouraged and assisted my interest in describing the Mesozoic rocks of the island and mainland, a project that will be pursued during the next several years.

Research Goals

The Grand Manan basalts should be mapped and re-interpreted to conform with the stratigraphy and tectonic history of the North Mountain Basalt group as determined elsewhere in the Fundy Basin. This will require solving some puzzles of cross-cutting relationships due possibly to erosional surfaces and faults, but it will provide a more realistic sequence of geological events for the basin during its Triassic-Jurassic time interval. There might also be dikes and sills within the basalt pile, although most or all of the massive units are probably surface flows, not intrusions as was formerly interpreted.

The large dike at Swallowtail Head is not likely to be a source for the massive North Mountain Basalt units, but it might correlate with some of the thinner amygdaloidal flows in the middle basalt sequence. This can be determined from new chemical analyses and thin-section examinations. At this time, it appears reasonable to believe that the Christmas Cove-Ministers Island-Buckman's Creek-Lepreau River dike system in Maine and New Brunswick was the main source of the North Mountain Basalts, both at Grand Manan and throughout the Fundy Basin. This can be demonstrated by closely comparing the Grand Manan basalts with these dikes and other dike systems in the region, much like what Philpotts and Martello (1986) did for very similar magmas in and around the Hartford Basin to the south. Sandra Barr and I are organizing a project in which we will gather evidence related to this model.

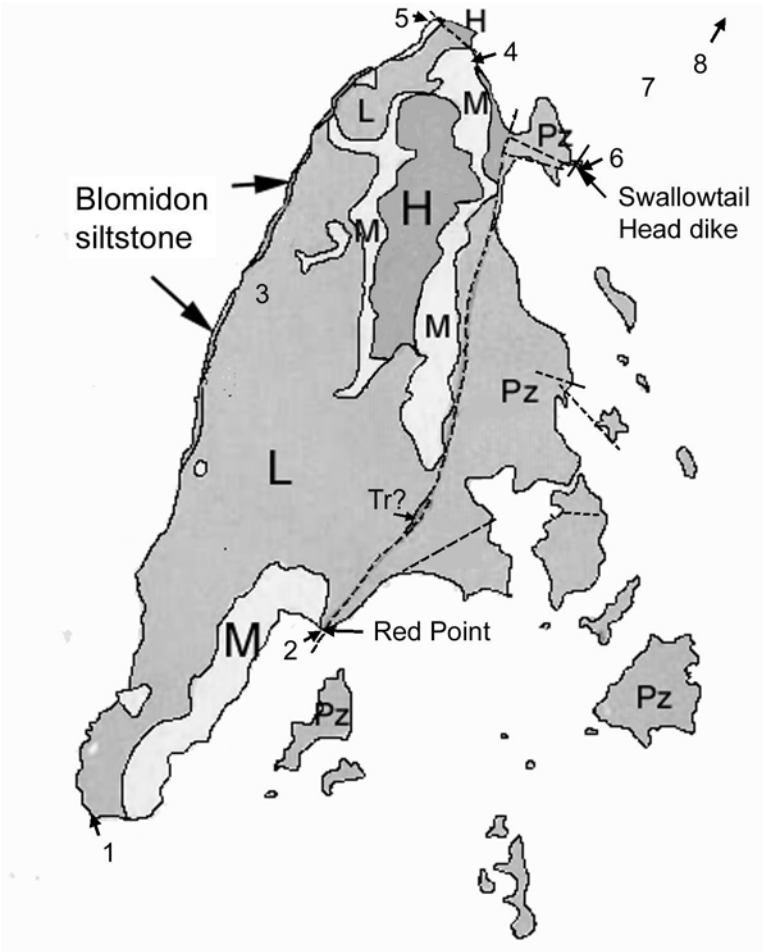

Figure 2. Preliminary sketch map of Mesozoic geological features of Grand Manan Island, based on the map depicted by Allaby (1984), McLeod and others (1998), and reconnaissance work by the author. L=lower massive basalt unit; M=middle thin-flow basalt unit; H=higher massive basalt unit; Pz=metamorphic units of the eastern island. Dashed lines are faults. Field stops are located by number.

MESOZOIC FEATURES

Basalt Age

Until the 1970s, the basalts of the Fundy Basin and other Mesozoic basins of eastern North America were believed to be Late Triassic in age, based on correlations with lower basin strata. A K-Ar isochron date of 190.9 ± 2.4 Ma by Hayatsu (1979) was widely accepted as Early Jurassic and a likely cooling age for the North Mountain Basalt, until a date of 202 ± 1 Ma was reported by Hodych and Dunning (1992), who used the superior zircon U/Pb method. Most older whole-rock K-Ar dates, such as the 189 ± 8 Ma date reported by Stringer and Burke (1985) for the Ministers Island dike, are probably too young because of argon loss. Recent $^{40}Ar/^{39}Ar$ dates between 199 and 202 Ma have been widely cited for tholeiites of the Central Atlantic Magmatic Province (West and McHone, 1997; Marzoli, 1999; Olsen, 1999; McHone, 2000), of which the North Mountain Basalt is a prime example.

Olsen (1997) described evidence that the earliest basin basalts flowed a few tens of thousand years (or less) after the Tr-J stratigraphic boundary, which might therefore be about 201 Ma in age. The Tr-J boundary also marks one of the greatest known mass extinctions (Palfy and others 2000). Although the North Mountain Basalt constitutes only one tholeiite type across the Fundy Basin, it is also correlated with the earliest of several basalt magmas in other basins, and this magma type therefore serves as a marker to divide Triassic from Jurassic strata in the basins (Puffer, 1994).

Large tholeiite intrusions of northeastern North America, including the Shelburne, Caraquet, Christmas Cove, and Higganum-Holden dikes, have likewise been assigned modern $^{40}Ar/^{39}Ar$ dates near 200 Ma (West and McHone, 1997; Dunn and others, 1998; Olsen 1999). This age coincidence with the great basalt flows of the basins is critical to a model in which the large dikes are fissure sources for the basalts (Philpotts and Martello, 1986; McHone and others, 1995; McHone, 1996).

Basalt Strata

The North Mountain Basalt is present through most of the Fundy Basin, which has an area about 16,500 km^2 (Wade and others, 1996), and it probably covered all of the basin and more when it formed, since it has been truncated by border faults and 200 m.y. of erosion. Across most of the basin the North Mountain Basalt is 400 to 500 m thick, but in the south-central area of the basin (east of Grand Manan) the basalt has been shown by seismic studies to be 600 to 1000 m thick (Wade and others, 1996). An average of 400 m thickness across the present basin yields a volume of 6,600 km^3 of basalt.

In the Digby area of Nova Scotia about 75 km east of Grand Manan, the North Mountain Basalt totals about 400 m thick and is divided into three units that were studied by Papezik and others (1988). The lower unit is apparently a single massive medium-coarse grained quartz-tholeiite basalt flow about 190 m thick. The middle unit consists of seven or more relatively thin zeolite-rich amygdaloidal basalt flows, totaling about 50 meters thick, and the upper unit is another massive flow of coarser porphyritic basalt about 160 m thick. These same units are traceable for 200 km to the northeast along the western shore of Nova Scotia (Stevens, 1987), and there are one or two thin layers of clastic sediment deposited between some of the middle unit flows. The upper part of the upper massive unit contains thin layers and bands of pegmatitic gabbro that Greenough (1992) related to a fractional differentiation model. Because these units and flows might have different sources and times of eruption, and might not represent the same magma, we should adopt a more inclusive term such as North Mountain Basalt Group (NMBG).

In the Chinampas exploration well about 25 km northeast of Grand Manan Island, 333 m of basalt was drilled and divided into two units (Papezik and Greenough, 1987). The lower 164 m unit has 17 "petrophysical cycles" of the well log that may correspond to individual flows up to 30 m thick. (Pe-Piper and others, 1992). The upper 169 m unit has 14 cycles with a lower cycle maximum about 70 m thick, becoming amygdaloidal in upper cycles. A weathered zone separates the two units, and other weathered layers occur in the upper unit as well (Pe-Piper and others, 1992). The well log and seismic data indicate possible clastic sediments between some flows, but these were not directly observed. The weathering and terrestrial sediments between NMBG flows shows that they were sub-aerial.

The massive North Mountain Basalt units are typically medium- to coarse-grained with subophitic to ophitic textures dominated by Ca-plagioclase and augite, with common pigeonite (usually rimmed by augite), and scattered magnetite. Granophyres or patches of fine-grained quartz and Na-feldspars are often observed. The lower sections of the massive basalt units contain scattered orthopyroxene (bronzite) phenocrysts that are partially corroded. Small grains of biotite, apatite, and other accessory minerals are also found in the massive basalt.

Stratigraphic Models

An interesting exhibit on the geology of the island is displayed in the Grand Manan Museum in Grand Harbour. Photographs, samples, and maps in the exhibit appear to date from field work by University of New Brunswick students and faculty in the mid-1960s. The exhibit map and cross-section of the Mesozoic rocks have been reproduced in a fine book by Allaby (1984) and in the Grand Manan web site (http://www.grandmanannb.com/geology.htm). The map and cross section show an unusual but interesting interpretation in which all of the massive columnar basalts are large sills that intrude smaller units of relatively thin amygdaloidal flows, which remain only as isolated blocks within the sills. This interpretation is also implied by the map legend of McLeod and others (1998).

Some of the reasons for calling the massive units “sills” were described by Gunter (1967). At several locations along the northern shoreline, massive columnar basalt is in conformable contact above or beneath sections of the thinner flows, but in a few places the massive unit crosscuts the flows at a relatively low angle. A sharper, high-angle crosscutting relationship also exists in at least one site, but the situation is confused by breccias and a fault or faults. A very gentle angular unconformity among some of the thin units can also be observed from the ferry along the northeastern shoreline (Seven Days Work), although it is difficult to see from the beach below the cliff itself. Along most of the western shore, the lowest section of massive basalt was all mapped as a sill, and it appears to be conformable with the underlying Blomidon siltstones in its limited exposures.

However, stratigraphic relationships among units of the NMBG have been well established at other places around the Fundy Basin, which can be applied to Grand Manan (Fig. 2). Based on the observations near Digby, my preference is for the three-division model in which all North Mountain Basalts were sub-aerial surface flows, with variations of the unit thicknesses to be measured on the island. As a rough estimate, the lower massive unit on the island may be about 120 m thick, the middle thin-flow unit about 50 m thick, and the upper massive unit at least 60 m thick -- but much of the upper two units is probably removed by erosion. It is difficult to make a direct correlation with the Chinampas well column, because much of that description is based on geophysical measurements of the well rather than the naked-eye observations elsewhere. For my model to hold up, the cross-cutting relationships observed at several locations must be accepted as erosional and tectonic features, not as intrusions of massive basalt sheets.

Possible Dike Sources

Several large tholeiite dikes are known in the northeastern region around the Bay of Fundy (Fig. 1). As shown by Philpotts and Martello (1986) for the area around the Hartford basin of southern New England, large local dikes are likely feeder sources for the basin basalts, as demonstrated through chemical and mineralogical comparisons. Dunn and Stringer (1990) observed that the Ministers Island dike has whole-rock and mineral compositions similar to the North Mountain Basalt, and its location in the southwestern section of the basin (Fig. 1) satisfies the proposal by Papezik and others (1988) for northeasterly flow of the basalt from a fissure source. The Ministers Island dike appears to be an exact petrological match for the Christmas Cove dike of coastal Maine, and it is very similar to large dike segments exposed to the east in Buckman's Creek, the New River, and the Lepreau River (Helmstaedt, 1968; new work for this project). That dike magma type has the same mineralogy as the lower massive units of North Mountain Basalt, except that the dike texture shows more rapid cooling features (finer grain sizes for the matrix), and a tendency toward porphyritic textures, with plagioclase phenocrysts, orthopyroxene phenocrysts, and clumps of augite grains.

Other large dikes in the region include the Caraquet dike of New Brunswick and Maine (Greenough and Papezik, 1986), the Shelburne dike of Nova Scotia (Papezik and Barr, 1981), and the Christmas Cove dike of coastal Maine (McHone and others, 1995). Each of these dikes is 4 to 30 m wide and over 200 km long. Reidel and Tolan (1992) related very large lava flows of the Columbia River basalt group to dikes smaller than these northeastern fissures. Moreover, the Christmas Cove dike has been traced to the southwest to essentially connect (a mapping gap of less than 25 km) with the Higganum-Holden-Onway dike of southern New England, which represents a source for the Talcott Basalt of the Hartford Basin (Philpotts and Martello, 1986). The Talcott Basalt is an exact stratigraphic and petrologic equivalent of the North Mountain Basalt (Puffer, 1994; Olsen, 1997).

The Caraquet dike is co-linear with, and petrologically equivalent to the Buttress-Ware dike of southern New England, which was a feeder to the large Holyoke Basalt of the Hartford Basin (Philpotts and Martello, 1986; Philpotts and others, 1996). This magma type is distinct from the North Mountain Basalt and Christmas Cove-Ministers Island dike petrology, and it has not been recognized in the Fundy Basin. The Shelburne dike, however, is reasonably similar to the NMBG and Christmas Cove-Ministers Island-Lepreau River dikes in chemistry and mineralogy (including the presence of orthopyroxene), except that the Shelburne dike tends to have slightly less titanium and more silica (Table 1). Pe-Piper and Piper (1999) provide a good discussion of the potential for the Shelburne dike to be a source of the NMBG in the Fundy Basin, with a conclusion that it is different enough to be unlikely. Other arguments related to the basalt distributions were presented by McHone (1996).

As pointed out above, recent radiometric dates are close to 200 Ma and allow any of the dikes to be co-magmatic with the North Mountain Basalt. Thin sections and whole-rock chemical analyses were provided by Sandra Barr for this study, which indicate that the Ministers Island dike is petrologically similar to the tholeiite of the Buckman's Creek dike, New River dike, and Lepreau River dike, all of which are indistinguishable from the Christmas Cove dike and Higganum-Holden-Onway dike system to the south. Photomicrographs of samples from the Buckman's Creek dike and the base of the basalt at Dark Harbour (Fig. 3) reveal similar forms of orthopyroxene phenocrysts, which after they flowed from the dike into the surface NMBG lavas became unstable and altered rapidly. The pyroxenes were described by Helmstaedt (1968) and Helmsteadt and others (1966).

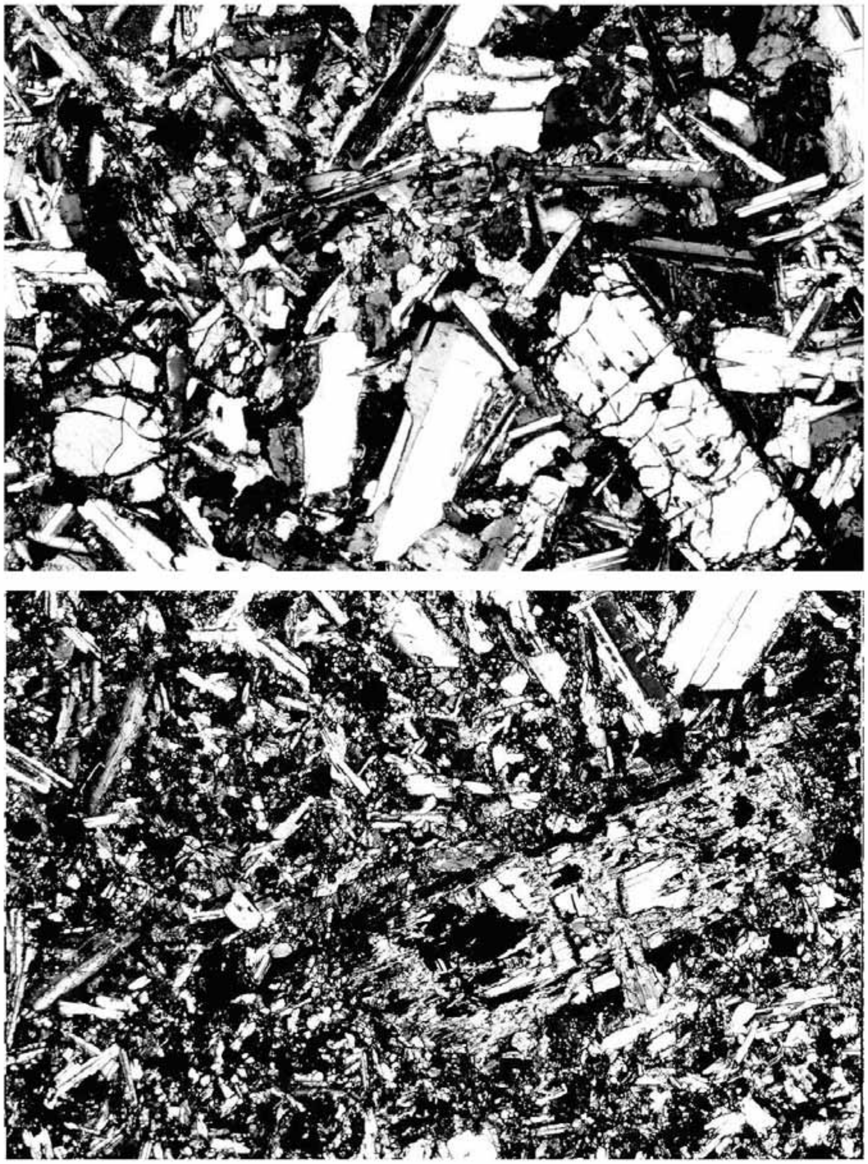

Figure 3. Photomicrographs of samples from the interior of the Buckman's Creek dike (upper image) near Beaver Harbour, and from the base of the North Mountain Basalt (lower image) at Dark Harbour, Grand Manan. The views are about 3 mm in width, under crossed polarizers. The large bright rectangular bronzite phenocryst in the lower right portion of the Buckman's Creek sample is comparable in form with the altered orthopyroxene phenocryst in the center-right area of the Dark Harbour basalt, which retains only patches of fresh pyroxene in the crystal interior. Clinopyroxene (augite) grains in both samples vary in size but remain relatively fresh, as does plagioclase.

Table 1 presents the new chemical analyses with some comparisons of other dikes. The Swallowtail Head dike (Table 1, nos. 12 and 13) is very evolved by mafic mineral fractionation, as shown by low Cr, Ni, MgO, and other elements. As such, it is an unlikely candidate to be a source for at least the massive units of North Mountain Basalt. Much of the major and trace-element variation in Grand Manan basalts and dikes from the adjacent area of New Brunswick (Table 1, nos. 3-11) can be attributed to fractionation of pyroxenes, and possibly olivine at a deeper level before eruption. Allowing for that fractionation, the Mg/Mg+Fe ratios are reasonable for a derivation as a melt of pyroxene-rich peridotitic upper mantle. In addition, variations in Sr isotopes and volatiles indicate some alteration and contamination of the tholeiite at shallow levels (Jones and Mossman, 1985; Dunn and Stringer, 1990). The Lansdowne dike near Digby, NS (Table 1, no. 14) has a petrography consistent with either the Ministers Island or the Shelburne dike types, but the sample appears to be strongly altered and needs more study.

TABLE 1. CHEMICAL ANALYSES OF DIKES AND BASALTS, GRAND MANAN REGION

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	51.93	53.49	50.85	52.94	52.56	52.87	52.12	51.37	51.30	52.27	52.09	53.22	51.96	45.56
TiO_2	0.87	1.06	1.13	1.14	1.190	1.212	1.310	0.832	1.118	1.005	1.207	1.514	1.535	2.094
Al_2O_3	15.28	14.94	13.83	14.13	14.46	14.77	14.31	15.43	14.76	13.80	14.34	13.54	14.17	16.02
Fe_2O_3	11.58	11.03	11.78	10.05	11.33	10.77	11.40	9.22	10.97	10.96	10.65	14.44	12.80	13.73
MnO	0.19	0.17	0.18	0.20	0.164	0.167	0.179	0.148	0.244	0.192	0.140	0.168	0.129	0.169
MgO	7.76	6.86	7.65	7.92	6.79	6.24	5.95	7.45	6.52	7.56	6.83	3.50	3.47	5.71
CaO	10.54	10.28	11.14	10.94	10.06	10.03	9.97	11.54	10.55	11.03	10.11	7.33	6.76	7.06
Na_2O	2.19	2.21	2.18	1.97	2.16	1.98	1.97	1.90	2.06	2.13	1.96	2.41	2.80	3.48
K_2O	0.50	0.75	0.63	0.55	0.75	0.83	0.76	0.43	0.42	0.67	1.32	2.12	2.08	0.38
P_2O_5	0.14	0.15	0.07	0.14	0.149	0.146	0.165	0.099	0.138	0.119	0.150	0.243	0.241	0.201
LOI			1.01		0.51	1.61	2.04	1.45	1.50	0.97	0.77	2.22	4.27	6.08
Total	100.0	100.9	99.9	100.0	100.1	100.6	100.2	99.9	99.6	100.7	99.6	100.7	100.2	100.5
Rb	15	29	17	20	25	28	24	19	20	23	24	56	58	16
Sr	134	206	184	168	180	190	223	183	223	166	185	164	175	266
Y	27	24	18	18	22	22	23	18	22	20	22	34	33	24
Zr	66	104	107	109	103	106	117	69	102	84	102	172	174	150
Nb	6	10	10	12	9	9	10	6	8	8	10	15	15	17
Ba	134	207	175	221	72	110	62	43	26	44	89	462	721	60
Cr	118	206	284	332	154	156	100	193	131	272	166	9	12	46
Ni	50	78	82	87	66	58	98	73	69	72	60	6	3	46
V	256	254	235	262	227	228	240	175	222	210	229	264	271	315
Co			68		64	64	53	50	62	59	53	57	52	61
Cu	65	68	130		119	115	133	78	84	<4	92	5	7	85
Zn	65	78	73		83	224	83	59	156	80	89	107	97	100
Ga	14	21			15	18	17	17	18	16	17	21	23	20
Nd					22	17	15	15	<5	6	10	36	34	16
La					16	18	14	14	<5	8	8	38	37	12
Pb					5	32	2	3	2	5	4	7	34	<3
Th					5	4	4	3	3	3	4	10	10	4
U					2	2	1	2	2	2	2	1	1	<1

Explanation

1 Average Caraquet dike, NB
2 Average Shelburne dike, NS
3 Average Christmas Cove dike, ME
4 Average Ministers Island dike, NB
5 Buckman's Creek dike interior
6 New River dike interior
7 Lepreau River dike "A"
8 Lepreau River dike "B"
9 Grand Manan basalt, island center
10 GM basalt, Red Point
11 GM basalt, Dark Harbour shoreline
12 Swallowtail Head dike interior
13 Swallowtail Head dike, SE margin
14 Lansdowne dike, near Digby, NS

Data Sources

1 Greenough and Papezik, 1986
2 Papezik and Barr, 1981
3 McHone, unpublished
4 Dunn and Stringer, 1990
5-14 new analyses by S. Barr, 2001

Notes: Oxides are in weight percent; trace elements in ppm. Blank = no data; samples 5-14 are by XRF at Acadia University's geochemistry facility.

A TiO2 versus MgO diagram is useful for studies of tholeiites because it is sensitive to fractionation of the mafic phenocrysts in the magmas, and thus can indicate co-magmatic groups and trends. In Figure 4, the Christmas Cove-Ministers Island-Lepreau River dike group plots on a linear trend of the North Mountain Basalt group, consistent with a source-dike relationship and mafic mineral fractionation in the lavas. Other major dikes such as the Caraquet and Shelburne do not intersect this North Mountain Basalt trend and are different enough to be less likely sources, as also discussed by Pe-Piper and Piper (1999).

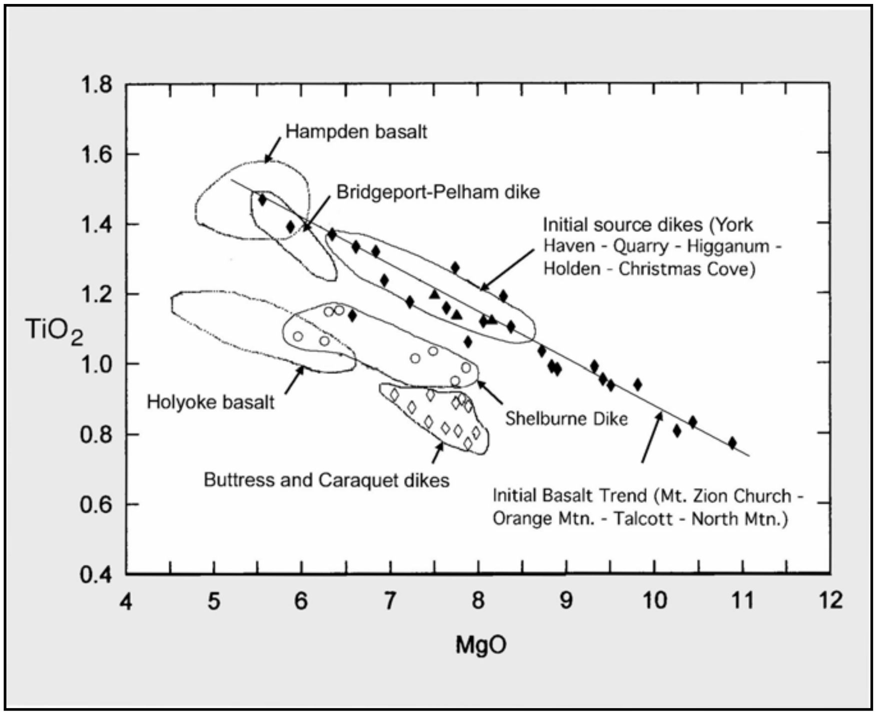

Figure 4. Weight percent TiO_2-MgO variations in Early Jurassic basalts and dikes in northeastern North America. Compositions of the Ministers Island, Buckman's Creek, New River, and Lepreau River dikes (Table 1) fall within the initial source dikes field (solid triangle symbols) on the North Mountain Basalt trend (defined by solid diamond symbols). Other dikes and basalts are mainly from southern New England. Sources: Philpotts and Martello (1986), McHone (1996), and references cited in Table 1.

Sub-Basalt Strata

For several km along the shoreline to the north and south of Dark Harbour, there are outcrop intervals of reddish to light gray siltstone and shale beneath and in contact with the basalt. This unit has been correlated with the late Triassic/earliest Jurassic Blomidon Formation of the northern Fundy Basin (Wade and Jansa, 1994), and it was referred to as “Annapolis Formation” by Gunter (1967). I visited two such intervals between ½ and 1 km south of the harbor, which appear in gentle hills or rises into the basalt above the beach, the first about 10 m long and 3 meters high, and the farther exposure about 40 m long and 8 m high. Other sections of this unit may be under basalt talus but become exposed or covered by shifting storms along much of the western shore.

I climbed the soft siltstone slope at the farther exposure to look for changes in the section toward the base of the basalt. The siltstone is very soft and mostly obscured by weathered materials. About 3 m beneath the basalt, the fine reddish siltstone grades into a bleached pale gray shale with a weak cleavage, and there is a thin horizon of blue-colored shale about 20 cm beneath the basalt. The color could be caused by hydrothermal copper mineralization. Otherwise, the change from the reddish colored siltstone at the beach into pale gray shale (or soft fissile mudstone) near the basalt appears to be gradational. I did not recognize any fossils or unusual structures. Paul Olsen recently visited a similar exposure north of the harbor and found no layer or feature that might be correlated with the Tr-J boundary, possibly because of thermal alteration from the basalt (pers. comm., 2000). Olsen (1997) and his colleagues have examined this boundary in Blomidon strata a few meters beneath the basalt in the northern end of the Fundy Basin.

However, it remains possible that the Tr-J boundary and mass extinction horizon is present in one or more of the Blomidon siltstone exposures along the western shore. At other locations, between 1 and 9 m of sediment separate the Tr-J boundary from the initial (lowest) basalt flows (Olsen, 1997; Mossman and others, 1998). It would be useful to determine a time interval for this stratigraphic section, and to make comparisons with distance from lava sources among locations for the Tr-J horizon in northeastern North America.

Coarse reddish-brown sandstone with conglomerate has been reported in one area along the Red Point Fault on the eastern side of the island (Alcock, 1948; McLeod and others, 1998), which is interpreted to be sub-basalt strata. Wade and Jansa (1994) did not locate this exposure, and it is apparently unlike the Blomidon siltstone strata of the western shore. We have not seen this unit in any roadcuts, but McLeod and others (1998) present an outcrop symbol near the highway that we intend to investigate. An interpretation of this material as immediately sub-basalt strata is problematic, given its differences from the siltstones to the west. Perhaps the sandstone actually overlies the NMBG, similar to "McCoy Brook" clastics of the northern basin (Wade and others, 1996), or it could be an independent fault slice from a deeper level.

Similar strata were encountered in a 660-foot (201.2 m) deep drill hole near Sloop Cove (western side of the island), drilled in the early 1960s by Keevil Mining Group, Ltd. Examples of this core are on display at the Grand Manan Museum, with the following description: the core penetrated 310 feet (94.5 m) of massive basalt, then 100 feet (30.5 m) of purple-red shale, and finally 250 feet (76.2 m) of medium sandstone. The lower sandstone description resembles the Triassic Wolfville Formation of the northern and eastern basin, which is up to 3000 m thick to the east of Grand Manan, but more likely it is a facies of the Blomidon Formation, which is 1157 m thick in the Chinampas well core to the north (Wade and others, 1996).

Structures

Most of the northern and western borders of the Fundy Basin are defined by faults that have significant post-basalt movement. The Cobequid Fault along the northern border had both vertical and lateral movement, and North Mountain Basalt is truncated in tectonic zones of the fault along the shoreline. Because the faults offset even the youngest sediments, they must have continued activity into Middle Jurassic or later times. Vertical offset along the western border fault is at least 3500 m as indicated by nearby basin strata in the Chinampas well (Greenough, 1995). Vertical offset on the north-south Grand Manan Fault, which defines the eastern border of the Grand Manan horst, could be as much as 9000 m through the adjacent deep-basin stratigraphy (Wade and others, 1996). North-south faults create five offset segments of the North Mountain Basalt ridge near and southwest of Digby, NS (Wade and others, 1996). Compressional folds and reverse faults also occur in the basin, which are considered to be late, and possibly a record of the first ocean crust production in mid-Jurassic time (Olsen, 1997).

However, border faults of this and other basins were also active earlier, during the Late Triassic development of the Fundy Basin, as shown by alluvial fans and other stratigraphic features along the margin faults. The model that is now promoted calls for a major acceleration of tectonic activity at about the same time as basalt magmatism in the basins (Olsen, 1997). On Grand Manan, we may expect syn-magmatic tectonism as well as the post-magmatic faulting recorded by the Red Point Fault. Fault movements during the sequence of basalt flows of the North Mountain Basalt Group on the island could be responsible for uplift and erosion within some sections, and even sharp relief could be developed along fault scarps between lava flow events. Syn-magmatic tectonic features may be interpreted for several locations around the northern shoreline Grand Manan.

ACKNOWLEDGEMENTS

Nancy McHone has assisted me on all excursions into Atlantic Canada, and it would be difficult to accomplish much without her help. Sandra Barr has provided thin sections and chemical analyses for several samples, and she has mapped several very important potential source dikes that add much value to this project. Other colleagues who have discussed this work and contributed materials include Jelle de Boer, Malcolm McLeod, Les Fyffe, Dick Grant, Chris White, and John Wade.

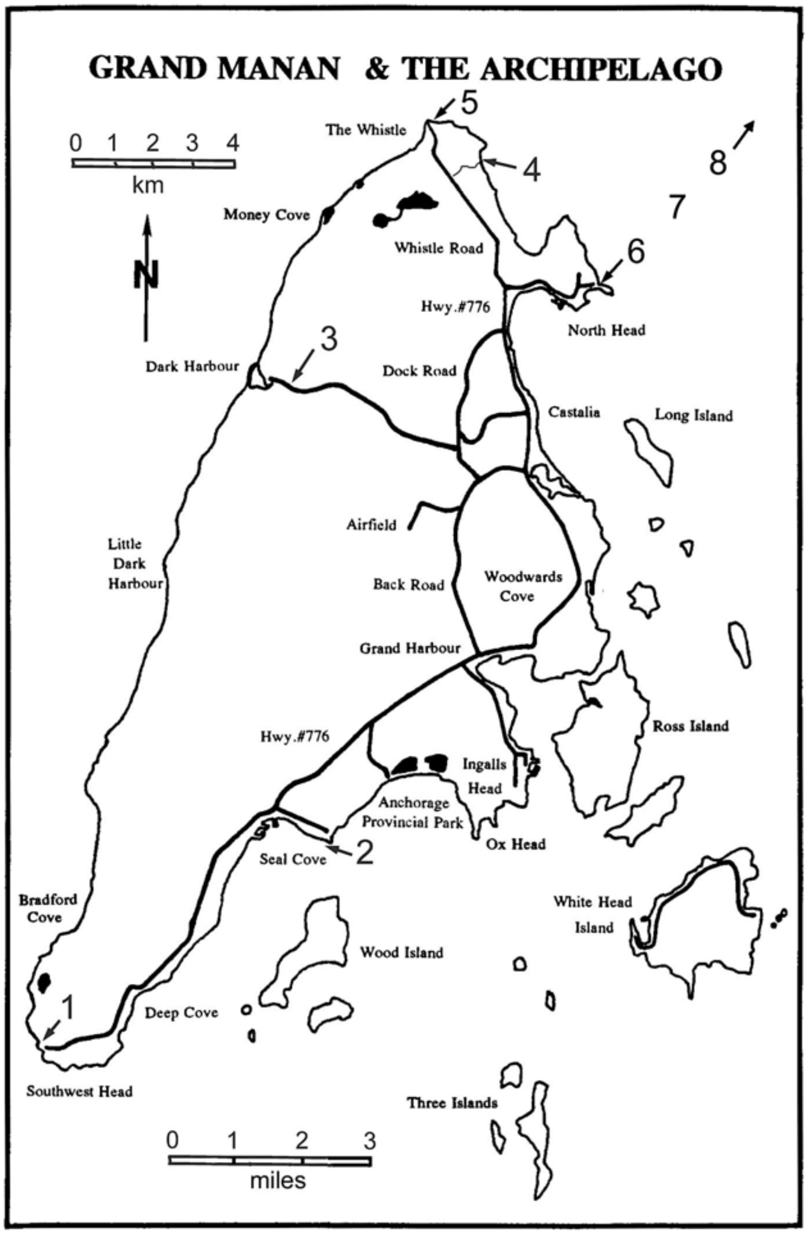

Figure 5. Road map of Grand Manan Island, showing stop locations. Adapted from a map published by the Grand Manan Tourism Council.

ROAD LOG

Participants who travel from the mainland to start this trip will miss the first few stops, because the first ferry to the island arrives late in the morning. All participants should purchase a return ticket a day in advance, or at least, immediately upon arrival in North Head. We will depart the island on the last (3:30 PM) return ferry trip of the day, examining the island as we go past it on the boat ("Stop 7"), and then we will make a final stop near Beaver Harbour on the mainland. Our schedule must be strictly monitored so that we will be lined up at the ferry dock ready to depart the island at 3:10 PM. We are at the mercy of the tides, weather, and waves, which might force some changes to the itinerary.

We will start at the southern end of the island and work northward. Because my vehicle only registers miles, I have used that obsolete measurement system for this road log (kilometers in brackets are calculated). Participants who have stayed overnight from the previous day's trip to examine metamorphic rocks of the island might especially enjoy a breakfast pastry from the North Head Bakery, on the east side of Rte. 776 about 1 mile west of the ferry dock in North Head. Participants need to bring their own lunch materials, which can be purchased at several stores and take-out restaurants along Rte. 776.

If you are sharing a ride with some colleagues, you should leave extra vehicles near the ferry dock at North Head (pick them up again for Stop 7). Assemble at Stop 1 (Fig. 5) by 8:30 AM.

Mileage

Miles	(km)	
0	0	Assemble at the southernmost end of Rte. 776, about 17 miles from North Head Village. Park near the lighthouse, but stay away from the top of the unstable cliff.

STOP 1. SOUTHWEST HEAD LIGHT (15 minutes)

This spectacular 50-meter cliff exposes a section of the lower massive basalt unit. The basalt columns are well developed and appear to be continuous, i.e. not interrupted by flow boundaries or horizontal segregations such as have been observed in other basins (Philpotts and others, 1996). This massive basalt unit is close to horizontal here, but there are bedding warps and eroded surfaces as well as faults across the island, which need to be accounted for when tracing the units. However, sub-basalt sediments are exposed along the beach a few km up the western side of the island, so the base of this cliff at Southwest Head is probably not more than a few 10s of meters above the bottom of the North Mountain Basalt pile. We will have an opportunity to observe and sample this same basalt unit up close at Stop 3, so there is no need for you to lean over the cliff to get a piece at this stop!

Visible to the west across the Grand Manan Channel is the coast of Maine, along which Paleozoic formations are placed against from the Grand Manan sub-basin by the NE-SW-trending western Fundy Basin Fault. The western border fault should have an offset at least equal to the Red Point Fault, perhaps more than 3500 m, and during or previous to the displacement interval the Mesozoic units probably extended some distance into eastern Maine, so that the present metamorphic/plutonic terranes were covered by Triassic sediments and/or Jurassic basalt lava flows. The basalt extrapolation is supported by the presence of the large Caraquet, Ministers Island, and Christmas Cove dike systems in central and eastern Maine, all of which were likely feeders to surface lavas.

Drive north along Rte. 776, observing the conservative speed limit, please.

5.6	(9.0)	Bridge over “the creek” in Seal Cove Village, where amygdaloidal flows crop out.
5.8	(9.3)	Turn right (southeast) onto Red Point Road.
7.1	(11.4)	Park in the lot at Red Point picnic area. Walk down the trail to the beach on the south end of the point.

STOP 2. RED POINT FAULT (20 minutes)

This is a rare exposure of a major displacement intra-basin fault. The massive lower (?) unit of North Mountain Basalt is in sharp contact with Ordovician or Silurian Long Pond Bay Formation meta-siltstones (argillites), which are reddish in color near the fault. The normal fault strikes about N50ºE and dips about 82º to the northwest, and it bisects the island as it extends and bends northward to Whale Cove (Fig. 2). At least 300 m (and possibly much more) of vertical offset is required for this juxtaposition. No other exposures of the Red Point Fault are known on the island, but it apparently truncates an east-west fault at North Head (Fig. 2).

The columns of basalt have been drag-folded into low angles (48º) along the Red Point Fault, indicating mainly vertical displacement down to the west. The columns gradually assume their normal sub-vertical orientation about 50 m to the south along the cliff face. This is also a good place to observe the development of basalt breccia, which is characteristic of basalt in brittle tectonic zones. The Red Point Fault normally produces a spring, and the island council members have become interested in faults because they are such obvious water conduits.

8.4	(13.5)	Return to Rte. 776. Turn right (north)
12.3	(19.8)	Turn left onto Hill Road (also called Back Road) just before Grand Harbour Village.
14.7	(23.7)	Past road to Grand Manan Airport.
15.2	(24.5)	Turn left onto Dock Road.
15.6	(25.1)	Turn left onto Dark Harbour Road.
17.1	(27.5)	Past a small roadcut with a possible inter-lava paleosol horizon.
18.6	(29.9)	Pull off into the parking area across from the basalt cliffs.

STOP 3. DARK HARBOUR OVERLOOK (15 minutes)

This long roadcut, elevated about 60 m above the ocean and base of the basalt, displays excellent columns developed during the cooling of the lower massive basalt unit. Samples from this cut were described by Pe-Piper and Piper (1999) as being chemically similar to the lower massive basalt unit across Fundy Bay at Digby, Nova Scotia. We have not been able to detect layering or separate flows in this unit, so it may represent a single flow about 120 m in thickness. The basalt has a very gentle dip of a few degrees, apparently eastward.

Dark Harbour is named for the gloomy shadows cast by the high (110 m) basalt cliffs along the western shoreline. It has a fine natural breakwater and at present a fish farm industry is being developed in the harbor. At low tide, it is possible to drive (4-wheel drive is helpful) to the southern and northern ends of the harbor along the beach strand, and then to walk along the base of the cliffs where Blomidon shales are well exposed in contact beneath the basalt (Wade and Jansa, 1994). We do not have time for it today, but I encourage you to come back for that adventure.

19.2	(30.9)	Dark Harbour. Turn around, return to Dock Road.
22.8	(36.7)	Left onto Dock Road. Follow Dock Road north to Rte. 776.
25.1	(40.4)	Left onto Rte. 776.
25.8	(41.5)	Tattons Corner. Turn left onto Whistle Road. *Watch the oncoming traffic*!
28.1	(45.2)	Trail to Seven Days Work on the right, just past an abandoned dump. Park along the road so as to not block traffic. Walk eastward along the trail for 0.5 miles, and down a steep trail section onto Eel Pond Brook Beach.

STOP 4. SEVEN DAYS WORK (75 minutes)

According to Allaby (1984), this section of the island was named for the time it might take to form the basalt layers in the cliff, assuming each layer took one day! The basalt layers are a major section of the middle unit of the NMBG, consisting of seven or eight amygdaloidal lava flows each a few meters in thickness. Differential erosion between the flows causes them to stand out in relief, and it appears that paleosols could be developed between some of them. Mineral collectors will find good zeolites (also see Trembath, 1973), plus amethyst, agate, rod-shaped calcite, and copper minerals. Spectacular gas-charged tubes called pipe vesicles are common near the base of some flows, and are probably caused by boiling of wet materials under the flow. The pipes can rise 10 to 20 cm or more and are now filled with mixtures of calcite, zeolites, and late basaltic magmas. Pipe vesicles can be deformed by the movement of the lava they rise through, in which case they provide flow directions (I saw little indication of that here).

The amygdaloidal flows now dip about 10 to 12 degrees to the south-southeast along the beach, so that as you walk south you travel up-section. A few hundred meters farther south along the beach, the overlying massive upper basalt unit is encountered, but it appears that not all of the upper unit and middle unit flow contacts are completely conformable, but instead some flows pinch down to thinner or steeper layers toward the south. Overlying contacts therefore appear to crosscut the lower flows at a very gentle angle.

Looking north from the beach across the Eel Pond Brook Valley, Ashburton Head is all massive basalt, with no thinner flows as at Seven Days Work. This is probably positioned by a fault in the brook valley, which extends across the Head and is exposed at the next stop (Fig. 2). At that exposure, it looks like the Ashburton Head basalt has dropped down, and so it represents the upper massive unit.

Return on the same trail to the cars and continue north.

28.5	(45.9)	The Whistle light and fog horn station. We may eat lunch at the next overlook.
28.7	(46.2)	Long Eddy Point boat launch. Park without blocking traffic. Walk northeastward along the cobble beach (tread carefully on the loose stones) about 0.3 miles to Whistle Beach.

STOP 5. WHISTLE BEACH (75 minutes)

Past the cobble beach is another good cliff exposure, but these rocks are especially unstable and everyone should stay away from the cliff base as much as possible. To the northeast of the amygdaloidal flows, a steep tectonic contact appears, across which is the massive unit that extends from Ashburton Head. This site was interpreted by Gunter (1967) and others to represent an intrusional contact, with the massive unit cross-cutting the thinner flows. It does look a bit like that, but I hope we can sort out a steep normal fault in the basalt breccias and lava flows.

Points to consider: Is there a fault here at all, or could the breccia be generated some other way? Could this be a steep bank eroded into the middle-unit amygdaloidal flows, so that the upper unit cascaded down the slope as a lava flow? Could this be a fault scarp in the middle units, not an eroded bank? And if there is a fault, does it crosscut the upper massive unit or only the foot-wall flows? Some of the flows appear to be deformed by drag folding, but then exactly where is the fault surface relative to those units? Your eyes and experience are needed!

Return to your vehicles and head back on Whistle Road to Rte. 776.

31.6 (50.9) Turn left onto Rte. 776, drive into North Head Village and past the ferry dock.
32.7 (52.6) Turn right onto Swallowtail Head road.
33.0 (53.1) Park in a small lot overlooking Swallowtail Head. Walk across the footbridge over "The Sawpit."

STOP 6. SWALLOWTAIL HEAD DIKE (25 minutes)

This is one of the greatest mafic dike exposures in northeastern North America (and I have seen a large percentage of them). Because it is hosted by Cambro-Ordovician Ross Island meta-basalt of the basement horst, which was formerly beneath the North Mountain Basalt, Gunter (1967) and probably others suggested that it might have been a feeder to the surface flows. Physically, it looks like a typical large tholeiite dike of Early Jurassic age. However, in thin section, it lacks the strong mafic mineral content of the other Mesozoic dikes in the region, with augite grains scattered among abundant feldspars (mainly sodic plagioclase), and no orthopyroxene. Although the rock is somewhat altered (also indicated by a high "loss on ignition" or volatile content, Table 1) it does not appear to be metamorphosed. It has abundant iron oxide minerals, which cause the rich rust-brown color as well as divert compass needles to a small degree.

The dike strikes N51ºE, dips 80º SE, and is 29 m (94 feet) wide at the bridge. The dike is split by erosion in the ravine, with about 2/3 of the northwestern part of the dike leaning as a massive unit against the cliff, and the southeastern third eroded. This might indicate a multiple or composite intrusion, but I have not observed internal chill margins. Jelle de Boer drilled plugs from the eroded section near the water, which have a near-vertical AMS orientation (pers. comm. 2001). The dike has not been traced to the southwest, so it might be truncated by the east-west fault that runs along the southern edge of Swallowtail Head (McLeod and others, 1998), which itself is apparently cut by the Red Point Fault near Whale Cove (Fig. 2).

As discussed above, the chemical/mineral composition of the Swallowtail Head dike precludes it from being a source for the massive units of North Mountain Basalt. It could, however, have fed some of the thinner amygdaloidal flows of the central basalt unit, which have yet to receive detailed chemical and petrographic study. The central amygdaloidal flows are widespread across the Fundy Basin, yet they appear to be distinct from the massive orthopyroxene-bearing upper and lower basalt units. Gunter (1967) listed high alkali analyses for amygdaloidal (?) flows in the southwestern area of the island, which could fit this intrusion. Alternately, the dike might be a member of the Triassic sub-alkaline basaltic dike group that appears intermittently in coastal regions of northeastern North America (Pe-Piper and others, 1992). It would have to be exceptionally well preserved to be even late Paleozoic in age. Perhaps a plagioclase concentrate from the dike would yield a reasonable Ar/Ar plateau date, for which I would be happy to provide a sample.

Return to the ferry dock at North Head village.

33.5 (53.9) Park in the lot near the dock for the ferry (show your ticket at the window). Board the boat for the trip to Blacks Harbour.

33.6 (54.1) Assemble on the port (left) side of the upper deck to view features of the island.

STOP 7. GRAND MANAN FERRY TRIP (90 minutes)

The Swallowtail Head dike stands out by its brown color, and its massive cooling columns are visible against the cliff. After the boat passes North Head, the thin amygdaloidal flows of Seven Days Work can be counted beneath the gentle slope of the overlying upper massive basalt unit to the south. Examination of the flows from this perspective reveals a low-angle unconformity in the upper flows that slope somewhat more steeply to the south.

We need to determine the sequence of flows and erosion that can explain this angular feature. The massive basalt unit at Ashburton Head north of the Eel Pond Brook gap is interpreted to also be the upper massive unit, which is a juxtaposed at this level by a fault in the brook gap, as also observed at Stop 5.

As the boat proceeds north away from the island, we can see a series of headlands along the western side of the island, which appear as steps in the top of the basalt cliffs. At least some of these steps are eroded tectonic zones within the massive lower basalt unit, probably faults that may be nearly contemporaneous with the magmatic activity.

After we depart the boat, assemble back into a vehicle queue in the parking lot to the right of the dock road.

35.1 (56.5) Turn right in Blacks Harbour onto Rte 778.
38.6 (62.1) (approximate distance) Beaver Harbour village. Continue northward.
40.1 (64.5) (approximate distance) Buckman's Creek Bridge. Park along the highway near bridge; do not block traffic.

STOP 8. BUCKMAN'S CREEK DIKE (15 minutes)

This dike was first described by Helmstaedt (1968), who recognized it as Mesozoic and very similar to the Ministers Island dike, and possibly the same dike exposed in the New River and Lepreau River on-line to the northeast of Buckman's Creek. Alternately, those river segments could connect with the Ministers Island dike if we allow for more offsets along that dike's trend. According to the map, the Buckmans' Creek dike should be exposed somewhere along the coast near or southwest of Blacks Harbour, but I know of no report of it. A magnetic survey is needed to trace this dike and others in the region. Helmstaedt (1968) reported a dike width of about 60 feet (18.5 m) at this location, but I have not observed any contacts in the stream bank. Judging from columnar structures, it trends about 50º to the northeast and is nearly vertical. If it connects with the New River and Lepreau River exposures, a minimum length of about 20 km is indicated. However, the dike is even wider (approximately 30 m) where it crosses the Lepreau River, so it likely continues much farther.

Thin sections and whole-rock chemistry (Table 1) confirm that the Buckman's Creek dike is essentially the same tholeiite as the other dikes nearby, with characteristic orthopyroxene (bronzite) phenocrysts that Helmstaedt and others (1966) also described in the Grand Manan basalts.

41.4 (66.6) End of trip. Continue north to Rte. 1 and other destinations.

REFERENCES

Alcock, F.J., 1948, Grand Manan, New Brunswick: Geological Survey of Canada, Map 965A, scale 1” = 1 mile, with descriptive notes.

Allaby, E., 1984, Grand Manan: Grand Harbour, Grand Manan Museum, Inc., 64 p.

Dostal, J. and Dunning, M., 1998, Geochemical constraints on the origin and evolution of early Mesozoic dikes in Atlantic Canada: European Journal of Mineralogy, v. 10, p. 79-93.

Dostal, J. and Greenough, J.D., 1992, Geochemistry and petrogenesis of the early Mesozoic North Mountain Basalts of Nova Scotia, Canada, *in* Puffer, J.H. and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism: Geological Society of America, Special Paper 268, p. 149-159.

Dunn, A.M., Reynolds, P.H., Clarke, D.B., and Ugidos, J.M., 1998, A comparison of the age and composition of the Shelburne dyke, Nova Scotia, and the Messejana dyke, Spain: Canadian Journal of Earth Sciences, v. 35, p. 1110-1115.

Dunn, T. and Stringer, P., 1990, Petrology and petrogenesis of the Ministers Island dike, southwest New Brunswick, Canada: Contributions to Mineralogy and Petrology, v. 105, p. 55-65.

Greenough, J.D., 1992, Cooling history and differentiation of a thick North Mountain Basalt flow (Nova Scotia, Canada): Bulletin of Volcanology, v. 55, p. 63-73.

Greenough, J.D., 1995, Mesozoic rocks, *in* Williams, H., ed., Geology of the Appalachian-Caledonian orogen in Canada and Greenland: Geological Society of America, The Geology of North America, v. F-1, Chapter 6, p. 567-600.

Greenough, J.D. and Papezik V.S., 1986, Petrology and geochemistry of the early Mesozoic Caraquet dyke, New Brunswick, Canada: Canadian Journal of Earth Sciences, v. 23, p. 193-201.

Gunter, W.D., 1967, Feldspars from a tholeiite sill, Grand Manan, New Brunswick [M.Sc. thesis]: Fredericton, University of New Brunswick, 130 p.

Hayatsu, A., 1979, K-Ar isochron age of the North Mountain Basalt, Nova Scotia: Canadian Journal of Earth Sciences, v. 16, p. 973-975.

Helmstaedt, H., 1968, Structural analysis of the Beaver Harbour area, Charlotte County, New Brunswick [Ph.D. thesis]: Fredericton, University of New Brunswick, 196 p.

Helmstaedt, H., Lee, D., Pajari, G.E., and Trembath, L.T., 1966, Co-existing pyroxenes in a tholeiite sill, Grand Manan, New Brunswick: G.A.C. – M.A.C Annual Meeting, Halifax, Nova Scotia.

Hodych, J.P. and Dunning, G.R., 1992. Did the Manicouagan impact trigger end-of-Triassic mass extinction?: Geology, v. 20, p. 51-54.

Jones, L.M. and Mossman, D.J., 1988, The isotopic composition of strontium in the Early Jurassic North Mountain Basalts, Nova Scotia: Canadian Journal of Earth Sciences, v. 25, p. 942-944.

Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesto, M., Bellieni, G., and De Min, A., 1999, Extensive 200 Million-Year-Old Continental Flood Basalts of the Central Atlantic Magmatic Province: Science, v. 284, p. 616-618.

McLeod, M.J., Stringer, P., and Johnson, S.C., 1998, Bedrock geological compilation of the Grand Manan Island area (NTS 21 B/10), Charlotte County, New Brunswick: Department of Natural Resources and Energy, Minerals and Energy Division, Plate 98-51, scale 1:50,000.

McHone, J.G., 2000, Non-plume magmatism and tectonics during the opening of the central Atlantic Ocean: Tectonophysics, v. 316, p. 287-296.

McHone, J.G, 1996, Broad-terrane Jurassic flood basalts across northeastern North America: Geology, v. 24, p. 319-322.

McHone, J.G., West, D.P., Jr., Hussey, A.M., II., and McHone, N.W., 1995, The Christmas Cove dike, coastal Maine: Petrology and regional significance: Geological Society of America, Abstracts with Programs, v. 27, p. 67-68.

Mossman, D.J., Grantham, R.G., and Langenhorst, F., 1998, A search for shocked quartz at the Triassic-Jurassic boundary in the Fundy and Newark basins of the Newark Supergroup: Canadian Journal of Earth Sciences, v. 35, p. 101-109.

Olsen, P.E., 1999, Giant Lava Flows, Mass Extinctions, and Mantle Plumes: Science, v. 284, p. 604-605.

Olsen, P.E., 1997, Stratigraphic record of the early Mesozoic breakup of Pangea in the Laurasia-Gondwana rift system: Annual Reviews of Earth and Planetary Sciences, v. 25, p. 337-401.

Palfy, J., Mortensen, J.K., Carter, E.S., Smith, P.L., Friedman, R.M., and Tipper, H.W., 2000, Timing the end-Triassic mass extinction: First on land, then in the sea? Geology, v. 28, p. 39-42.

Papezik, V.S. and Barr, S.M., 1981, The Shelburne dike, an early Mesozoic diabase dike in Nova Scotia: Mineralogy, petrology, and regional significance: Canadian Journal of Earth Sciences, v. 18, p. 1346-1355.

Papezik, V.S. and Greenough, J.D., 1987, Note on the petrology of North Mountain Basalt from the wildcat oil well Mobil Gulf Chinampas N-37, Bay of Fundy, Canada: Canadian Journal of Earth Sciences, v. 24, p. 1255-1260.

Papezik, V.S., Greenough, J.D., Colwell, J.A., and Mallinson, T.J., 1988, North Mountain Basalt from Digby, Nova Scotia: Models for a fissure eruption from stratigraphy and petrochemistry: Canadian Journal of Earth Sciences, v. 25, p. 74-83.

Pe-Piper, G., Jansa, L.F., and Lambert, R.St.J., 1992, Early Mesozoic magmatism on the eastern Canada margin: Petrogenetic and tectonic significance, *in* Puffer. J.H. and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism: Geological Society of America, Special Paper 268, p. 13-36.

Pe-Piper, G. and Piper, D.J.W., 1999, Were Jurassic tholeiitic lavas originally widespread in southeastern Canada? A test of the broad terrane hypothesis: Canadian Journal of Earth Sciences, v. 36, p. 1509-1516.

Philpotts, A.R. and Martello, A., 1986, Diabase feeder dikes for the Mesozoic basalts in southern New England: American Journal of Science, v. 286, p. 105-126.

Philpotts, A.R., Carroll, M., and Hill, J.M., 1996, Crystal-mush compaction and the origin of pegmatitic segregation sheets in a thick flood-basalt flow in the Mesozoic Hartford basin, Ct.: Journal of Petrology, v. 37, p. 811-836.

Powers, S., 1916, The Acadian Triassic: Journal of Geology, v. 16, p. 1-26, 105-122, 254-268.

Pringle, G.J., Trembath, L.T., and Pajari, G.E., Jr., 1974, Crystallization history of a zoned plagioclase (microprobe analysis of zoned plagioclase from the Grand Manan tholeiite sheet): Mineralogical Magazine, v. 39, p. 867-877.

Puffer, J.H., 1994, Initial and secondary Pangaean basalts, *in* Pangaea: Global Environments and Resources: Canadian Society of Petroleum Geologists, Memoir 17, p. 85-95.

Reidel, S.P. and Tolan, T.L., 1992, Eruption and emplacement of flood basalt: An example from the large-volume Teepee Butte member, Columbia River Basalt group: Geological Society of America Bulletin, v. 104, p. 1650-1671.

Stevens, G.R., 1987, Jurassic basalts of northern Bay of Fundy region, Nova Scotia, in Roy, D.C., ed., Centennial Field Guide - Northeastern Section: Geological Society of America, v. 5, p. 415-420.

Stringer, P. and Burke, K.B.S., 1985, Structure in southwest New Brunswick: Excursion 9: Field Guide for the Annual Meeting, Geological Association of Canada - Mineralogical Association of Canada, 32 p.

Trembath, L.T., 1973, Zeolite mineral assemblage, Grand Manan Island, New Brunswick, *in* Geology of New Brunswick: New England Intercollegiate Geological Conference, Trip A-1, p. 1-3.

Wade, J.A., Brown, D.E., Traverse, A., and Fensome, R.A., 1996, The Triassic-Jurassic Fundy Basin, eastern Canada: regional setting, stratigraphy, and hydrocarbon potential: Atlantic Geology, v. 32, p. 189-231.

Wade, J.A. and Jansa, L.F., 1994, Preliminary interpretation of sub-North Mountain Basalt strata, Dark Harbour, Grand Manan Island, New Brunswick: *in* Current Research 1994-E, Geological Survey of Canada, p. 227-231.

West, D.P., Jr. and McHone, J.G., 1997, Timing of Early Jurassic "feeder" dike emplacement, northern Appalachians: Evidence for synchronicity with rift basalts: Geological Society of America, Abstracts with Programs, v. 29, p. 88.