# Geological Map of the North Mountain Basalt from Cape Split to Brier Island, with Comments on its Resource Potential

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## Introduction

The Jurassic North Mountain Basalt (NMB) forms a prominent cuesta along the southern coastline of the Bay of Fundy, and is contiguous with outliers along the northern side of the bay (Fig. 1). This prominent topographic feature, roughly 200 km in length, is the focus of this paper and the topic of field studies over the past few years (Kontak, 2000, 2002; Kontak *et al.*, 2005). One result of this work is the first geological map of this unit over the length of the North Mountain (Kontak, 2005, 2006), which provides a basis for assessment of the area's resources. Previous work indicated that the NMB contained three distinct flow units, referred to as the Lower, Middle and Upper flow units (Kontak, 2002), and the results of this work have shown that this subdivision can be extended over the area from Cape Split to Brier Island.

The resources of interest in the NMB are high-quality basalt aggregate and zeolites, which happen to be mutually exclusive. This makes it necessary to map the NMB and indicate the geographical distribution of the units and resources of interest. Previous studies have identified the nature of the zeolites within the NMB (e.g. Aumento, 1962, 1966; Colwell, 1980; Pe-Piper, 2000; Pe-Piper and Miller, 2002), but there has been little work on the volcanology of the unit hosting the zeolites, which is necessary for an understanding both the grade and distribution of zeolites in the host basalt.

In this paper the results of mapping the 200 km stretch of the NMB from Cape Split to Brier Island are presented and the nature of the contained resources are discussed in the context of the lava flows that constitute the NMB. There has been increased interest shown in this unit in recent years, in particular for high-quality aggregate, and a map of the area southwest of Digby at Whites Cove is shown since this has been a site of interest. A more detailed paper on the volcanology of the NMB is in preparation and will be published elsewhere (Kontak, in prep.), where it is demonstrated that the sequence corresponds to other continental flood basalt provinces (e.g. 65 Ma Deccan Traps, 17-15 Ma Columbia River Basalt Group) that have analogues in the active flows of Hawaii. This correspondence provides a basis for interpreting the volcanological features of the NMB (see Kontak, 2002, for discussion).

## Geological Setting

Numerous, early Mesozoic continental tholeiitic basalt flows, dykes and sills formed along the eastern margin of North America, concurrent with the infilling of basins with non-marine sedimentary rocks during Pangean rupture, as a prelude to the opening of the present-day Atlantic Ocean. These basaltic rocks are associated with the infilling of nine major rift basins, mostly half-grabens, and collectively form the Newark Supergroup, which is exposed from the Carolinas to Nova Scotia (Fig. 1a; Froelich and Olsen, 1985). These basins, as noted by Olsen and Gore (1989), coincide with the Appalachian gravity gradient that traces the edge of the pre-Pangean North American continental margin (Fig. 1a). The presence of large and extensive dyke systems, such as the Minster Island, Caraquet and Shelburne dykes (Fig. 1a), have been interpreted to suggest that these may be feeder zones for some of the lava flows, including the NMB (e.g. McHone, 1996, 2005; Dostal and Durning, 1998).

The most northerly and largest of these basins is the Fundy Basin of southern Nova Scotia, host to the NMB, which records Triassic-Jurassic sedimentation spaning 65 million years (Wade *et al.*, 1996) and is punctuated with a brief interval of basaltic volcanism coincident with the Triassic-Jurassic boundary (Hodych and Dunning, 1992).

Kontak, D. J. 2006: *in* Mineral Resources Branch, Report of Activities 2005; Nova Scotia Department of Natural Resources, Report ME 2006-1, p. 39-66.

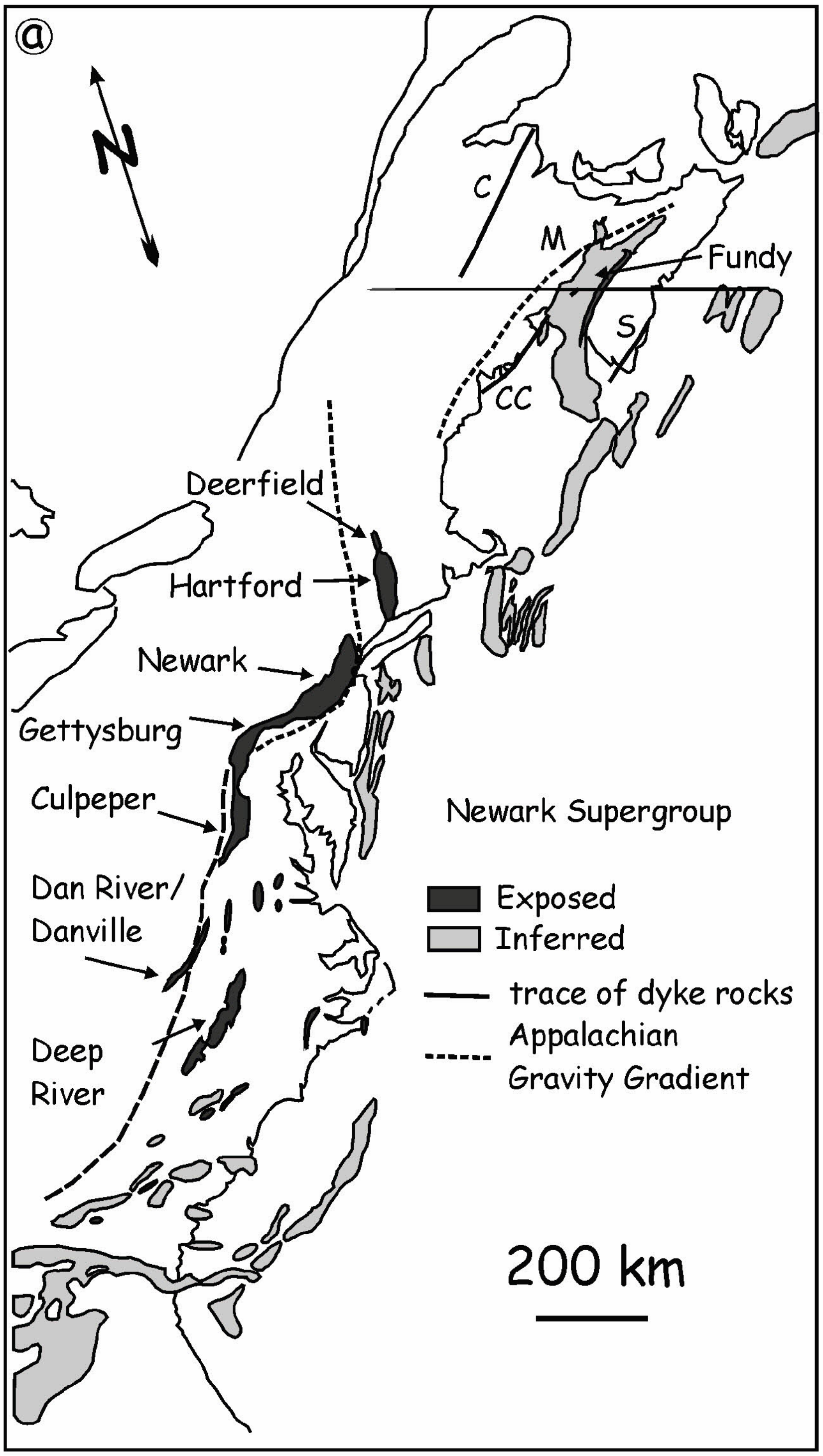
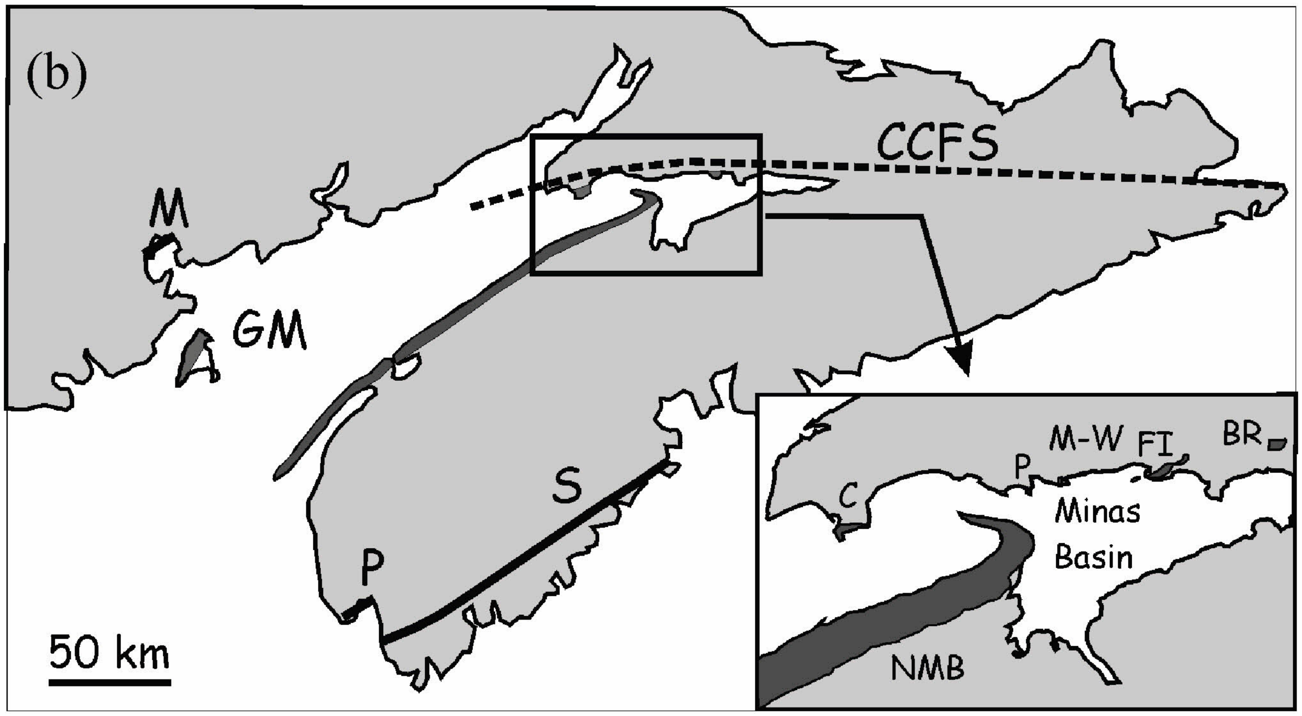


**Figure 1.** (a) Outline of the Newark Supergroup of Eastern North America with some of the more prominent basins named. The most northerly of the onland basins is the Fundy Basin of southern Nova Scotia. The figure has been modified from Olsen and Gore (1989). The bold lines with initials are the traces of Jurassic tholeiitic dyke rocks: S-Shelburne dyke, M-Minster Island dyke, CC-Christmas Cove dyke, C-Caraquet dyke. **(b): (facing page)** Outline of the Bay of Fundy showing the onland extent of the Jurassic North Mountain Basalt and inset figures showing the isolated outcrops on the north shore of the Minas Basin at Bass River (BR), Five Islands (FI), McKay Head-Wasson Bluff (M-W), Parrsboro (P), and Cape d'Or (C). The extent of dyke rocks is shown as before with the addition of the Plymouth (P) dyke and also outcrop of Jurassic rocks on Grand Manan Island (GM). The trace of the terrane-bounding Cobequid-Chedabucto Fault System (CCFS) separating the Meguma (south) and Avalon (north) terranes is shown.



The similar petrological characteristics of the tholeiitic basalts and dyke rocks filling these basins along eastern continental North America (e.g. McHone and Butler, 1984; Greenough and Dostal, 1992a; Puffer, 1992; Pe-Piper *et al.*, 1992; Pe-Piper and Piper, 1999) are relevant to the present work, since in many of the areas these basaltic rocks are quarried for high-quality aggregate, such as the Holyhoke basalt of the Hartford Basin, Connecticut. Thus, present interest in the NMB relates to the fact that this unit is similar to basaltic rock quarried elsewhere in the Newark Supergroup.

The NMB is an Early Jurassic (i.e. Hettangian; 201 Ma; Hodych and Dunning, 1992) sequence of basalts that formed in the Fundy Rift Basin of southern Nova Scotia. The basalts are located both onshore along the Bay of Fundy and offshore in Mesozoic basins southeast and west of Nova Scotia (e.g. Scotian Basin, Georges Basin). Formation of the Fundy Basin and the smaller, related basins within it, was controlled by structures related to the Cobequid-Chedabucto Fault System (CCFS; Fig. 1), a major fault separating the Meguma and Avalon terranes. The formation of depocentres in the Fundy Basin was controlled by normal and oblique-slip faults (Olsen *et al.*, 1989; Wade *et al.*, 1996; Schlische *et al.*, 2002) with multiple periods of movement during and after basin development occurred, best observed along the north side of the Minas Basin.

Rocks underlying the NMB are Triassic, red to pale green-grey, fluvial-lacustrine siltstone and shale of the Wolfville and Blomidon formations, whereas the overlying rocks are lacustrine limestone of the Jurassic Scots Bay Formation and time equivalent, red fluvial-lacustrine siltstone-shale of the McCoy Brook Formation along the north shore of the Bay of Fundy (Fig. 1). Whereas upwards of 250 m of McCoy Brook Formation sediments are exposed, only 9 m of Scots Bay Formation rocks remain as remnant inliers (De Wet and Hubert, 1989). Considerably greater thicknesses of the units are seen offshore, however, as shown in seismic sections and drillholes (Wade *et al.*, 1996). Based on the depositional environment of the enveloping rocks (Hubert and Mertz, 1980, 1984; De Wet and Hubert, 1989; Wade *et al.*, 1996) and the volcanological features of the NMB flows (Kontak *et al.*, 1985), it is inferred that the NMB was deposited sub-aerially and not sub-aqueously, as suggested by some earlier workers (e.g. Lollis, 1959; Sinha, 1970), but pillow basalts have been described in Jurassic basins in the southern part of the Newark Supergroup (Olsen and Gore, 1989). In addition, the paleo-topography during NMB volcanism was characterized by large flat planes with very low slope angles, again as inferred from the nature of both the sedimentary and volcanic rocks.

## Previous Work

Previous mapping that relates to the present study was carried out in the western part of the NMB in the late 1950s and early 1960s. This work contributed significantly to resolving the stratigraphy of the NMB, as it indicated the potential for subdividing the sequence into laterally continuous flow units. The regional mapping of Hudgins (1960) provided the first detailed account of the internal stratigraphy, based on a measured section around the Digby Gut area (Fig. 2). Of particular significance from Hudgins' (1960) work (Table 1) was the observation that zeolites are not found throughout the NMB, but are confined to what he called the "intermediate flows" and that the bottom and upper flows were similarly massive and devoid of zeolites. The area west of Digby, in particular Long Island and Brier Island (Fig. 2), was mapped by Lollis (1959) and Koskitalo (1967), the latter having conducted an exploration program for copper based on analogies with the Precambrian Keweenawan basalt province of the mid-continent region of North America. These authors recognized that the NMB could be conveniently subdivided into three units based on the features of the flows observed in the field. Lollis (1959) provided the nomenclature for these units: the South Shore member (SSM), Middle member (MM), and North Shore member (NSM) for, respectively, the lower massive flow, the amygdaloidal middle flows, and the upper massive flow(s). Assigned thickness were 185 m, 92 m, and 154 m, respectively, based on sections measured in the East Ferry area (Fig. 2). A significant finding of Lollis (1959) was the presence of coarse pegmatite layers in the upper part of his SSM that he referred to as dolerites. As will be seen, these are a common feature of the Lower Flow Unit. More recently, Mallinson (1986) measured a section along the west end of Long Island at Freeport (Fig. 2), integrating this with a diamond-drill core (Koskitalo, 1967) to provide a stratigraphy of: (1) SSM = 112 m of massive basalt; (2) MM = four flows of 1.5 m to 2.5 m along the coast, but seven flows of 3.3 m to 9 m in drill core with a total thickness of 41 m, a rapid change in flow number and thickness that characterizes the middle part of the NMB; and (3) NSM = 61 m of massive basalt. This is a minimum thickness for this unit since the upper contact is not exposed.

The preliminary maps of the NMB provided by these authors, in conjunction with the topographic profile of the land portrayed in digital elevation model (DEM) images, indicated that the three-fold subdivision of the basalt could be extended at least to the Digby area and possibly beyond, as first noted by Kontak (2002). In fact, as shown in the sections to follow, this same stratigraphy can be extrapolated for 200 km to Cape Split.

A final point to note is that the NMB has been penetrated to various depths by several drillholes as part of exploration programs. In the western area (Whites Point on Digby Neck) are recent (2002) drillholes that penetrate the upper part of the sequence to the zeolite-bearing unit. These holes were drilled to assess the nature of the NMB for aggregate, and to define the thickness of the uppermost unit (J. Lizac, personal communication, 2004). In the middle part of the mapped area are several holes drilled in the 1960s (AV series) and 1970s (GAV series), now stored at the Nova Scotia Department of Natural Resources core storage facilities, that were collared in the NMB and in

**Table 1.** Stratigraphy of the North Mountain Basalt measured in the Digby Neck area (after Hudgins, 1960).

| **Flow** | **Thickness** | **Comment** |
|---|---|---|
| Top flow | 9+ m | greenish-black to greyish-black, columnar jointed |
| Second flow | 11+ m | greyish-black massive flow |
| Intermediate flows | 20+ m | varying thickness, fine-grained, zeolite-bearing |
| Intermediate flows | 51+ m | undetermined individual thickness, zeolite-bearing |
| Bottom flow | 90+ m | greenish-black to greyish-black, columnar jointed |

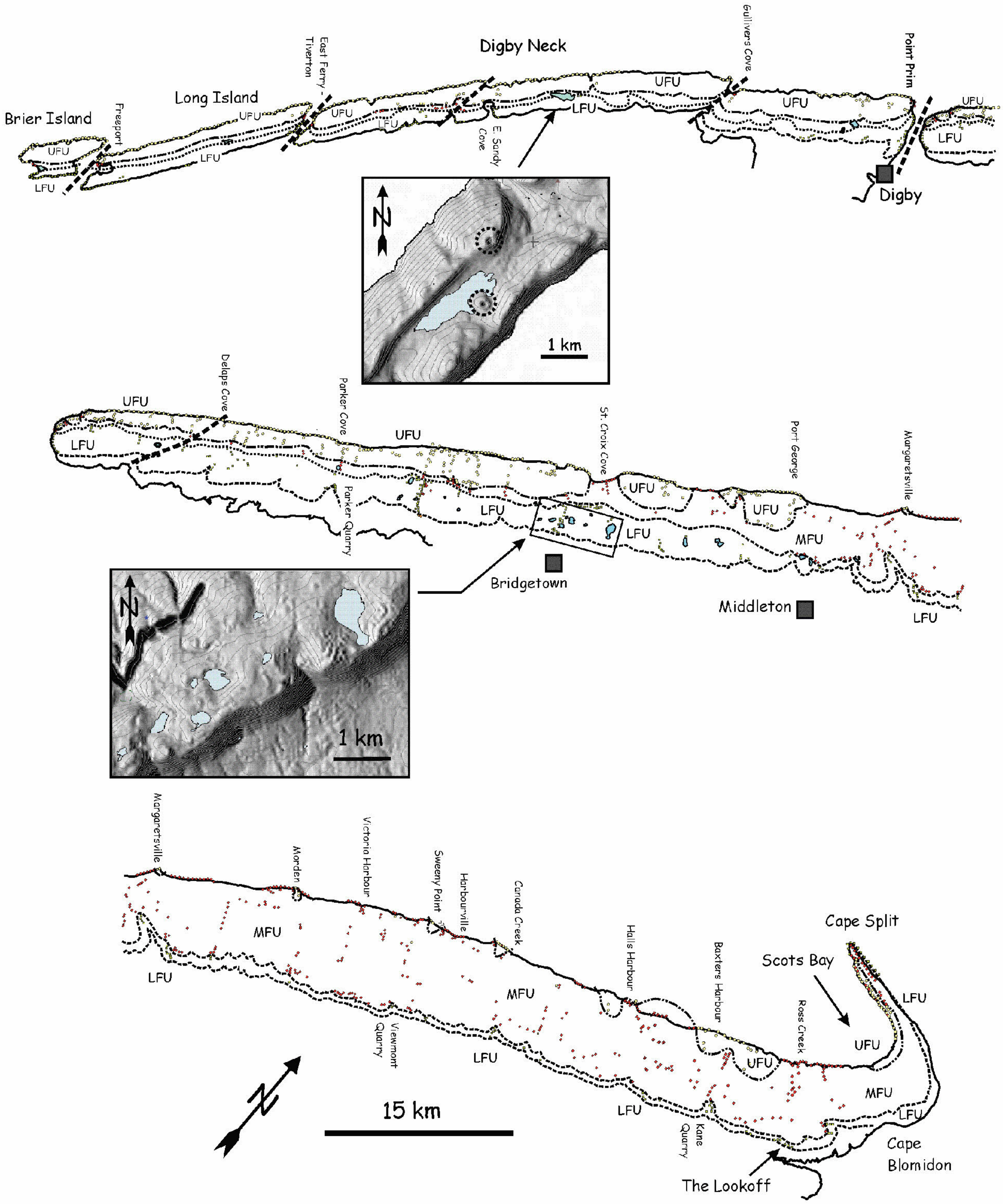


**Figure 2.** Geological map of the North Mountain Basalt from Cape Split in the northeast to Brier Island in the southwest showing the subdivisions of the Lower, Middle, and Upper flow units (LFU, MFU, UFU, respectively). The map has been conveniently broken into three contiguous maps. Place names referred to in the text are indicated. The inset Figures are digital elevation model (DEM) images showing topographic features that may reflect volcanological features (i.e. rootless cone structures). Top image is from along Digby Neck near Lake Midway and the lower one is north of Bridgetown showing the shallow lakes in the LFU. See text for further discussion. The DEM images generated in this figure and others were done using digital data from Nova Scotia Department of Natural Resources web site (NSDNR ArcIMS Application http://gis2.gov.ns.ca/website/nsgeomap).

some cases penetrated to the underlying Triassic sedimentary rocks. Collectively, the core from these drillholes provides a continuous record of the third dimension of the sequence that would otherwise not be accessible.

## Methodology of the Present Study

The present study represents a summary of field work conducted on the NMB from Cape Split in the northeast to Brier Island in the southwest. The results are presented in Figure 2, but a more detailed map incorporating a high-resolution LIDAR DEM (Webster, 2005) will be released as an Open File Map in the near future. As a basis for this map, coastal sections were examined in detail, roads were traversed, and when necessary to fill in areas lacking sufficient outcrop density, stream traverses were made. Detailed mapping of cliff sections was done to assess the nature of the basalt flows and determine their affiliation to modern day flows (cf. Hon *et al.*, 1994) based on analogies with work in ancient lava fields (Self *et al.*, 1996, 1998; Thordarson and Self, 1998). As a complement to the field studies, digital elevation model (DEM) images were integrated to extend boundaries between the flow units where outcrop was lacking or inaccessible (see Kontak, 2002, for detailed discussion). Figure 3 includes the DEM of the Digby area with the outlines of the areal extent of the three flow units to illustrate the application of the methodology for defining the lateral continuity of the three-fold subdivision.

## Nomenclature of Flow Stratigraphy

The nomenclature of the basalt flows used here follows that of Self *et al.* (1997, 1998), which has been used to describe, for example, ancient and recent flows in the Columbia River Basalt Group (CRBG; Self *et al.*, 1996), Deccan traps (Keszthelyi *et al.*, 1999), and the historical 1783-84 Laki flow, Iceland (Guilbaud *et al.*, 2005). This nomenclature was used mainly for flows of the Middle Flow Unit which are of pahoeheo type, as described below.

At the top of this classification is the lava flow field, which describes the entire lava product of the eruption over its duration. In this context, the NMB is a flow field, including all three units recognized. A ‘lava flow’ is a lava body formed by solidification of a single outpouring of lava from a vent and would correspond, therefore, to a single episode of eruption, as part of a longer-duration event. Morphologically such a flow has well-defined boundaries and a continuous flow top, and its vertical scale is metres to tens of metres with aerial extent measured in tens to thousands of square kilometres. Hence, the three units of the NMB are considered in this context, with the LFU and UFU as single flows, but the MFU comprising multiple lava flows. From the observations of Hon *et al.* (1994), based on observations of active flows in Kilauea, it is now realized that pahoehoe flows constitute continuous lobate segments of sequentially emplaced lava or lava lobes. Herein, a ‘lobe’ is considered to represent a lava entity surrounded by its chilled crust. In some circumstances, individual lava lobes are preserved and are evidence of such emplacement and growth of a lava flow. The flows may locally rupture, with lava breaking through the crust; at the front of flows these are ‘lobe tongues’ and on surface they are ‘outbreak lobes’, both of which are observed in the NMB.

Outbreak lobes along the advancing margins of a lava flow may eventually lead to coalescence of the lobes to form a large, continuous crust. The continued growth of this flow is internal or endogenous, and the process of ‘inflation’ is used to describe such vertical expansion of the flow. Keszthelyi *et al.* (1999) refer to such a body as a ‘sheet flow’ and the smaller, discrete parts of it as ‘sheet lobes’. If the coalescence has not been everywhere seamless and inflation uniform, then an irregular surface results and is described as ‘hummocky’. The dome-shaped features on such surfaces are called ‘tumuli’ (singular is tumulus), whereas depressions are ‘lava-rise pits’. Tumuli structures may also owe their origin to excess pressure generated due to constrictions in lava tubes feeding the flows. The fractures and openings created along the margins of inflating flows are ‘inflation clefts’, and the term ‘crack’ is used for openings not generated by inflation.

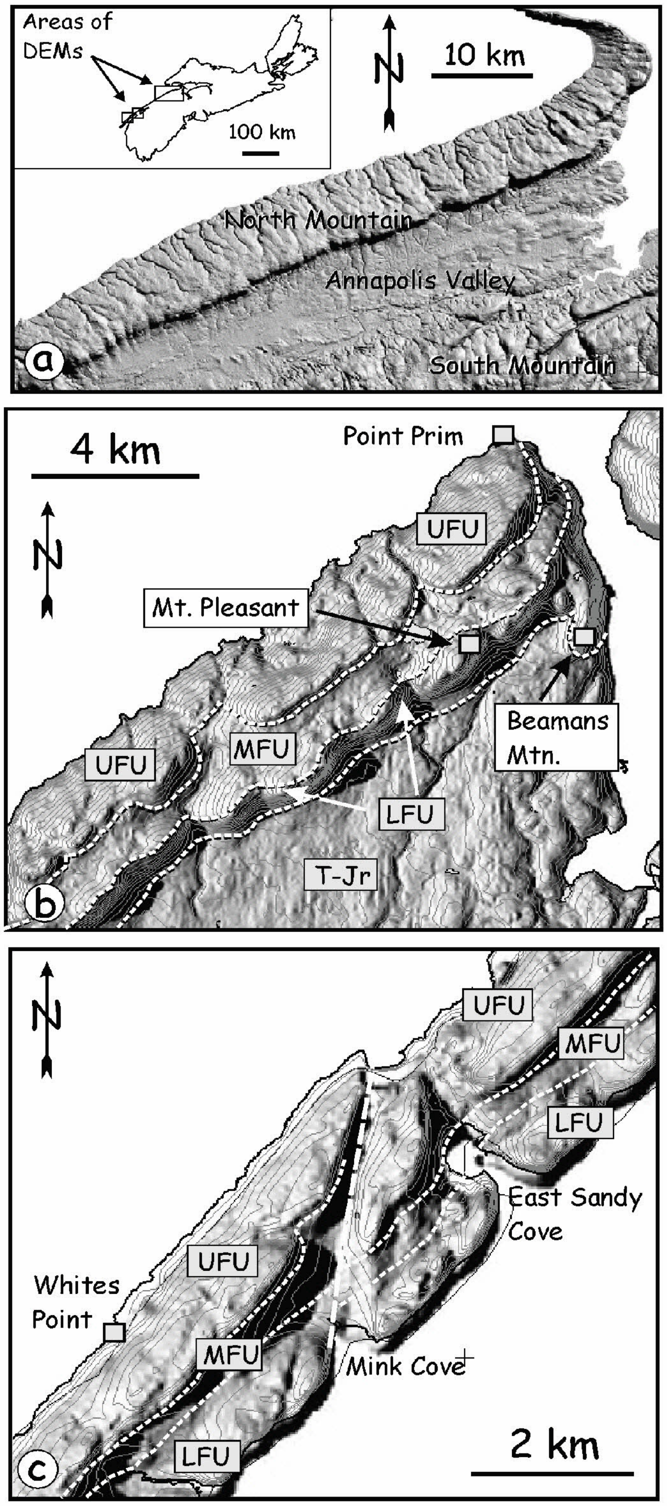


**Figure 3.** Digital elevation model (DEM) images of the Annapolis Valley region of southern Nova Scotia. (a) The North Mountain, Annapolis Valley and South Mountain physiographic areas highlighted with DEM image. The image is viewed with light at Az45, Alt45, Z10. (b) The Digby area showing the trace of the three flow units of the North Mountain Basalt, the Lower, Middle and Upper flow units, LFU, MFU and UFU, respectively, and the area underlain by Triassic-Jurassic (T-Jr) sedimentary rocks. The DEM image is viewed with light at Az315, Alt45, Z10.(c) Area west of Sand Cove on Long Island (see Fig. 2) showing the trace of the three flow units of the North Mountain Basalt, the Lower, Middle and Upper flow units. The DEM image is viewed with light at Az270, Alt45, Z05.

The interior of inflated lava flows can be divided into two distinct parts, one which initially solidified and thickened during the inflation process and the remainder which was active lava flow. These parts of the flow are referred to, respectively, as the 'upper lava crust' and the 'lava core'. Hon *et al.* (1994), based on measurements of active Hawaiian flows, determined that thickness of the upper crust was proportional to the duration of time that the interior of the lava flow was replenished, the relationship being: $t = 164.8 \times C^2$, where t is time (h) and C is the upper crust thickness (m). The only assumption here is that the thermal properties and heat transfer for the NMB flows are similar to inflated Hawaiian flows. Keszthelyi *et al.* (2004) have examined this issue and found that realistic differences in thermal properties do not translate into any more than 25% error. Thus, it requires 7 ± 1.4 days to form a 1 m thick crust and 5 ± 1 months of inflation to form a 5 m thick crust As will be seen below, the individual flows constituting the MFU have upper crusts $\leq$1-2 m thick, hence duration of flow emplacement was on the order of 1 to 4 weeks.

## Stratigraphy and Distribution of Flow Units

A proposed stratigraphic framework for the NMB is a modification of that in Table 1 and was first presented by Kontak (2002) where the terms Lower, Middle and Upper flow units (represented here as LFU, MFU and UFU) are used as proxies for the terms introduced by Lollis (1959) and Hudgins (1960). The term unit is used in the context of a flow field: each of the three flow units describes the end product of distinct, long-lived eruptions based on their field characteristics. The flow units are described in more detail below. What is important in terms of the proposed stratigraphy and map (Fig. 2) is that these units are internally consistent in their features and, as seen on the map, can be traced laterally for ~200 km. The vesiculated and altered nature of the MFU makes it possible to construct the accompanying map and allow integration of DEM data, for two reasons: (1) the MFU is readily recognized by its friable nature, red oxidized flow tops, and multiple flows, and (2) the MFU is topographically recessive compared to the relatively fresh, massive flows above and below it. In a similar manner, the fresh, massive homogeneous nature of both the LFU and UFU is reflected by the topography of the Annapolis Valley and Digby Neck areas (Fig. 3). In the former case, the LFU defines the wall of the prominent cuesta along the Annapolis Valley from Cape Blomidon to Digby. West of Digby the UFU becomes the prominent topographic feature with the MFU occupying a topographic depression between it and a smaller topographic high underlain by the LFU to the south (Fig. 3c).

The extent of the flow units is first discussed with respect to their distribution on the map before describing other details of the units. The geological map reveals several first-order features about the NMB. (1) The distribution of the flow units is not uniform along their strike length. The LFU appears widest in plan view from Digby to Middleton; west and east of there the LFU narrows. (2) The MFU is narrowest west of Bridgetown, but abruptly broadens in areal extent east of there, whereas the LFU narrows. Where the UFU is breached and exposes the MFU, as occurs at St. Croix Cove, the MFU is more extensive. (3) The UFU is almost absent in the central to eastern part of the North Mountain, occurring as isolated patches at the following sites (from west to east) - St. Croix Cove area, Port George, Margaretsville, Morden, Sweeney Point, Canada Creek, Halls Harbour, Baxters Harbour - before becoming continuous again along the coastline towards Cape Split. Along Digby Neck the UFU forms the dominant topographic feature (Fig. 3c), much as the LFU does in the central and eastern part of the North Mountain. (4) Topographic offsets along the strike of the North Mountain are also reflected in the offsets of contacts of the flow units, this being most apparent along the waterway passages between the land masses along Digby Neck (e.g. between Digby Neck and Long Island at East Ferry).

A long section of the NMB was constructed using measured sections and drillhole logs to assess the stratigraphic thicknesses of the units along the North Mountain (Fig. 4). This work is considered preliminary, as more detailed studies will result in modification, but sufficient data are available to illustrate some significant variation. First, there is a change in thickness of the LFU from west to east. The thinnest part of this unit occurs at Brier Island

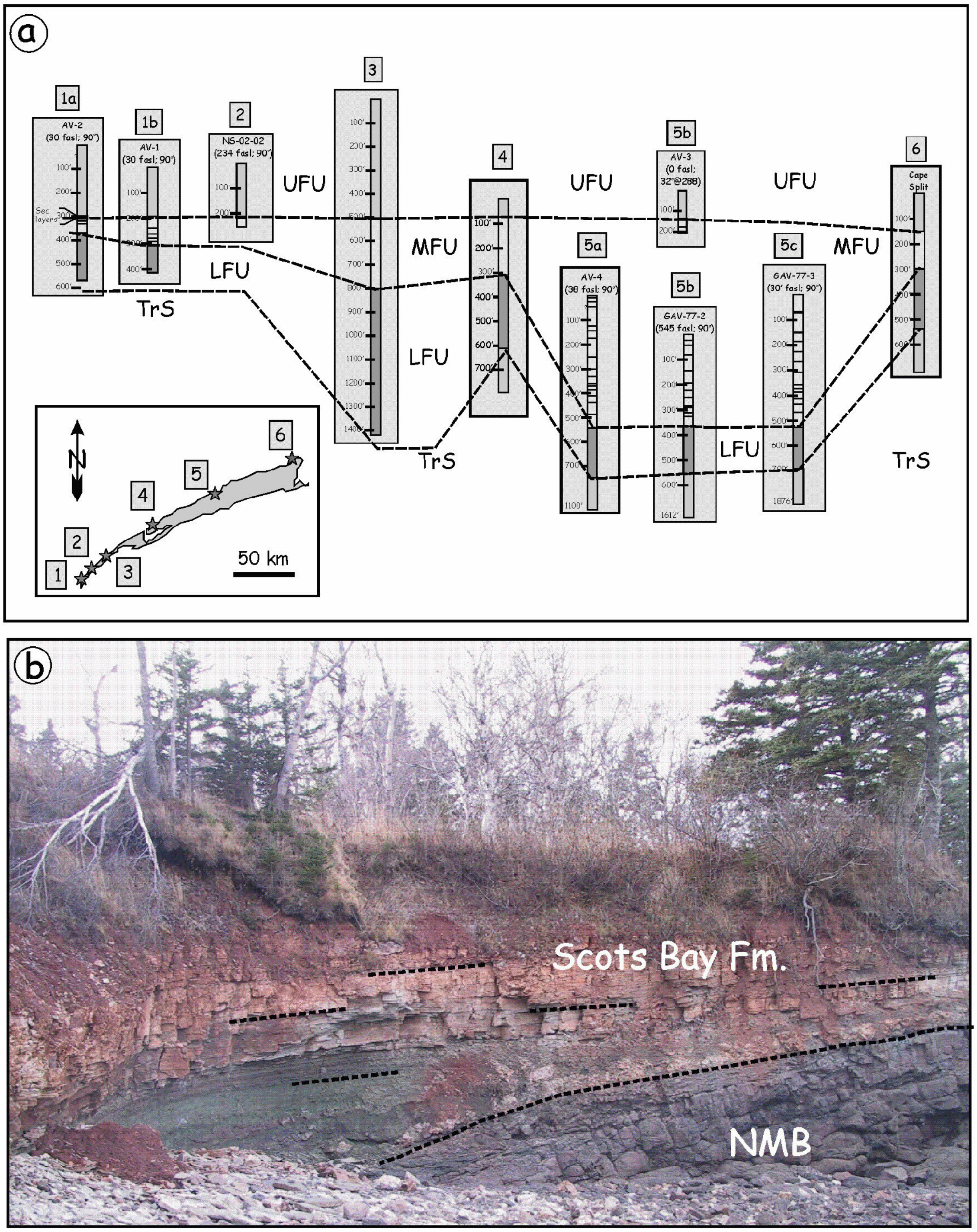


**Figure 4.** (a) Longitudinal section showing the extent of the Lower (LFU), Middle (MFU) and Upper (UFU) flow units in the North Mountain Basalt. The grey area in the inset box shows the areal extent of outcropping Triassic-Jurassic rocks along the North Mountain with locations of the sections. Section was constructed based on logging drill cores (sections 1, 2, 5) and using constructed sections at East Ferry-Tiverton (section 3; Lollis, 1959), Digby (section 4; Hudgins, 1960 and this study) and Cape Split (section 6; this study). Note that in the drill core sections (1, 5) individual sheet flows are indicated for the MFU. For purposes of construction, the top of the MFU is assumed to represent a paleohorizontal surface, as discussed in the text. Abbreviations follow: fasl - feet above sea level, TrS - Triassic sedimentary rocks (i.e. Blomidon-Wolfville formations). (b) The contact between the Middle Flow Unit of the North Mountain Basalt and overlying Scots Bay Formation sediments along the coast at Broad Cove northeast of Ross Creek (see Fig. 2). The dashed lines trace the contacts between units.

(sites 1a and 1b), whereas the thickest section is at site 2 near East Ferry. Along the length of the North Mountain the unit appears to be fairly uniform in thickness from sites 4 to 6, but sections perpendicular to its strike suggest otherwise (see below). A similar, but more dramatic variation in thickness is observed for the MFU. The MFU is thickest in the area of maximum areal extent (Fig. 2), such as site 5 where there are at least 16 distinct flows of ~170 m aggregate thickness. This section of MFU contrasts markedly with the presence of only 4 to 7 flows of ~20 to 40 m aggregate thickness for the MFU in the Brier Island-Freeport area (site 1a and 1b). The apparent thickness of the UFU is greatest in the western end of the long section towards Digby and west, but this is considered an artifact of the exposure, with much of the UFU underlying the Bay of Fundy in the central and eastern areas.

An important aspect of the long section is that site 2 is off the section compared to the other localities. Site 2 is a more southerly section for the LFU, which impacts the interpretation. This relationship is illustrated with the use of a cross section near site 5, where outcrops and diamond-drill holes provide good control points (Fig. 5) (note that Kontak, 2002, presented a similar section). The section shows the following characteristics. (1) The thickness of the LFU decreases northward from the valley wall to the diamond-drill hole. Kontak (2002) suggested that this change in thickness, also seen in other similar sections, may relate to pre- to syn-volcanic faulting, discussed in further detail below. (2) A dip of 3° can account for the base of the LFU contact, rather than a dip of 5-8° that has been used as a regional average for the flows (e.g. Hudgins, 1960; Lollis, 1959; Mallinson, 1986). This low dip is significant, as pahoehoe flows that dominate the MFU only occur where regional topography is ≤2-3°; steeper dips would favour a'a flows, which are absent in the NMB. The sections in Figure 5c and 5d show a possible interpretation of the structural control on the distribution of the NMB during deposition and subsequently, to explain the present day variation in thickness of the LFU from east to west.

Not shown on the long section, but apparent from field work, is the presence of Jurassic Scots Bay Formation sediments resting with a slight disconformity on the MFU in the Scots Bay area east of Ross Creek (Figs. 2, 4b). This is the only place such a relationship is observed along the coastline from Cape Split to Brier Island, although a similar relationship is apparently seen along the north side of the Bay of Fundy east of Parrsboro (observations of Kontak and see below). The implication of the observation at Ross Creek is that, for some reason, the UFU was never deposited in this area.

# Geology and Volcanology of the North Mountain Basalt

## Contact between LFU and the Underlying Triassic Blomidon Formation

The contact between sedimentary rocks of the Triassic Blomidon Formation and overlying LFU basalt has been observed at isolated localities along the length of the NMB, with similar relationships seen along the spectacular exposure of the NMB and underlying sediments at Five Islands, Colchester County, where Olsen *et al.* (2005 and references therein) describe the contact in detail. In summary, fine-grained, red-brown terrestrial clastics of the Blomidon Formation change dramatically and give way to a 60-100 cm thick sequence of white, greyish-white or greenish-white sediment of distinctly more granular nature. The basalt at the contact is aphanitic, black to brownish-black, and rubbly for 10-20 cm before gradually coarsening. In some cases veins of gypsum cut the base of the NMB. What is crucial from the nature of the basalt is that the inferred fluvial-deltaic nature of the sedimentary deposits indicates that the overall landscape immediately preceding volcanism was generally flat-lying.

## Lower Flow Unit (LFU)

The LFU outcrops extensively on the south face of the North Mountain along the Annapolis Valley, and is also accessible along road cuts and stream sections. Southwest of Digby, however, there is a marked change in topography and the LFU occurs, instead, along the southern coastline of Digby Neck and contiguous Long and Brier islands. The LFU is generally a massive, dark greenish to dark grey-

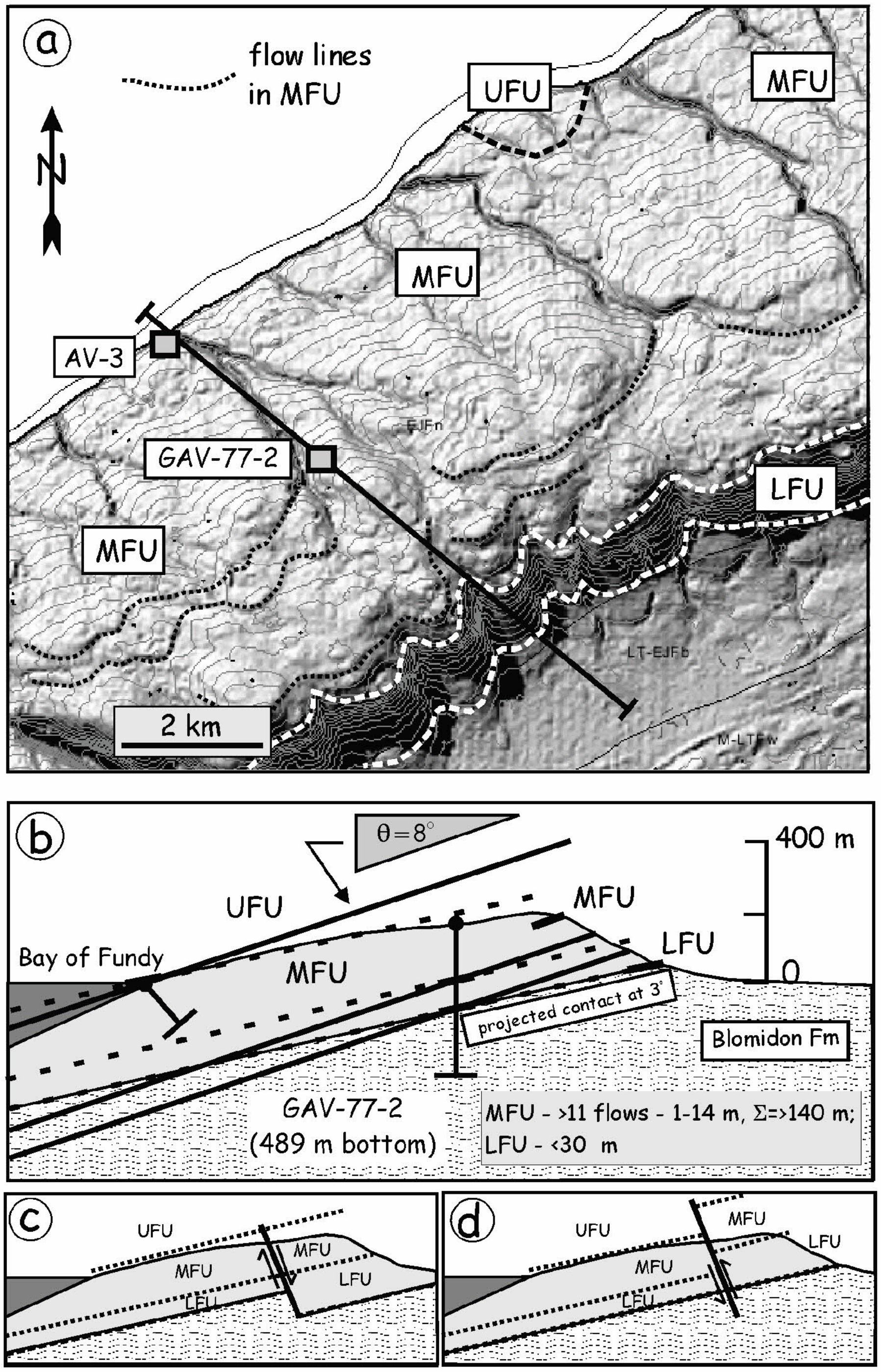


**Figure 5.** (a) Digital elevation model (DEM) image (sunlight from Az315, Alt45, Z10) of the Morden area showing the extent of the Lower, Middle and Upper flow units of the North Mountain Basalt. The dashed black lines are traces of flow sheets of the MFU inferred from the topography. The location of diamond-drill holes (AV-3, GAC-77-3) and the trace of the cross section shown in Figure 4b are highlighted. (b) Cross section from southeast to northwest across the North Mountain contrasting the geology inferred from the surface control points and that constrained by the drill cores. The dashed lines are contacts drawn assuming a regional dip of 3°, whereas the black line traces the contacts assuming an 8° dip. See text for further discussion and implications. (c, d) Interpretative sections using the data in Figure 4b, first showing the possible geological setting ca. 200 Ma with a down-faulted basin formed into which basalt was deposited, first the LFU into different depth basins, hence the reason for the variation in thickness, and then the MFU and UFU of similar inferred thickness. Later reverse movement along the same fault created the present geological section.

green basalt with microcrysts of plagioclase and pyroxene with variable mesostasis (≤10-15%) present. The upper and lower contacts are chilled, as observed in drill core and rare outcrops, and these parts of the LFU are devoid of phenocrystic phases, although some microlites occur. The lower contact has a thin (≤10-15 cm), chilled zone with trace amygdules and rare pipe vesicles, both containing zeolites. In only one locality were abundant amygdules seen in altered basalt near the base of the LFU (Fig. 6a), possibly where the flow intersected a water-rich environment. The upper contact is locally vesiculated and occluded with zeolite, silica or a green-black mica. The best exposure of such vesiculated basalt is seen at Kane quarry west of Cape Blomidon (Fig. 2), where several 10-30 cm thick layers of amygdule-rich, altered basalt occur. In other cases the upper zone consists of several metres of fresh, fine-grained basalt. Rarely the upper zone is red-brown due to oxidation prior to deposition of the MFU. Throughout the main part of the LFU the texture is generally homogeneous, medium grained and holocrystalline, but locally the texture may be both finer and much coarser grained, in multi-metre thick sections best observed in drill core. Some rare core sections show centimeter thick seams of aphanitic basalt.

The most significant feature of the LFU is the presence of horizontal layers of mafic pegmatite (cm, but rarely ≤2-3 m) with or without thin (≤1-2 cm) granophyric, sometimes rhyolitic, bands that occur mainly in the upper (i.e. top 30-50 m) part of the flow (e.g. Fig. 6b), although at one locality (Beamans Mountain, Fig. 3b) it is lower in the flow. This layering in the LFU, first reported in detail by Lollis (1959) along the section exposed at Petite Passage between Digby Neck and Long Island, has since been recognized at several localities and is also seen in drill cores from the LFU. The zones of pegmatite layers have not been traced laterally due to limited exposure, but are inferred to continue for several kilometres based on the exposures on both sides of Petite Passage at East Ferry. The most accessible and best exposed occurrences of multi-layered pegmatites (≤2-3 m thick) are exposed in quarry faces at Mt. Pleasant and Beamans Mountain (Fig. 3b). At these latter localities, the pegmatite layers consist of three components, the first two of which dominate: (1) leucocratic material consisting of granophyre (Fig. 6c); (2) Fe-rich pyroxene (to $En_{15}Fs_{70}Wo_{15}$; Fig. 6e) with comb textures that locally constitute 80% of the layers; and (3) red-brown glassy material, now altered to stilpnomelane, with vesicles (gas escape features) that occur as veins cross-cutting the other material and also extending into the host basalt. This material is considered to represent mobilized, rhyolitic melt. These occurrences have been described in a preliminary manner by Baldwin (2004) and more detailed work continues. The layered pegmatites of the LFU are similar in their stratigraphic position and petrological features to the exceptional examples of layered pegmatites exposed at McKay Head on the north side of the Bay of Fundy (Fig. 1b; Greenough *et al.*, 1989; Greenough and Dostal, 1992b, 1992c). The pegmatitic layers are considered to be a product of extreme fractionation of the residual melt and may, in part, represent immiscibility.

Joints were well developed throughout the LFU with both colonnade (to 2.5 m) and entablature types (<40 cm width) observed (Fig. 6d, f, g). The exposure in some places indicates that a single type dominates, as at Parker Mountain quarry or East Sandy Cove (Fig. 2), whereas in others there is a complicated mixture in terms of both size and orientation (e.g. Kane quarry, Fig. 2; or Viewmont, Fig. 6d, g). In fact, based on the complicated nature of joints at the Kane quarry, Stevens (1980) suggested up to five flows occurred, but Kontak *et al.* (2005) interpret this as a single flow with the complicated fracturing a later, superimposed feature. Where vertical exposure permits, uniform orientation of columns is followed through the entire LFU (e.g. Parker Mountain quarry), whereas along coastal sections the continuity of joint development can be followed over great lateral distances. In some localities, intense fracturing has imposed a platy or hackly jointing, manifest as triangular columns, as exposed along the west side of Digby Gut. This jointing is considered to relate to movement along the terrane-bounding Cobequid-Chedabucto Fault System (Fig. 1b; and work in prep.).

Examples of circular structures of tens to several hundred metres width have been noted in the LFU by many workers, based on air photo interpretations or outcrop distribution (e.g. Lollis, 1959; Hudgins, 1960; Koskitalo, 1967; Stevens,

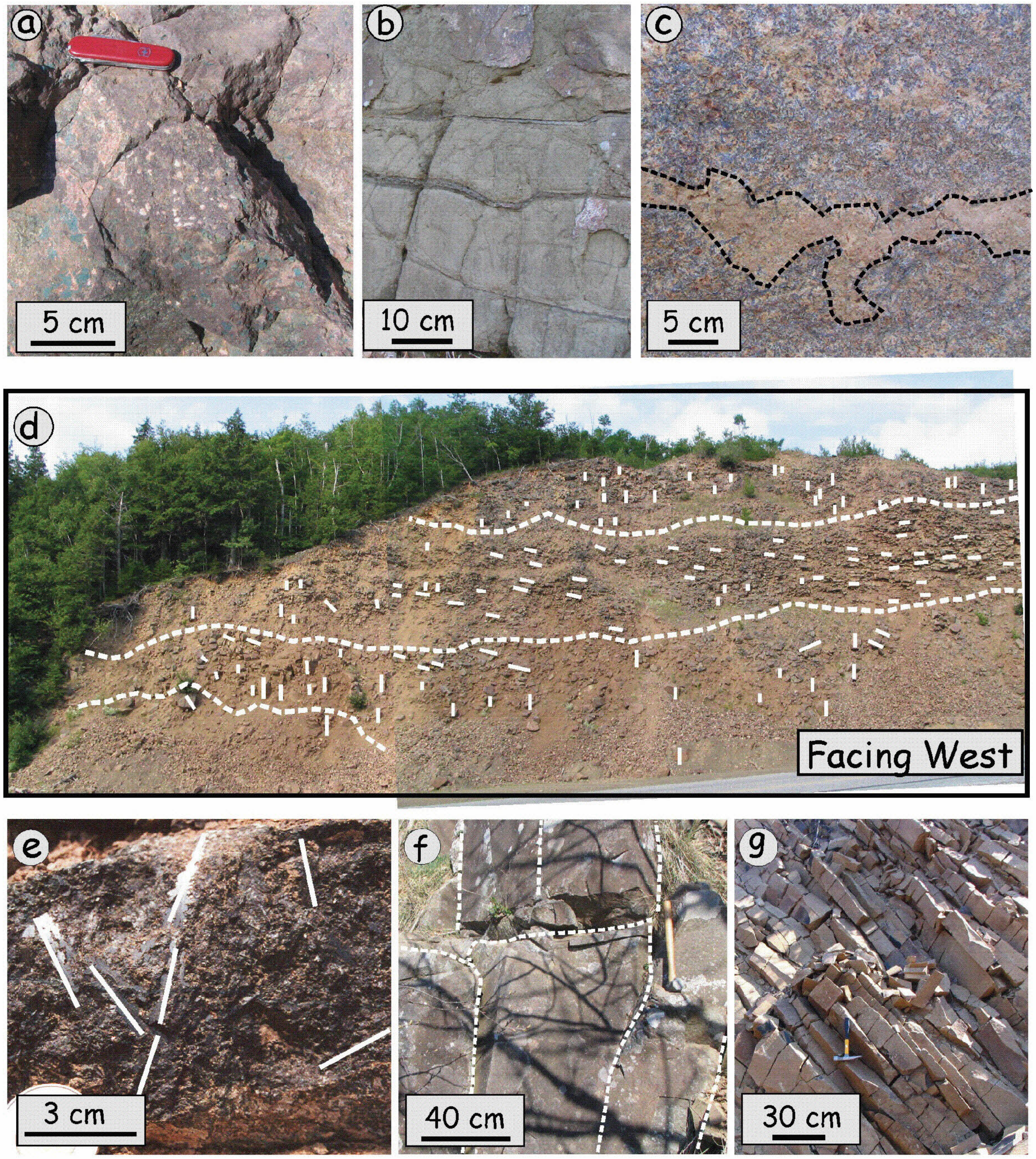


**Figure 6.** Photographs showing features of the Lower Flow Unit (LFU) of the North Mountain Basalt. (a) Amygdaloidal-rich zone near base of the LFU along Stewart Road east of The Look Off. This basalt is fine-grained and grey-red-brown, in contrast to the medium- to coarse-grained fresh basalt only a few m above in non-vesiculated material. (b) Layered felsic bands (granophyre) in the upper part of the LFU above the quarry at Viewmount. Note the regular spacing of the 2-3 cm thick layers. (c) Pegmatite layer cutting basalt at Beamans Mountain quarry (see Baldwin (2004) for details) showing zone of pyroxene-plagioclase cut by a 4-5 cm thick, irregular seam of granophyre. (d) Face of quarry wall in middle of LFU at Viewmount. The dashed white lines separate the flow into distinct areas based on the size and orientation of columns, whereas the white bars are the inclinations of the columns. The large columns are at the base and there is a distinct zone in the middle where the columns are shallowly inclined. (e) White lines trace pyroxene grains. (f) Massive basalt near top of the LFU at The Look Off, north of Canning. Note the wide, sub-vertical colonnade jointing and very massive nature of the basalt. Hammer for scale. (g) Entablature jointing, inclined about 40° east, in the upper part of the LFU in rock quarry at Viewmount (see Fig. 6d).

1980; G. Prime, personal communication, 2002). The use of digital elevation models (DEM) has revealed many more such structures (inset Fig. 2 and see Kontak *et al.*, 2005) and with higher resolution LIDAR DEM these are even better defined, with a regularity of spacing also indicated (Webster, 2005; Webster *et al.*, 2006). Also present locally are shallow (<14-20 m) lakes along the top of the LFU in, for example, the Bridgetown area (inset Fig. 2), which are presumed to be water-filled occurrences of such structures. Although some have suggested these textures may be artifacts of exposure and erosion (Koskitalo, 1967), others have argued for a primary volcanogenic origin (e.g. vents; Lollis, 1959), whereas a glacial origin is considered unlikely (I. Spooner, personal communication, 2004). Recently, Webster *et al.* (2006) related their origin to phreato-magmatic activity, the release of late-stage volatiles of either cognate or exotic origin, by analogies with structures of similar size and shape in the Miocene Columbia River Basalt Group (CRBG) and historical flows in Iceland. In the Icelandic case these features, referred to as 'rootless cones', cluster in areas where flows converged with pre-existing water-rich environments (Guilbaud *et al.*, 2005).

Finally, isolated cases of sedimentary dykes penetrating the LFU along cooling joints or more irregular fracture patterns are rarely seen (e.g. Parker Mountain quarry), but these are not as spectacular as those at McKay Head, on the north shore of the Minas Basin (Fig. 1; Kontak *et al.*, 2005).

## Middle Flow Unit (MFU)

The MFU outcrops extensively along the coastline, particularly northeast of Port George to Scots Bay, and underlies much of the topographically flat North Mountain proper. The MFU is easily recognized due to the presence of numerous, thin (≤10-20 m) sheet lobes with all the features of inflated pahoehoe flows, as noted above (flow lobes, tumuli, vesicle zonation, grain-size variation, etc.), and rubbly character due to subsequent weathering. The maximum number of sheet flows observed in one area is sixteen, as seen in drill logs (site 5 in Fig. 4a), but this a minimum since the contact with the overlying UFU is not observed.

The sheet flows constructing the MFU are seen to develop as either a series of flows of similar dip and uniform thickness, or as more architecturally complex sequences. Two sections are used to illustrate this (Figs. 7 and 8). In the first case, a 4.5 km coastal section northeast of Margaretsville follows three to five flows of generally uniform thickness, but with obvious irregularities (Fig. 7), the most notable being pinch and swell features and in some cases complete pinching out (e.g. flow 3; Fig. 7). These irregular features probably reflect the presence during formation of pressure ridges, subsurface obstructions, and incipient formation of tumuli. A closer view of such complex features is shown in Figure 9a, where several thin sheet lobes are seen to intersect, probably reflecting the coalescence of several flow lobes. Seen within the sheet flows is the development of vesicle zones (see Fig. 8), common in pahoehoe flows, which are more fully described below. Locally abundant silica-zeolite veins probably reflect occlusion of extensional features created in the brittle flow crust during inflation.

A more extreme case of irregular architecture is seen in a coastal section at Morden where well-developed tumuli are preserved (Figs. 8 and 9), similar to those described in ancient flows from the CRBG (Thordarson and Self, 1998) and recent flows in Iceland (Rossi and Gudmundsson, 1996). At Morden the features are developed in the uppermost flow sheet of the MFU, directly below the UFU. Just past this section, the flows are more regular in thickness, hence the tumuli are locally developed. An important feature seen in this section is the presence of vertically plunging vesicle cylinders (see below), which indicate that the dome and basin configuration of the flows are tumuli structures and not of tectonic origin (folds). In addition, the vertical orientation of vesicle cylinders indicates minimal post-extrusion tilting of the flows.

The individual sheet flows that collectively make up the MFU have a regular internal vesicle zonation similar to that observed and documented in other pahoehoe flows (Abule *et al.*, 1988; Cashman and Kauahikaua, 1997; Self *et al.*, 1996, 1997; Thordarson and Self, 1998). Vesicle development takes place in the following sequence.

1. Chilled base (≤10-20 cm) with disseminated, round- to irregular-shaped amygdules and vesicles,

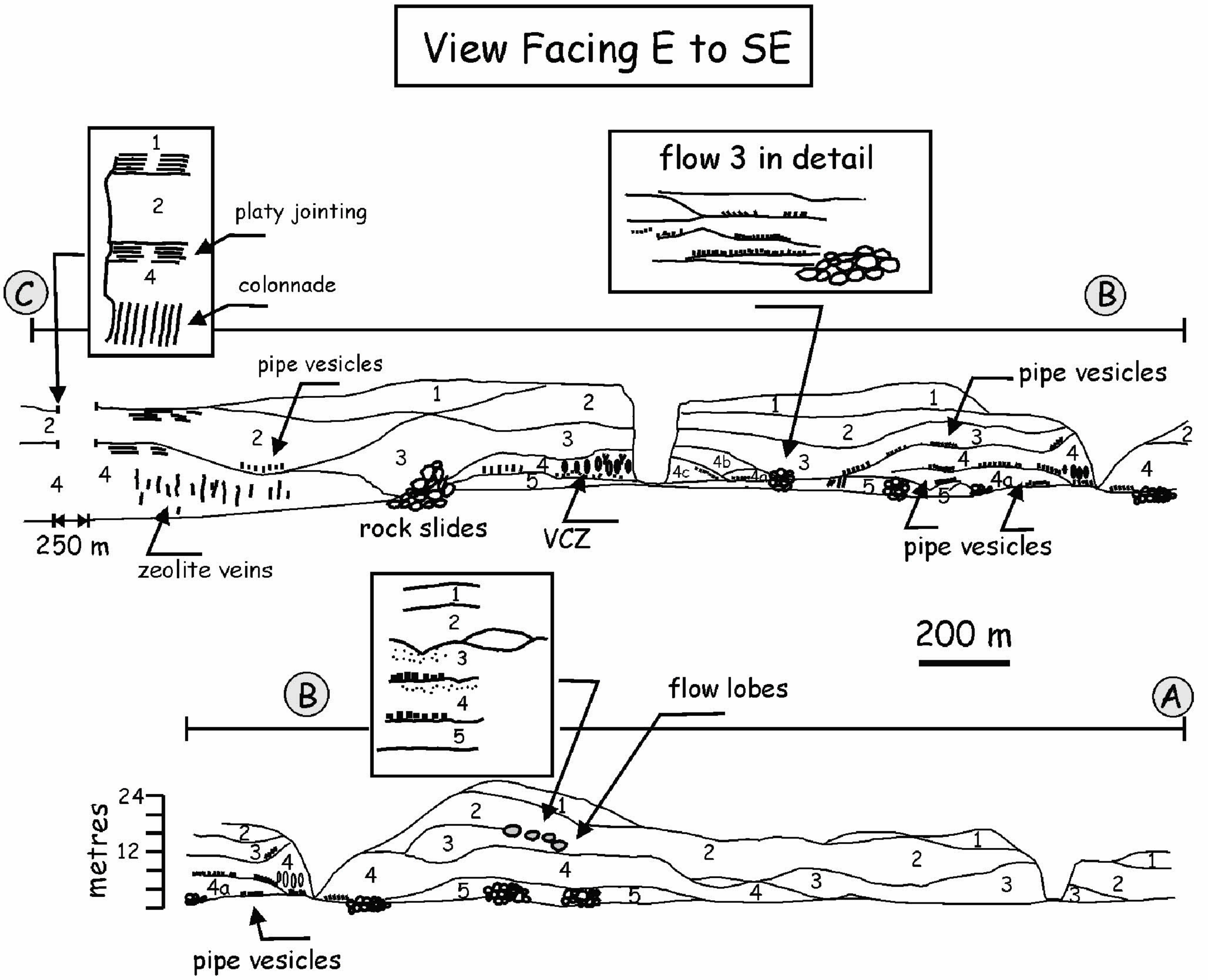


**Figure 7.** Long section (ca. 4.5 km) paralleling the coastline from Margaretsville northeastwards to Bishop Creek (see Fig. 3) showing a section of the upper part of the Middle Flow Unit of the North Mountain Basalt. This figure has been modified after Kontak (2002). Note that flow 5, only partly exposed in the section, outcrops extensively during low-tide conditions. The section shown commenced northeast of Lighthouse Point past the village wharf at a concrete retaining wall in front of a cottage (see Kontak *et al.*, 2005, for details). Inset figures show details of flows at different localities, in particular the flow lobes seen in sheet flow 3. Note that there is a vertical exaggeration and a 250 m break in the northeast part of the section (towards point C), where the stratigraphy remains unchanged. VCZ = vesicle cylinder zone.

and inclined pipe vesicles. The pipe vesicles are important features, as they are strain indicators and indicate flow movement (Fig. 10a, b).

2. Core zone (≤1-4 m, rarely 8-10 m) with massive texture, void of macroscopic vesicles, and rarely is jointing well developed. There are commonly two very distinct features in this zone: (1) a nodular texture with knobs of 1-2 cm diameter standing above the host, having been highlighted by differential weathering (Fig. 10c and Morden section in Fig. 8). These areas are discontinuous, the knobs vary in density and, although their origin remains unresolved, autobreccia has been suggested (G. McHone, personal communication, 2004); and (2) fracture-controlled, discontinuous discoloration zones of ≤20-30 cm height and laterally continuous for tens of metres. Joints when developed in the MFU, are best seen in the core zones of the flows. Most common are platy joints in the upper parts of sheet flows, but columnar joints also occur. The best example of columnar joints is seen at Ross Creek where well-developed,

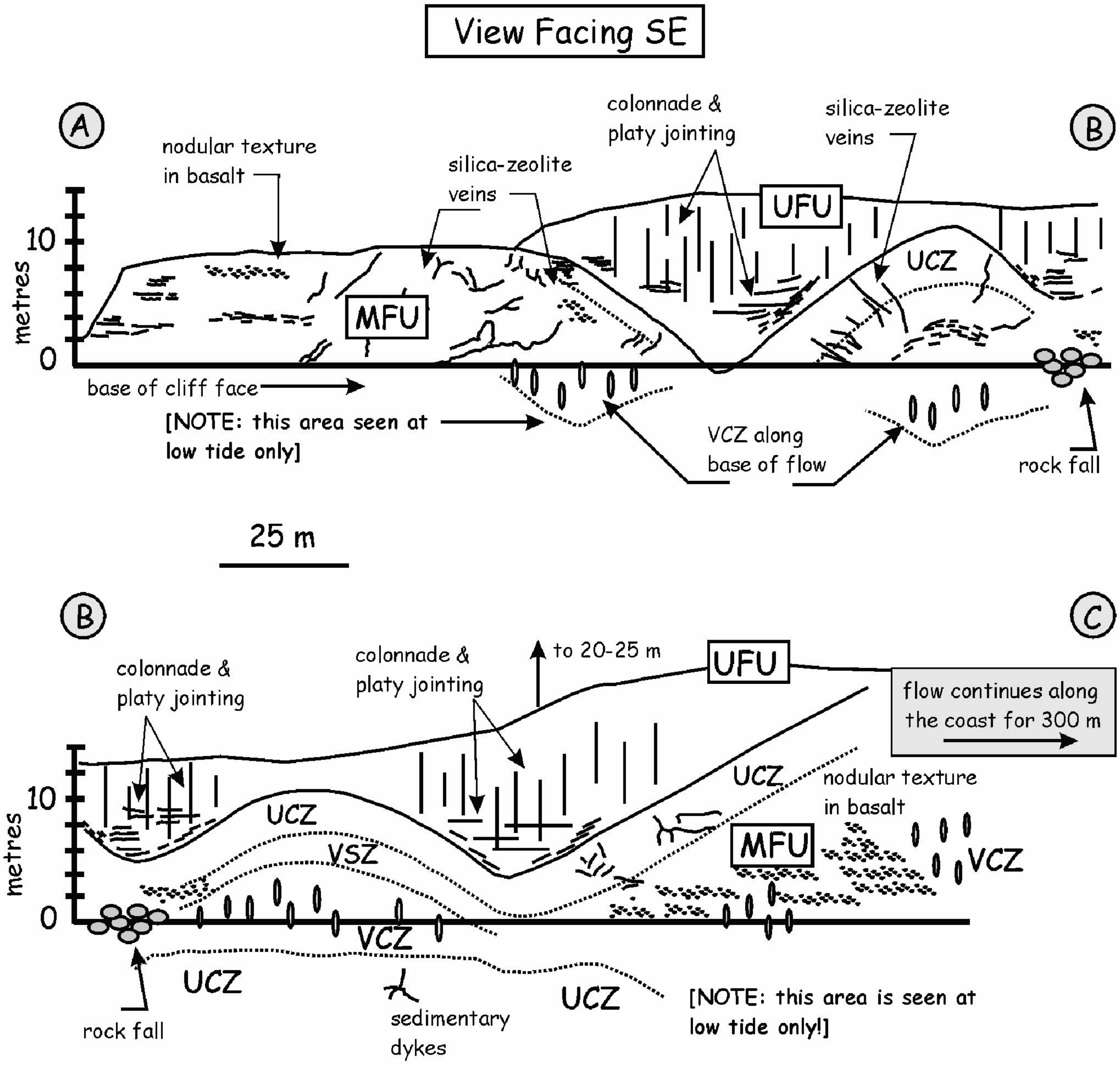


**Figure 8.** Long section (ca. 350 m) running parallel to the coastline at Morden just west of the French Cross statue (see Kontak *et al.*, 2005, for details) showing many features typical of the MFU. Abbreviations follow: MFU - Middle Flow Unit, UFU - Upper Flow Unit, UCZ- upper crust zone, VSZ - vesicle sheet zone, VCZ - vesicle cylinder zone. The tumulus feature in the section A-B is shown in Figure 9b. Note that at low tide the UCZ of the next flow down is exposed.

subvertical, columnar joints (entablature type) occur in a lava core that is, interestingly, characterized here by its fresh nature, medium-grained texture and locally with ≤10-15% mesostasis, a feature generally seen in outcrops of UFU basalt.

3. Vesicle cylinder zone (VCZ; ≤1-3 m; Fig. 10d, e), which reflects late-stage mobilization of volatile-rich, chemically evolved residuum (e.g. Anderson *et al.*, 1984; Goff, 1996; Self *et al.*, 1998). These are the bubble trains that Hudgins (1960) described in similar flows in the Digby area. The vesicle cylinders (VC) are exceptionally well displayed in coastal exposures and can be followed laterally for hundreds of metres. The VC are generally spherical in plan view (Fig. 10d, e), can

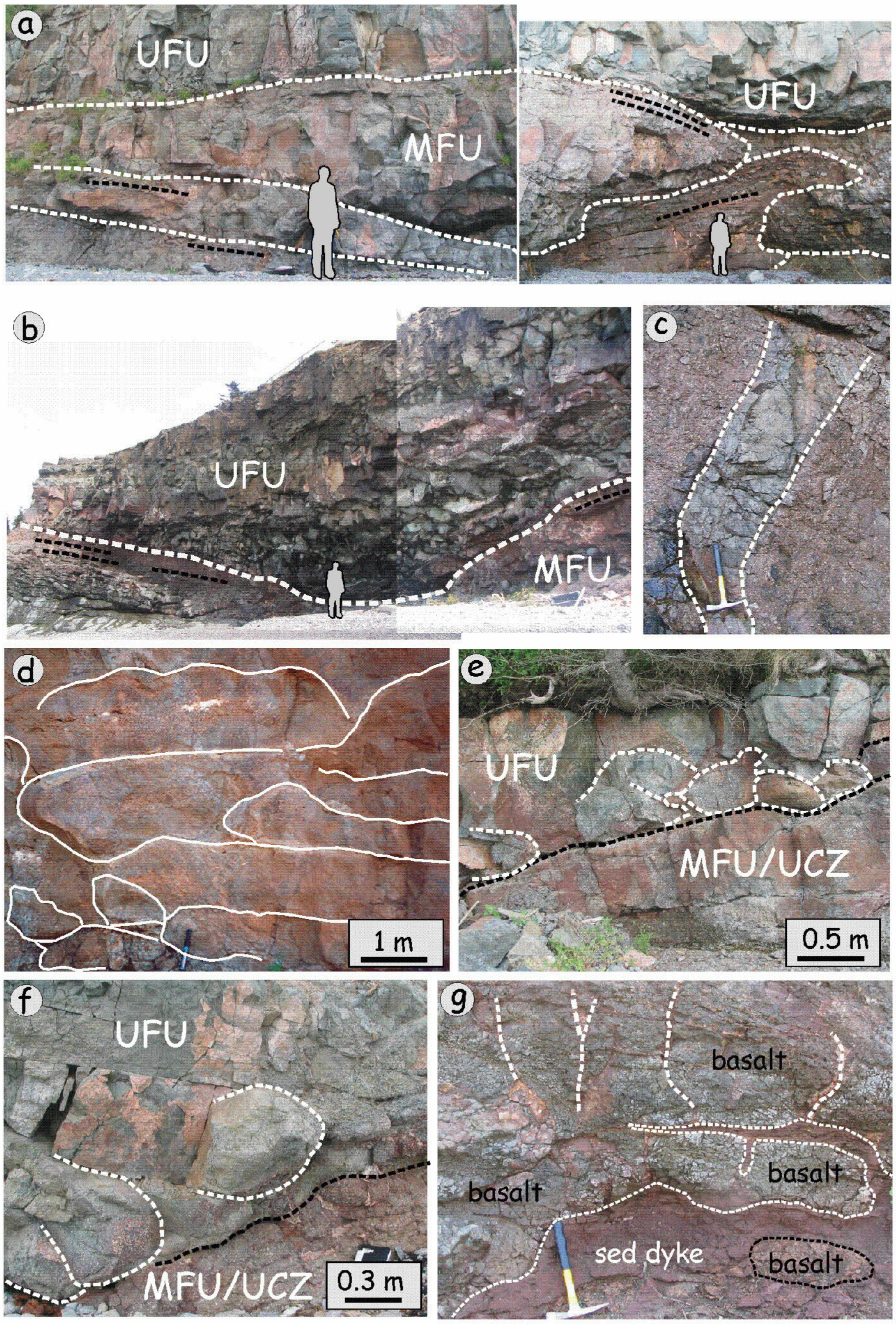


**Figure 9.** Field photographs of Middle Flow Unit (MFU) showing some features typical of the sheet flows of this unit. (a) Long section of flow sheets underlying the base of the Upper Flow Unit (UFU). The individual flows are outlined to highlight the complex nature of the flows. The dashed black lines indicate vesicle layering in the upper crust zone (UCZ). Person for scale is 1.7 m. Photograph taken at Canada Creek. (b) Tumulus structure generated by the last flow sheet of the MFU with the lower part of the UFU filling the pre-existing depression. There is another similar structure immediately to the right of the photo. View facing southeast at Morden just southwest of French Cross (see Fig. 8 for location of the photo). (c) Dyke cutting vesicle-rich, upper crust zone of sheet flow at Halls Harbour. Note that the dyke is free of vesicles and originally had a glassy margin. The dyke could not be followed into an outbreak. (d) Flow lobes in part of a thick sheet flow. Each lobe has a chilled margin and vesiculated core. This photograph is part of flow 3 in the long section from Margaretsville show in Figure 7 (see Kontak (2002) for further discussion). (e, f ) Flow lobes from breakouts on top of the upper crust zones of sheet flows with the base of the UFU on top. The outlines of the flow lobes and the top of the sheet flows are indicated with dashed lines. From coastal exposures near Halls Harbour and Harbourville, respectively. (g) Sedimentary dykes penetrating into the UCZ of a flow at Sweeney Point west of Harbourville. Dykes are highlighted by the dashed white lines and lower part of photograph is all fine-grained, red-brown sediment.

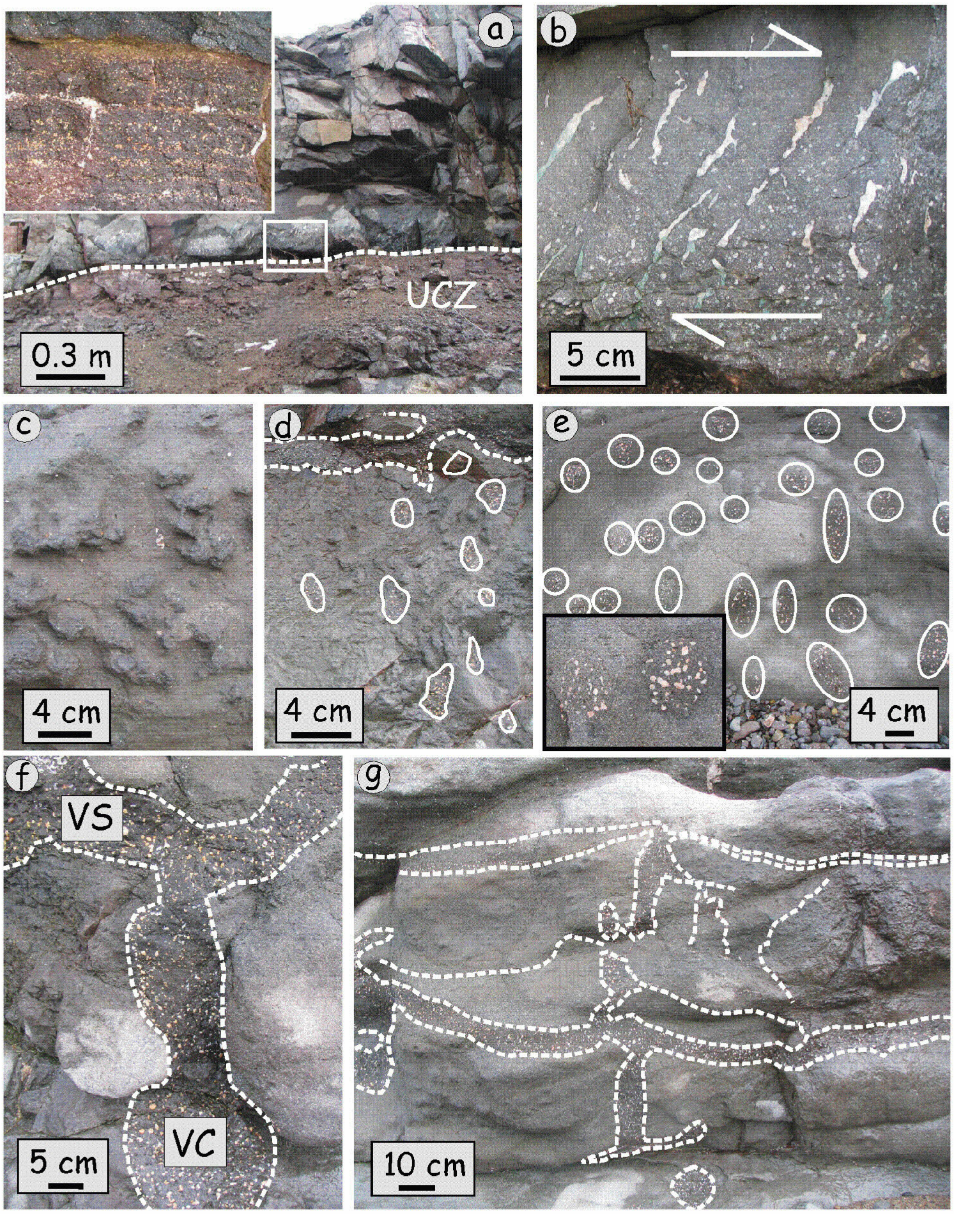


**Figure 10.** Photographs (all facing southeast) illustrating vesicle distribution in typical pahoehoe sheet flows of the Middle Flow Unit (MFU). All photographs taken at Margaretsville, southwest of Lighthouse Point (see Kontak *et al.* (2005) for details of this area). (a) Contact between the two flows of the MFU with the upper crust zone (UCZ) of the lower sheet flow against the lower crust zone of the last sheet flow of the MFU in this area beneath the Upper Flow Unit. The UCZ is characterized by its fine-grained nature, abundance of amygdules (to 30-50%), red-brown colour (i.e., oxidized flow top), and friable nature. The base of the overlying sheet flow is lined with pipe vesicles (in box area; Fig. 10b) and the inset shows typical vesicle layering commonly seen in the UCZ. (b) Pipe vesicles at base of the upper flow (box in previous photo) indicating dextral shear or southwest flow direction, as shown by arrows. Note the presence of the smaller vesicles (now amygdules) restricted to the base of the flow and massive, vesicle-free part of the flow at top of photo. (c) Lava core of sheet flow showing nodular texture, as defined by the differential weathering of the basalt. (d) Vesicle cylinders, outlined by dashed white lines, just beneath the vesicle sheet zone (at top of photograph). (e) Near bottom of the VC zone showing area enriched in the VSs (outlined by white lines). Note that the photograph goes from plan view to oblique section from top to bottom, hence the change in vesicle shape from sphere to cone. Inset is close-up of two cylinders in plan view from top of this outcrop. (f) Transition from the vesicle cylinder (VC; outlined by dashed white lines) to vesicle sheet (VS) zone in a sheet flow. Note the amygdaloid-rich and dark, fine-grained nature of the late-stage material cutting coarser grained basalt. (g) Vesicle sheet (VS) zone of the flow beneath the upper crust zone. The dashed white lines trace areas of fine-grained, vesicle-rich, dark material originating from mobilization of a late-stage, volatile-rich residuum (e.g. Self *et al.*, 1997).

be of varying width (3-4 cm to 10 cm) and density, with an inverse relationship between size and number, and heights of 3-50 cm, rarely to 1.5 m. The VC Zones are invariably vertical, thus indicating their emplacement when flows had stagnated, and also that post-emplacement tilting of flows was minimal, although tilting is recorded by inclined VC along the north side of the Bay of Fundy east of Parrsboro (Fig. 1b). Vesicles, mostly occluded with zeolites, constitute <10-30% of the pipe feature, are 2-10 mm wide, and are spherical to flattened in plan view. Compression of the vesicles occurred during emplacement of the VCs, that is strain was induced by flowage of the VC material rather than external stress. Basalt surrounding the pipes is distinctly finer grained and darker than that within the VC. In the upper part of the VCZ, the VC merge with the overlying vesicle sheet zone and take on more irregular shapes in their upper part (Fig. 10f).

4. Vesicle sheet zone (VSZ; ≤1-3 m; Fig. 10f, g) is continuous with the VCZ. This is a laterally continuous zone of mixed, vesicle-rich material and massive, non-vesicular basalt with the former occurring as flat sheets within the latter. The nature of this zone is complex, with the proportions of vesiculated versus non-vesiculated material variable. In addition, both the percentage of vesicles and their shapes can vary. Vesicles are often flattened (aspect ratios of 1-20:1) with the long axes parallel to the flow top.

5. Upper crust zone (UCZ; Fig. 10a) of fine-grained basalt with disseminated amygdules (≤30-70%; disseminated zone, DZ), which is red-brown (oxidized) in the upper 1-2 m. The zone contrasts with the VSZ by having a more uniform distribution and density of vesicles, which generally show a progressive increase in size downward. In some instances the UCZ consists of several sub-parallel, amygdule-rich layers in which the amygdules and vesicles are variably flattened and inclined, reflecting multiple pulses of injected lava accompanied by inflation with imbrication-related shear (cf. Walker *et al.*, 1999). Megavesicles of ≤10-12 cm, as noted in modern and ancient pahoehoe flows, are rarely observed and instead most vesicles are ≤1-2 cm. The shapes of vesicles are highly irregular, but to date no detailed studies have been done on this aspect of the flows.

The absence of clinkery or rubbly tops typical of a'a flows probably relates to the distal aspect of the lava flows, as such features are usually restricted to pahoehoe flow fields proximal to their vent sites (Swanson and Wright, 1980), and an overall regular, low-slope topography. The planar tops of flows are rarely seen due to the nature of exposure along cliff faces, but in rare localities with appropriate surfaces (e.g. St. Croix Cove) ropy textures are observed.

Internally, individual sheet flows are rarely seen to have lobes or toes, the vestiges of breakouts at the advancing front of pahoehoe flows (Hon *et al.*, 1994) that build up to form sheet flows. In a few exceptional cases, however, the relicts of lobes have been observed (Fig. 9d) within lava core zones, similar to what Thordarson and Self (1998) observe in the sheet flows of the Columbia River Basalt Group. Thus, these are vestiges of the past coalescence of lava lobes during construction of the larger sheet lobes. These small lobes of a few metres section have zonally arranged vesicles, as is typical of spongy pahoehoe flows (Walker, 1989). More commonly seen are lobes that are manifestation of surface breakouts, with stacked lobes seen overlying sheet lobes (Fig. 9e, f). Such surface breakouts have been observed along the strike length of the MFU and more rarely the feeder dykes (5-50 cm width) can be traced cutting the UCZ (Fig. 9c), whereas in other cases feeders are seen but cannot be traced to an outbreak. The margins of such feeder dykes were originally glassy, now altered, and contrast markedly with the host basalt by a lack of vesicles.

The presence of abundant pipe vesicles in the base of sheet lobes of the MFU indicates a generally southwest flow direction for the early stage of flow eruption, as summarized for several sites in Figure 11. There are, however, a few places where contradictory directions are indicated and which probably reflect flows being fed by different lava tubes. The only marked departure from the regional trend noted occurs as at Point Prim at Digby Gut (Figs. 3, 11), which suggests a change in flow movement towards the southeast rather than southwest. Unfortunately data have not been obtained from west of the Digby area to see if this trend continues. The data for the pipe vesicles are compared with flow directions inferred from anisotropy of magnetic susceptibility (AMS)

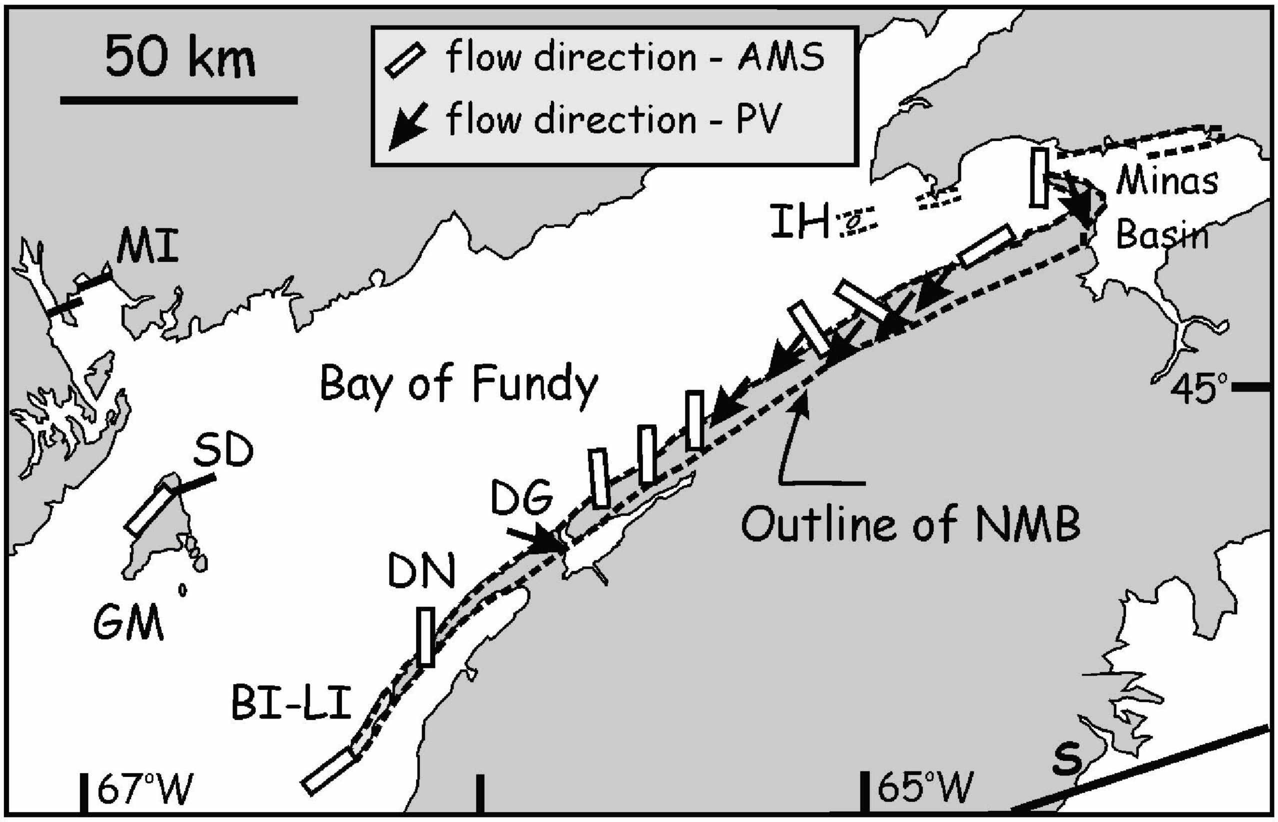


**Figure 11.** Map of southwestern Nova Scotia and contiguous southern New Brunswick along the Bay of Fundy with outline of the North Mountain Basalt (dashed lines) and trace of Jurassic basaltic dyke rocks (S Shelburne dyke, SD - Swallow Tail, M-Minster Island). Also shown are the flow directions for the North Mountain Basalt inferred using pipe vesicles at the base of flows (this study; both Middle and Upper flow units) and anisotropic magnetic susceptibility (AMS) fabrics (from Ernst *et al., 2003). Place localities are BI-LI -Brier Island-Long Island, DN - Digby Neck, DG - Digby Gut, GI - Grand Manan Island, IH - Isle Haute.*

measurements (Ernst *et al.*, 2003) in Figure 11, where AMS indicates a generally northeast-southwest or north-south flow direction, but the technique cannot distinguish the polarity of the flow movement (i.e. NE or SW).

The MFU is fine-grained, dark grey to grey-green and massive, except where intensely vesiculated, and it is rare to see phenocrystic phases, as in the LFU and UFU. The internal, massive part of individual flows (the lava core) weathers, as noted, to reveal a nodular texture. Also present in the massive core of flows are flat, lens- or sheet-shaped areas of discoloration that are considered to reflect fracture-controlled alteration. Columnar jointing, either colonnade or entablature, is rarely developed in the massive lava core.

Almost exclusive to the MFU, but also rarely seen in the LFU (e.g. McKay Head; Kontak *et al.*, 2005), is the presence of sedimentary dykes (≤ 1 cm to 1 m width; Fig. 9g) that penetrate to several metres into the core zones of the flows. These dykes are red-brown, very siliceous (90-95 wt. % $SiO_2$ from chemical analysis), indurated, and commonly contain angular fragments of altered basalt, but rounded or subrounded pebbles and cobbles of basalt also occur. Although the dykes can have variable orientations, often irregular on a small scale, they often have preferred orientations at a large scale. Structural analysis of 680 filled fissures in the NMB by Schlische (1993) indicates a preferred northwest extension direction, similar to the extension direction for the 200 Ma Shelburne dyke of southern Nova Scotia. The sedimentary dykes are rarely cut by veins composed of silica ± zeolites, which provides an important relative constraint on the timing of fluid flow related to zeolite formation.

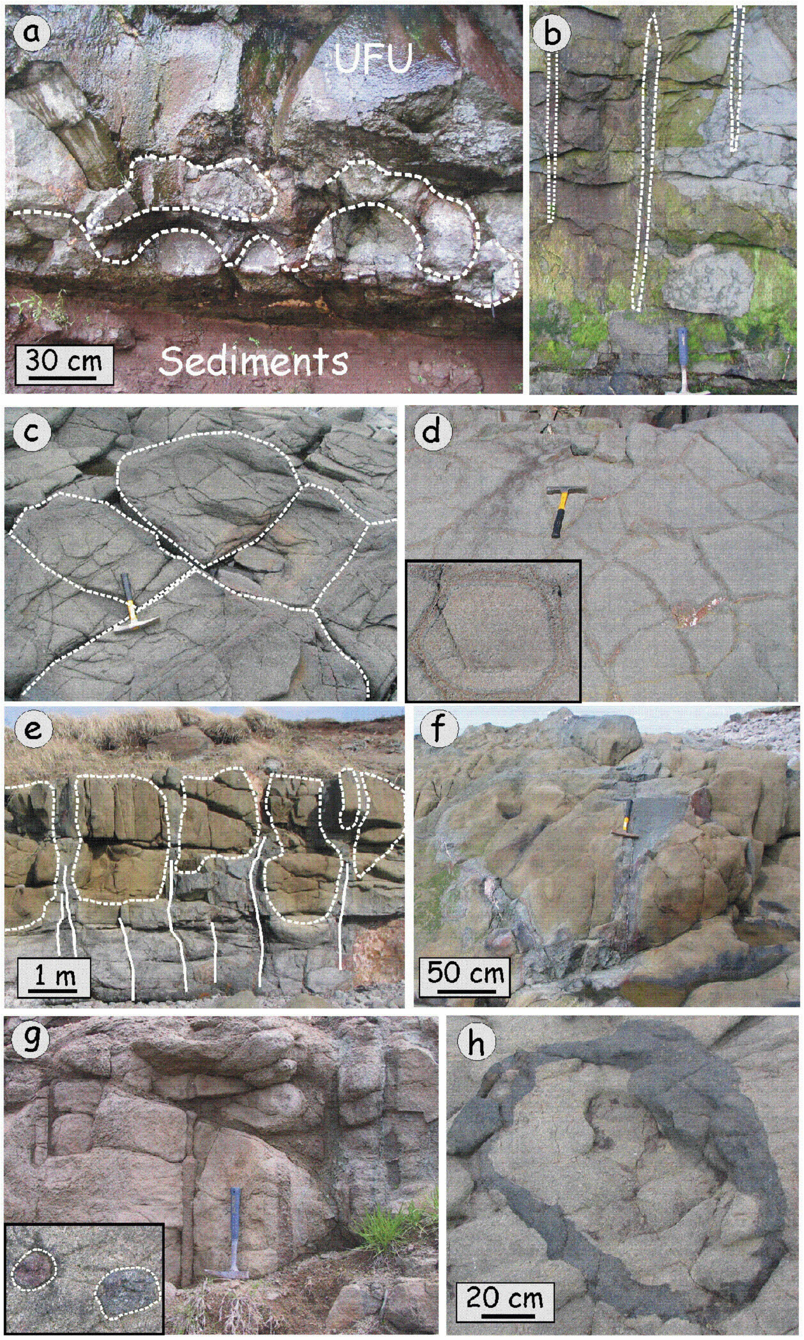


**Figure 12.** Field photographs showing features typical of the Upper Flow Unit (UFU) of the North Mountain Basalt. Hammer for scale in photographs is 32 cm long. (a) Red siltstone beds filling depression beneath UFU. Note the small flow lobes (outlined with dashed white line) on top of the sediments which are overlain by massive UFU flow. Photograph at coastal section, Point Prim north of Digby. (b) Massive UFU basalt with three subvertical vesicle cylinders (outlined by dashed white lines). The outcrop is in the lower part of the UFU exposed at low tide at Port George. (c) Plan view of vertical mega-columns, outlined by dashed white lines, in the UFU at Canada Creek. (d) Plan view of colonnade jointing with alteration along primary cooling joints in outcrop at Delaps Cove northeast of Digby. The inset photograph is a close-up of a single column with the alteration zone defining its boundaries. In detail, the red-brown alteration zone in dark is cored by fine-grained silica and bounded by a dark grey alteration zone which goes into fresh basalt. (h) Elliptical feature of aphanitic basalt (glass in thin section) in medium-grained, mesostasis-rich UFU basalt. The origin of this feature is not known. Photo along coast south of Cape Split. (g) Cross-sectional view of a series of segregation pipes in the lower part of the UFU (i.e. <8-10 m from base) at Margaretsville. Inset photograph shows plan view of 4-5 cm wide segregation pipes in the same area. (e, f) Alteration (i.e. silica enrichment) along cooling joints in the lower part of the UFU at Maragetsville, as defined by the discoloration of the basalt (i.e. light coloured areas). In Figure 12e the areas of fresh basalt are outlined in dashed white lines, all other areas are grey and altered.

## Upper Flow Unit (UFU)

The UFU is observed from Cape Split to Brier Island. Outcrop of the UFU is discontinuous along the Port George to Scots Bay coastal section, but continuous west of Bridgetown (Fig. 2). The unit is generally massive with ≤3-5% microphenocrysts of plagioclase and pyroxene, and varying amounts of a dark mesostasis (20-80%), a feature that is most characteristic of this unit, in addition to the well-developed columnar jointing. The dark mesostasis material rarely occurs as dark, aphanitic material, seen to be glassy in thin section, which forms irregular patches of ≤15-25 cm width and ≤5-10 cm wide dykes and sills.

The features of the UFU are very regular even though it is laterally extensive. The base, where observed, often commences with several small flow lobes, rarely seen above a thin, local sedimentary layer as at Point Prim north of Digby (Fig. 12a). Locally, the lower section of the flow may be altered with traces of vesicles, perhaps related to having passed over a water-rich horizon. The base of the flow locally has pipe vesicles, as at Margaretsville, with southwest flow directions indicated, similar to those of the underlying sheet flows of the MFU. The UFU is characteristically massive and features seen in the MFU, such as vesicle zonation, tumuli and flow lobes, are lacking. Locally, vesicle cylinder features are present (Fig. 12b), but they are not laterally extensive and do not feed upwards into overlying vesicle sheet zones. The rare occurrence of such features may indicate passage of the flow over a water-rich surface.

Jointing in the UFU is distinct (Fig. 12c, d) and pervasively developed, but it varies in width, orientation and fabric (i.e. planar versus curvilinear). Based on the nature and abundance of jointing, it is possible to distinguish a lower part of the UFU in which jointing is more prevalent, and an upper part where it is less pervasive. Although the smaller zone of entablature jointing (i.e. <40 cm width) is more abundant, colonnade jointing is also present in the lower part of the unit. As with the LFU, multi-tiered layers of both colonnade and entablature jointing, with zones of chaotic jointing, are present, as well exposed at East Ferry (see Fig. 14 in Kontak *et al.*, 2005). Unique to the UFU is the presence of joint-controlled alteration (Fig. 12e, f), which is seen throughout the strike length of the unit. The alteration is regular in appearance, since it is controlled by jointing, and in areas can affect a large percentage of the outcrop. Where well developed, silicification occurs along the joints and forms a bleached or grey zone several centremetres wide. The silicified zones form ridges with the fresher core areas of the basalt preferentially weathered to form small depressions. Also present and generally more common is fine-grained, siliceous material lining the joint, with a red-brown oxidation zone bordering this followed by a dark grey zone between the fresh basalt and the red-brown zone (Fig. 12d).

Another feature restricted to the UFU is the presence of segregation pipes (Fig. 12g), a feature that is documented in pahoehoe flows elsewhere (e.g. Anderson *et al.*, 1984; Goff, 1996; Self *et al.*, 1998; Costa *et al.*, 2006). These pipes, 1-60 cm in width and to ≤1.5 m in length, are located near the base of the MFU in Morden, Margaretsville and Port George. The pipes have a range in bulk composition due to variable mixtures of both basic and felsic (rhyolite) components. Kontak and Dostal (2002) considered the pipes to represent mobilization via filter-pressing of late-stage, highly fractionated residual melt developed on a microscopic scale in the NMB via immiscibility (Kontak *et al.*, 2002). In this sense, the felsic pipes are similar to rhyolite bands and granophyre associated with mafic pegmatites in the LFU, noted above.

Locally in the UFU rootless cone-type features are seen, but they are less abundant compared to the LFU. The best examples of this occur along the Digby Neck area (inset, Fig. 2). Areas underlain by shallow circular lakes, as seen in the LFU, are lacking. In one locality near Cape Split, unusual occurrences of doughnut-like features composed of black, aphanitic, glassy material are seen over an area of a few hundred square metres (Fig. 12h). These features must represent mobilization of a late-stage melt into dilatant zones commensurate with sudden quenching to generate the glass.

## Discussion

The nature of NMB volcanism, style of eruptions and its petrological features have several geological implications: (1) the contributory impact of vented aerosols as part of the Central Atlantic Magmatic Province (CAMP) magmatism on atmospheric evolution and its role in the Triassic-Jurassic extinction; (2) origin of the large CAMP and Eastern North American (ENA) basalt provinces with regard to mantle processes and regional tectonics; (3) implications for the landscape during the Early Jurassic (Hettangian); (4) petrological processes in general, such as silicate-liquid immiscibility, formation of layered pegmatites and segregation pipes; and (5) nature and origin of vesiculation in pahoehoe flows. These issues are beyond the scope of the present study and are addressed in part in other papers (e.g. Kontak *et al.*, 2002; Baldwin, 2004; Kontak, in prep., and work in progress). Instead, the implications of the current work are discussed below in the context of the aggregate and zeolite resource potential of the NMB.

## Aggregate Resource

This study has not specifically addressed the quality of the NMB for aggregate, but instead the focus has been to outline those areas that offer the greatest potential for resource assessment and development. At present there are numerous quarry operations along the North Mountain, developed in all three flow units. Based on the results of mapping (Fig. 2) and the nature of the flow units described above, it is clear that the most favorable areas for aggregate are underlain by the LFU and UFU, the MFU being less desirable as a consequence of alteration related to zeolite development. Thus, in the central and eastern part of the North Mountain (east of Middleton) the LFU offers the greatest aggregate potential due to favorable exposure, topography and access. West of this area both the LFU and UFU have sufficient outcrop distribution and access to offer aggregate potential. Along Digby Neck and west, the combination of outcrop exposure and topography makes the UFU the more favorable target for aggregate. The additional advantage in this area is the proximity to the coast, which could allow for transport by ship. Thus, it is this coincidence of exposure of the UFU, vertical exposure, and location along an accessible coastline that makes this a focus of possible aggregate quarry development.

One area for possible aggregate development along Digby Neck is at Whites Point, shown in Figure 3c. At this locality the UFU is ≥72 m thick, as indicated from diamond-drilling, and is exceptionally fresh. Outcrops expose massive, columnar-jointed, very fresh basalt over the landscape and coastal areas. The only signs of alteration occur along joints, typical of the UFU, which may be lined with silica and a red-brown alteration selvage of 4-5 mm. Representative sections of the rock from drill core have been examined in thin section and petrographic observations indicate that the flow is uniformly fresh (Fig. 13). There is a progression in texture of the basalt from the top to bottom of the hole, with most being medium-grained and holocrystalline until the bottom 20 m, where an increasing amount of finer grained material occurs.

## Zeolites in the North Mountain Basalt

The North Mountain Batholith has long been recognized for the occurrence of a large variety of zeolite minerals throughout its exposure (Walker and Parsons, 1922; Aumento, 1962, 1966; Pe-Piper, 2000; Pe-Piper and Miller, 2002); in fact, Morden is the type locality for mordenite (How, 1864). Although not directly a part of the present study, a few comments regarding the distribution of the zeolites is appropriate given that this study has elucidated the occurrence of these minerals (Kontak, 2000; Kontak and Kyser, 2003). Significantly, the occurrence of zeolites reflects the primary volcanological features of the flow units, with zeolites primarily occluding vesicles. Thus, the following points summarize the distribution of zeolites, beginning with the most prominent.
(1) Zeolites occur within all the vesiculated zones of the MFU (UCZ, SZ, CZ, PV), but the VSZ, VCZ highest concentrations are within the upper crust zone and underlying vesicle sheet zone, since such areas have the largest percentage of primary vesicles. Since plagioclase, both as microcrysts and matrix, and also intergranular mesostasis glass are both altered to zeolite, the rest of the flow sheet is also enriched in zeolites. (2) Zeolites occur in the upper vesiculated part of the LFU where such zones are developed, as seen in the Kane quarry (Fig. 3). In such areas zeolites occlude the vesicles

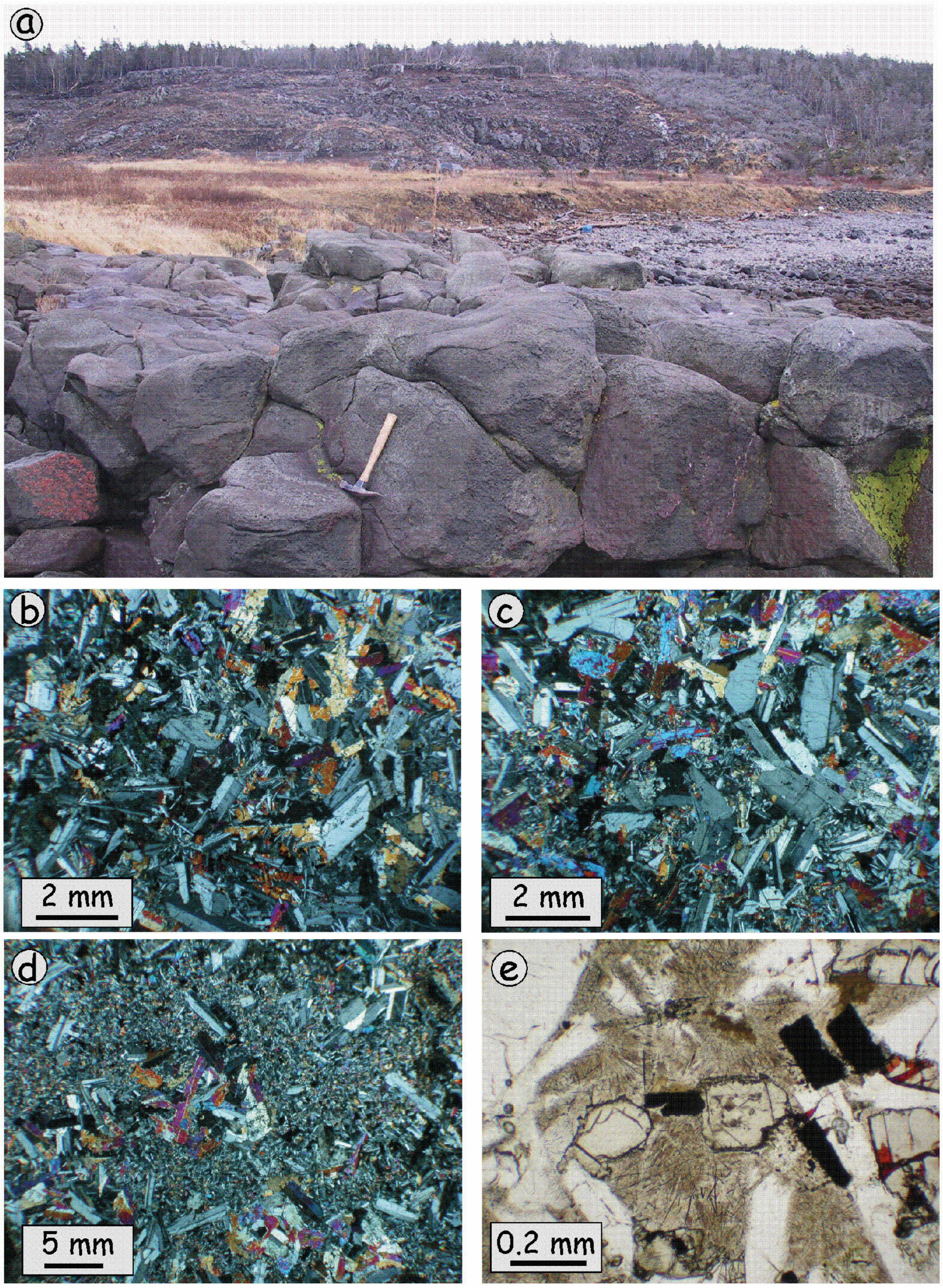


**Figure 13.** Photographs of outcrop and thin sections of White Point area. The thin sections are for samples from a drill hole which was collored at the top of the hill in this area. (a) View looking southeast of area underlain by Upper Flow Unit basalt showing the rising topography in the background and outcrop of massive basalt in the foreground. The coarse fracture patterns formed as cooling joints in the basalts. (b) Medium-grained holocrystalline basalt dominated by clinopyroxene and labradoritic plagioclase with trace Fe-Ti oxides. Note the presence of a some finer grained material, hence a bimodal grain size. Sample from 17.8 m depth in drill hole. (c) Similar to the previous sample, but with slightly more finer-grained material. Again note how fresh the sample is. Sample from 40 m depth in drill hole. (d) Fine-grained basalt with 10% of coarser material of plagioclase and clinopyroxene. Note that the fine grained material is holocrystalline and there is little glass present. Sample from 50 m depth in drill hole. (e) Close up of part of previous sample showing glassy mesostasis material with euhedra of clinopyroxene and Fe-Ti oxides. Again, note the freshness of the sample.

and also occur as alteration minerals in the intervening matrix material. Such zones are laterally discontinuous and have limited vertical extent. (3) Zeolites occur in the vesicle cylinders of the lower part of the MFU, although such areas are rare and do not have lateral continuity. (4) Zeolites occur lining fractures in the upper crust zone of inflated sheet flows of the MFU (see Fig. 8), probably relating to extensional features (clefts) formed during the inflation process (Self *et al.*, 1997, 1998). (5) Zeolites occur coating fractures and veins that traverse all three flow units. In the case of the MFU, such fractures are probably early formed, stress features related to emplacement of the sheet flows, and can be very abundant. In contrast, the silica-zeolite veins (≤5-10 cm) in the LFU and UFU have regular orientations, with northeast trends dominant, and are laterally continuous (to several 100 m). The geometry and nature of the veins suggest that they formed as part of a regional structural environment related to movement on the east-west CCFS (Fig. 1). In summary, the entire MFU is considered a zeolite-bearing resource, with the abundance and quality within any single flow sheet variable and something to be assessed for a given locality. Given the outcrop exposure of the MFU, the area between Bridgetown and Scots Bay offers the greatest opportunity for resource development.

The timing of the zeolite (±silica) mineralization is constrained from the following observations. (1) Zeolites fill remaining void space in vesicles that have initially been occluded by fine-grained aeolian sediment. (2) Zeolite-rich, vesiculated basalt occurs as fragments within sedimentary dykes cutting sheet flows of the MFU. (3) Silica-zeolite veins cross-cut sedimentary dykes. (4) Zeolites coat fractures that traverse all the flow units and are seen in the sedimentary rocks of the overlying Scots Bay and McCoy Brook formations. These observations indicate that zeolite mineralization occurred over a protracted period, post-dating cooling of the host volcanic rocks, and the fluids responsible for such mineralization utilized whatever permeability and porosity was available in the volcanic stratigraphy. Thus, the highly vesiculated MFU sheet flows provided a favorable host for the lateral migration of such fluids, whereas a variety of fracture systems, probably formed at the same time as the fluids, also focused these fluids. Stable isotopic data ($\delta^{18}O$) suggest that these fluids are of basinal type, presumably derived from the thick, underlying succession of Triassic sediments (Kontak and Kyser, 2002). A more detailed study of zeolite mineralization in the NMB is in preparation.

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