Field Trip B3

Geology and volcanology of the Jurassic North Mountain Basalt, southern Nova Scotia

Dan Kontak[1], Jarda Dostal[2], and John Greenough[3]

[1]*Nova Scotia Department of Natural Resources, P.O. Box 698*
Halifax, Nova Scotia, Canada B3J 2T9
[2] *Department of Geology, Saint Mary's University*
Halifax, Nova Scotia, Canada B3H 3C3
[3]*Department of Earth and Environmental Sciences, Okanagan University Collage, 3333 College Way, Kelowna, British Columbia*
Canada V1V 1V7

Department of Earth Sciences
Dalhousie University
Halifax, Nova Scotia, Canada B3H 3J5

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HEALTH AND SAFETY

During the three days of this field trip time will be spent along rocky shorelines with precipitous cliff exposure, in quarry sites, and along roadside outcrops - safety is of utmost concern for all the participants. ***The field trip leaders will attempt to ensure a safe environment at all times, but individual safety requires the concern, participation and alertness of each participant at all times, so please take precautions during field trip activities.***

Roadside stops: several stops will be made to look at roadside outcrops. Please exercise caution when listening to field trip leaders and when looking at outcrops. Do not venture onto the pavement unless you are crossing the road, and only cross the road with the group to minimize traffic disruption.

Tides: note that some areas are subject to large variation in tides, so be careful at such sites and plan ahead accordingly. For persons using this guide on their own, ensure that you have obtained correct information on the tide tables to ensure that you will not be caught in a dangerous situation when the tide does turn.

Weather: the weather in mid-May in Nova Scotia, especially along coastal areas, can be unpredictable, brutal and change quickly. Ensure that sufficient clothing is packed for a variety of weather conditions, from warm to bitterly cold and wet.

Ground conditions: a variety of ground conditions will be encountered and boots, preferably safety, with good traction are essential. Along the coast be careful where seaweed and algae cover rocks, as this makes for slippery conditions. In addition, be careful in all areas, but in particular along the coast, where there are overhangs or steep cliff exposures with loose rock overhead. **Hard hats** are recommended for those that are going to work near cliffs with overhangs and loose rock.

Rock Hammers: when hammering on outcrops please beware of the fact that other participants are nearby and pieces of rock are dangerous projectiles. Safety glasses are highly recommended for protection of the eyes.

INTRODUCTION

Subaerial basalt flows and their submarine equivalents are the most voluminous and aerially extensive volcanic rocks on earth and, presumably, occupy a similar significance on planetary bodies (e.g., Mars, Venus, Io). Among basalt flows it is the sheeted pahoehoe type that is the most dominant with the channelized, faster-moving a'a flows more rare in the geological record. For example, classic terrestrial examples of large, sheeted pahoehoe basalt provinces include the well known Columbia River Basalt Group (CRBG; Shaw and Swanson, 1970; Thordarson and Self, 1998) and Deccan Traps (Agashe and Gupte, 1971; Beane et al., 1986). In addition, of the larger basalt flows known, the majority are pahoehoe type and include the historical Laki flow of Iceland (1783 A.D.; 65 km long, 14.7 km^3), Undara flow of Australia (190 Ma; 160 km long, 25 km^3), and the Roza Member of the CRBG (15 Ma; 350 km long, 1300 km^3) (data in Self et al., 1998).

The occurrence of large, sheeted, continental-flood basalt flows or provinces is significant as they appear to coincide in some cases with mass extinctions, have implications for crustal processes (i.e., mantle evolution) and also to atmospheric evolution. These continental flood basalts were, until relatively recently, generally thought to represent rapid outpourings of superheated, low-viscosity magma emplaced as 10- to 100-m thick coherent sheets of lava (compound lava flows; Walker, 1971) based on such observations as glassy selvedges on flow lobes regardless of distance from source (e.g., Shaw and Swanson, 1970; Swanson et al., 1975). As recently discussed by Thordarson and Self (1998) though, glassy lobe margins of flows are not unequivocal evidence for rapid outpouring of lava. Thus, relevant are the recent studies of mode of emplacement of modern, active analogues in Hawaii (Mattox et al., 1993; Hon et al., 1994), in addition to parallel studies on the thermal conditions of lava flows (Flynn and Mouginis-Mark, 1992; Realmuto et al., 1992), which have demonstrated that thermally efficient transport of sheeted basalt flows can occur over both greater distances and longer periods of time than previously considered due to an insulating mode of emplacement (see review in Self et al., 1998). This mode of emplacement, referred to as inflation, is presently the preferred mechanism of formation for large pahoehoe-type flows. This endogenous process, discussed in more detail below, is supported by the occurrence of such features as tumuli, lava-rise plateaus, inflation pits, and sutures (e.g., Walker, 1991; Chitwood, 1994; Rossi, 1996; Self et al., 1998) which are commonly observed in young flows (i.e., Holocene and younger), but also in older analogues (Self et al., 1996; Thordarson and Self, 1998). It is with analogy to these studies, discussed in more detail later, that we will look at the North Mountain Basalt. Do these basalts fit into the current, popular models for extrusion of large flood basalts dominated by inflated sheeted pahoehoe-type flows, or is there a difference? We leave this question for you, the observer, to consider, ponder, and answer for your self, based on the field observations provided.

REGIONAL SETTING AND PREVIOUS WORK

Numerous early Mesozoic continental tholeiitic basalt flows, dykes and sills crop out along the eastern margin of North America from South Carolina to Nova Scotia and Newfoundland, and form part of the Newark Supergroup (e.g.,Mc Hone et al., 1987; McHone, 1992; Schlishe et al., 2002; Fig. 1). Detailed geological studies within correlative parts of these basins of along eastern North America indicates eruption occurred at 200 Ma with a duration of 580 ka (Olsen, 1997; Olsen et al., 1998) and may have been more widespread than currently seen, the so-called broad-terrane hypothesis (McHone, 1996; Pe-Piper and Piper, 1999). In addition, similar petrological characteristics of these continental tholeiitic basalts and dyke rocks (e.g., McHone and Butler, 1984; Greenough and Dostal, 1992a; Puffer, 1992; Pe-Piper et al., 1992; Dunn et al., 1998; Pe-Piper and Piper, 1999; Marzoli et al. 1999) suggest that they relate to a single extensive magmatic event and collectively form a Large Igneous Province (LIP), referred to as the Eastern North American (ENA) LIP.

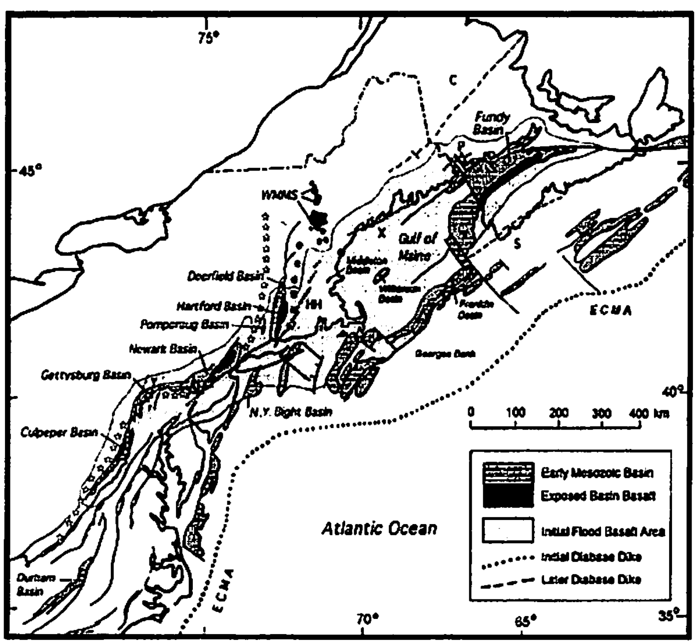


Figure 1. Extent of the Mesozoic extensional basins in eastern North America showing the Fundy Basin of Maritime Canada at the north end. Note the extent of the East Coast Magnetic Anomaly (ECMA) along the continental margin. From G. McHone web page.

The presence of a long, continuous geophysical reflector off the continental margin of North American (the ECMA in Fig. 1) indicates a much more extensive offshore continuation of these basalts (e.g., Marzoli et al., 1999; Schlische et al., 2002). Whether this LIP relates to a mantle plume or simply upwellling of the aesthenosphere remains a point of debate (e.g., King and Anderson, 1995; McHone, 2000), with both interpretations currently being promoted. The extent of the ENA LIP, related to the opening of the Atlantic Ocean, is impressive, having recently been extended to cover parts of western Europe, Africa and South America based on similar geochronology and chemistry. The expanse of the basaltic magmatism is now referred to as the Central Atlantic Igneous Province (CAMP, ca. 4.5 x 10^6 km^2; Marzoli et al., 1999) and is regarded as the world's largest igneous province (Fig. 2). Given the similar petrological characteristics of these continental tholeiites around the circum Atlantic, we emphasize that features documented within the North Mountain Basalt (NMB herein) may well extend to all the basalt sequences within CAMP. ***In fact. comments regarding this very point are encouraged and we invite correspondence on any matter.***

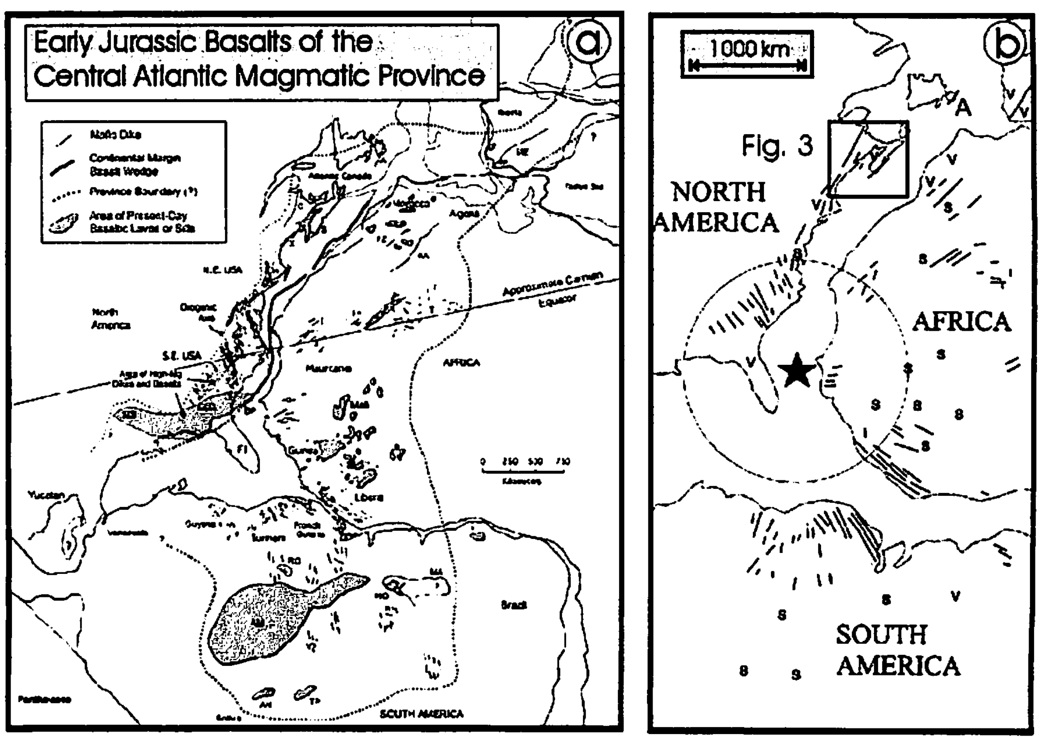


Figure 2. (a) Map showing the extent of the Central Atlantic Magmatic Province (CAMP) at ca. 200 Ma (reconstruction of Pangea) throughout North America, South American, Africa and Europe (left figure; after Marzoli et al., 1999). (b) Simplified diagram (after Ernst et al., 2003) showing the distribution of dykes (lines), sills (s) and volcanics (v) in CAMP. The star is the location of overall convergence of the dyke swarm and potential location of a hot spot.

The basaltic rocks of the ENA LIP were emplaced during lithospheric extension in the initial stages of the opening of the Atlantic Ocean. Along with sedimentary rocks these basalts were deposited within extensional basins that formed as part of aborted rifts related to the extension. The most northerly of these sub-basins is the Fundy Basin of Atlantic Canada. Within this basin and surrounding it occur basaltic rocks that include foremost the North Mountain Basalt (the NMB herein) of Nova Scotia and three prominent dykes: the Avalon dyke of Newfoundland, the Shelburne dyke in Nova Scotia, and the Caraquet dyke in New Brunswick (Fig. 3). In addition, we note that the NMB also occurs on Grand Manan Island, offshore southern New Brunswick (Fig. 4), where recent work (McHone, 2005 and pers. commun.) has shown that the geology there mimics that of the NMB in southern Nova Scotia. The dykes and NMB both trend towards the northeast (Fig. 3) and like comparable basaltic lavas and dykes in northeastern U.S.A. (McHone and Butler, 1984; Seidemann et al., 1984; Seidemann, 1988), the NMB yielded radiometric ages (U-Pb, $^{40}Ar/^{39}Ar$) of 201 Ma (Hodych and Dunning, 1992; Kontak and Archibald, 2003) and have been assigned paleontologically to the earliest Jurassic (Olsen et al., 1982, 1987). The dykes give similar ages with a $^{40}Ar/^{39}Ar$ whole rock age of 200 Ma for the Shelburne dyke (Dunn et al., 1998) and whole rock K-Ar ages of 189 ± 3 Ma for the Avalon dyke and 191 ± 2 Ma for the Caraquet dyke (Hodych and Hayatsu, 1988).

The first descriptions of the NMB were provided by Powers (1916) and Lund (1930), whereas the first comprehensive regional studies, in part included with the enveloping sedimentary sequences, were undertaken by Klein (1957, 1960), Hudgins (1960) and Sinha (1970) east of Digby, whereas Lollis (1959) and Koskitalo (1967) mapped west of Digby to Brier Island (Fig. 4). These studies provided the general framework, that is the recognition of the regional relationships and the three-fold subdivision of the NMB, although there were variations on the number of flows. Stevens (1980, 1987) presented a summary of field relationships around the Bay of Fundy, providing detailed descriptions of flow units in different areas. The early results of chemical analysis, summarized by Sinha (1970), indicated that the flows west of Digby area are more mafic, that is more Mg- and Ca-rich; thus, this early work already recognized a regional variation that may indicate the source area of the basalt. In addition, this work also indicated the similarities to such rocks as the Palisades sill, New York. Since that time, additional geochemical studies have recognized that these continental tholeiites, sourced in the upper mantle, have chemistry transitional to oceanic basalts due to eruption through a thinned continental crust as a result of incipient rifting leading to active sea-floor spreading (Wark and Clarke, 1980; Dostal and Dupuy, 1984; Jones and Mossman, 1988).

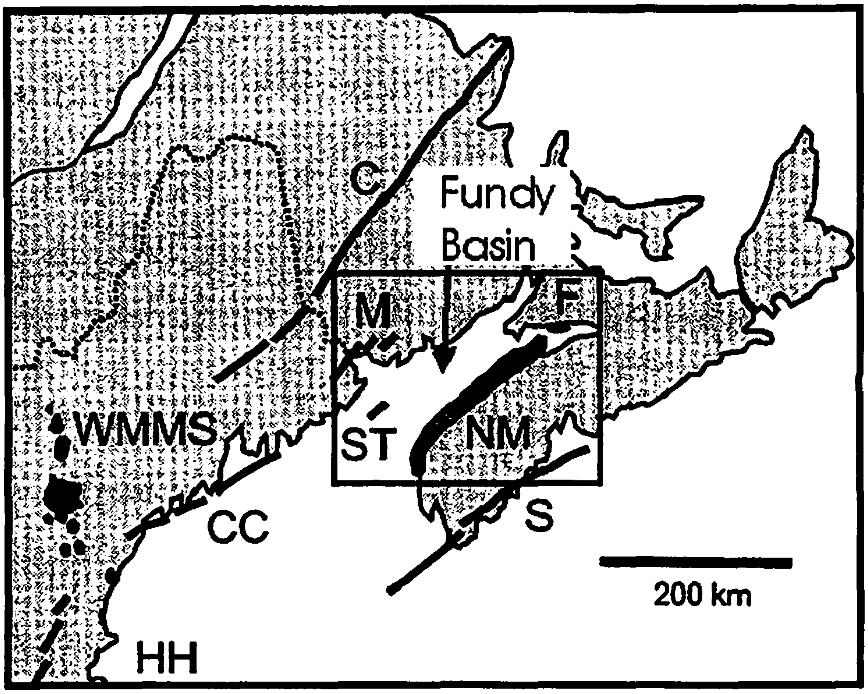


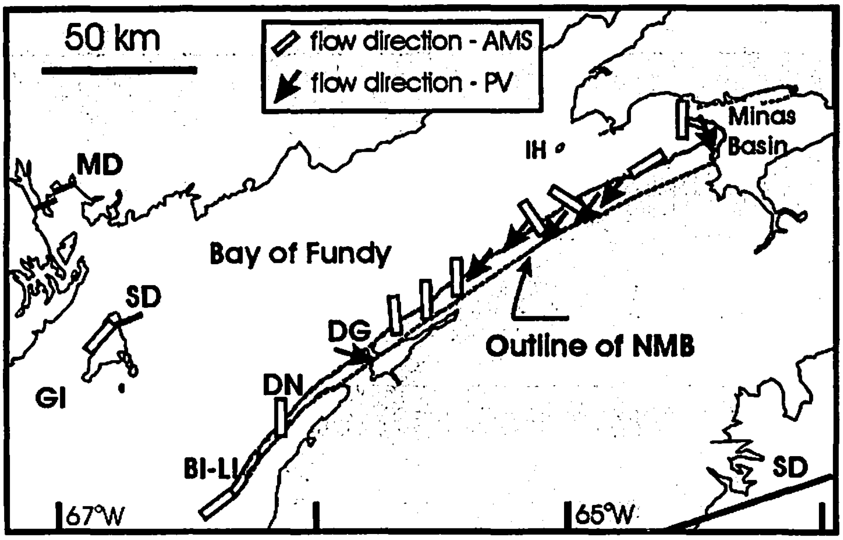
Figure 3. Regional map of northeastern USA and Maritime Canada showing the location of ca. 200 Ma dykes (S, Shelburne; C, Caraquet, M; Minster Island; ST, Swallowtail; CC, Christmas Cove; HH, Higganum-Holden) and the onland extent of the NMB (F is the Five Islands area where the NMB outcrops along the north shore of the Bay of Fundy). WMMS labels the White Mountain Magma Series. Map from Ernst et al. (2003).

The NMB has long been known for its varied and abundant zeolite minerals and, consequently, has long attracted mineral collectors. In fact the type locality for mordenite is from the Annapolis Valley area (i.e, Morden). Early work on the zeolites is summarized in Walker and Parsons (1922), whereas Aumento (1962, 1966) did the first modern work on these minerals. Colwell (1980) provided a field trip excursion in the 1980 GAC-MAC meeting for zeolites, and the results of more modern studies on the nature of zeolites are in Pe-Piper (2000), Kontak (2000), Pe-Piper and Miller (2002), and Kontak and Kyser (2003). Although this guide does not focus on the origin of the zeolites, they will be visited as part of the physical volcanology of the NMB.

GEOLOGICAL SETTING

The NMB were emplaced in the Bay of Fundy graben, one of the largest and most northerly of

Figure 4.Outline of the Bay of Fundy showing the distribution of the North Mountain Basalt (NMB); note the outcrops on the north side of the bay along the Minas Basin, on Isle Haute (IH) in the bay, and on the central and west side of Grand Manan Island (GI). The dark lines show ca. 200 Ma dykes, Shelburne (SD), Swallowtail (SD) and Minister Island (MD, that are correlated with the NMB. The flow directions of the NMB flows are inferred from magnetic fabric studies (AMS; Ernst et al., 2003) and orientation of basal pipe vesicles (PV) in flows of the MFU and basal UFU (unpubl. data of DJK). Place names are Brier Island-Long Island (BI-LI), Digby Neck (DN), and Digby Gut (DG).



the sixteen basins of the Newark Supergroup that run parallel to the continental margin of North America (Fig. 1; see Schlische et al. (2002) and references therein). The rift basins are filled with late Triassic-early Jurassic (i.e.., Hettangian) fluvial and/or lacustrine sediments of the Newark Supergroup (Olsen et al., 1982; Froelich and Olsen, 1985), which are intercalated with tholeiitic basalt flows and accompanied by diabase dykes and sills. In Maritime Canada, the early Mesozoic rocks occur around the margins of the Bay of Fundy and Minas Basin. The Mesozoic strata (Fundy Group) lie unconformably on Carboniferous and older rocks.

The oldest Mesozoic rocks are continental red to pale grey-green, conglomerate and sandstone (Wolfville Formation) and siltstone and shale (Blomidon Formation). The sedimentary sequence is conformably overlain by flows of the NMB, which begin just above the Triassic-Jurassic boundary (Olsen et al., 1987). The subaerial basalts are in turn unconformably overlain by the Scots Bay (south side of

Bay of Fundy) and McCoy Brook (north side of Bay of Fundy) formations, which are composed of lacustrine limestone and calcareous sandstone and their time-equivalent continental clastic sediments (Klein, 1962) that make up the floor of the Bay of Fundy. Whereas upwards of 250 m of McCoy Brook Formation sedimentary rocks are exposed, only 9 m of Scots Bay Formation remain as remnant inliers along the Scots Bay coastline (De Wet and Hubert, 1989).

The NMB forms a topographically prominent *cuesta*, which gently dips to the northwest (3-10°) and stretches for about 200 km along the southeastern shore of the Bay of Fundy (Fig. 4). The basalt flows are also exposed at several places along the north shore of the Bay of Fundy (Fig. 4) in the Minas Basin (Greenough et al., 1989a), on Grand Manan Island (McHone, 2005) and on Isle Haute in the Bay of Fundy, and were intersected in the wildcat oil well southwest of Point Lepreau, New Brunswick (Greenough and Papezik, 1987). These occurrences suggest that the basalt flows underlie most of the Bay of Fundy and originally covered an area of about 10,000 km^2 (Colwell, 1980; Greenough and Papezik, 1987). Along the southeastern shore of the Fundy Basin, the NMB thins from southwest (~ 400 m thick around Digby) to the northeast (~ 275 m thick in the Cape Split area) (Papezik et al., 1988).

The lower contact of the NMB in the Annapolis Valley area is seen along some coastal areas (e.g., Cape Blomidon area) and also in drill core that transects this unit in several holes collared on the top of the North Mountain. Along the Parrsboro coastline the contact is well exposed at several localities, the most impressive being at Economy Mountain cliff face in Five Islands Provincial Part near Parrsboro, where a white horizon occurs at the basalt-sediment interface, probably related to alteration (clay ?) of the underlying Blomidon Formation rocks. Another similar alteration zone is seen in a small pit at Victoria Beach on the east side of Digby Gut (a stop in the Digby area).

STRATIGRAPHY OF THE NORTH MOUNTAIN BASALT

Earlier Work

The regional mapping of Lollis (1959), Hudgins (1960) and Koskitalo (1967), collectively extending from Long Island to Scots Bay, provided the first modern account of the internal stratigraphy, albeit based in part on earlier workers (e.g., Klein, 1957, 1960). Hudgins (1960) recognized the following stratigraphy (Table 1) for the NMB mostly based on a measured section around the Digby Gut area (see Fig. 4 for location).

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	Vary in 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

West of Digby, in particular Long Island and Brier Island, the area was mapped by Lollis (1959) and Koskitalo (1967), with several diamond drill holes part of the exploration work of the latter author. These authors both recognized that the NMB could be conveniently subdivided into three units based on the nature of the flows. Lollis (1959) provided the nomenclature for these units of 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 thicknesses were 185 m, maximum of 92 m, and 154 m, respectively, based on sections measured in the East Ferry area. More recently, Mallinson (1986) measured a section along the west end of Long Island at Freeport and integrating information from a diamond drill hole (Koskitalo, 1967) provided the following stratigraphy.

1. SSM - 112 m of massive basalt;
2. MM - 4 flows of 1.5 m to 2.5 m at Ronnie's Point, but 7 flows of 3.3 m to 9 m in drill core with maximum thickness of 41 m. (Note: this rapid change in flow number and thickness characterizes the MM of the NMB, as noted by Mallinson (1986) and observations of the authors);
3. NSM - 61 m of massive basalt.

Sinha (1970) proposed a subdivision of four flows for the NMB, from the Blomidon Flow at the base, an Older and Younger Cape Split Flow (collectively the MFU), to a younger Scots Bay Flow. He also suggested that interflow sediments separated the latter two flows (Younger Cape Split and the Scots Bay).

Recent Studies

Integrating previous studies with additional work, Kontak (2002) proposed the stratigraphic framework for the NMB that is presented in Figure 5. In this diagram the terms lower (LFU), middle

(MFU) and upper flow (UFU) units are used as proxies for the terms of Lollis (1959). With respect to Figure 5, the following points are noted from the base upwards.

1.Very little is known about the relationship of the basal flow contact with the underlying sediments, either Triassic or older. Locally there are areas of intense bleaching and clay alteration and local concentrations of Fe mineralization (Hudgins, 1960; G. O'Reilly pers. Commun., 2002; our observations), but the extent and significance of such zones remains unconstrained. An important aspect of the basement rocks to the NMB is their paleotopography at the time of basalt eruption. Given the fluvial-deltaic and aeolian nature of the deposits (Hubert and Mertz, 1980, 1984), it is assumed that the overall landscape at this time was generally flat with limited relief. Such low relief is supported by the presence of abundant pipe vesicles at the base of NMB flows – such structures are favored by low slopes (e.g., Walker, 1987) – and the presence of pahoehoe flows in the MFU, which are also favoured by low slopes (e.g., Hon et al., 1994).

	McKay Head-Parrsboro	Valley	Digby	East Ferry	Freeport
	Greenough et al (1969a)	this work	Hudgins (1960)	Lollis (1959)	Mallinson (1986)
	McCoy Brook Fm.	Scots Bay Fm			
UFU	???????	? thickness	20 m, 2	154 m, 2	>61
MFU	75 m, 3 flows - McKay Head ≥50 m, 3 flows - Cape D'Or	150-165	>71 m,	92 m,	9-41 m,
LFU	≥90 m - Economy Mtn. ≥175 m - McKay Head ≥150 m - Cape D'Or	40-80 m -	>90 m,	185 m,	112 m,
Basement	Carboniferous or Triassic sediments	Triassic	Triassic	Triassic	Triassic

Figure 5. Stratigraphic sections for the NMB along the Annapolis Valley and north side of the Bay of Fundy in the McKay Head-Parrsboro area (modified after Kontak, 2002).

2. The LFU varies in thickness from 40 to 185 m. As will be demonstrated below, this variation is real and may relate to structurally-controlled topographic variation that existed prior to extrusion of the LFU basalt. All previous workers have inferred that the LFU represents a single homogeneous unit. The LFU is fully exposed at Parker Mountain quarry near Annapolis Royal, where the unit appears as a uniform-textured, massive, holocrystalline, rarely hypocrystalline, basalt with well-developed columnar jointing

without any apparent break in the exposed section. Well-exposed sections of the LFU at East Ferry (Figs. 3, 4 of Lollis, 1959), McKay Head (Greenough et al., 1989a; Greenough and Dostal, 1992b), and Mount Pleasant (Baldwin, 2004) display mafic pegmatite (dolerites of Lollis, 1959) and rhyolite bands in the upper parts, but pegmatites also occur lower in the flow (e.g., Beamans Mountain; Baldwin, 2004).

3. The MFU varies in aggregate thickness, number of flows, and thickness of the individual flows (maximum ca. 20 m) along the strike length of the NMB. In the McKay Head-Parrsboro area, the flows are consistently thicker than in the Annapolis Valley, but are fewer in number. There appears to be a thinning of the MFU southwestwards towards Freeport-Brier Island. The MFU contrasts markedly with the LFU and UFU in several ways, discussed in detail later, but two are noted here: (1) the presence of abundant, zonally arranged amygdules; and (2) preservation of many features suggesting growth by endogenous growth of sheeted pahoehoe flows (e.g., flow toes, horizontal vesicle zones, tumuli, ropy tops; Hon et al., 1994; Self et al., 1996).

4.The UFU is overlain by sedimentary rocks of the Jurassic Scots Bay Formation in the Annapolis Valley area, but by McCoy Brook Formation sedimentary rocks along the north side of the Bay of Fundy. Interestingly, in the latter area abundant interflow sediments and sedimentary dykes within the MFU, whereas such features are much less abundant in the MFU along the length of the Annapolis Valley. The MFU, although overlain by sediments in the Ross Creek area (field stop below) of the eastern Annapolis Valley, is overlain by the UFU further to the northeast in the Scots Bay-Cape Split area.

5. The UFU forms promontories along the coastline in the central and eastern part of the Annapolis Valley and further west they become dominant, such that the MFU rarely outcrops along the shore, but only inland. The nature of this exposure probably relates to dextral offsets along northeast-trending faults at several locations between Brier Island and Digby Gut. In places (e.g., Freeport) the UFU can be subdivided into a lower and upper part based on the presence of columnar jointing in the base and a more massive textured upper part with a honeycomb network of silica veins. This subdivision has been variably interpreted to represent either a single flow with internal variation or two separate flows. Further work is required to reconcile this problem.

6. There is an apparent absence of UFU basalt along the north shore of the Minas Basin; the reason for this presently remains unknown. However, further west on Grand Manan Island McHone (2005) has recognized a similar three-part subdivision of the equivalent-age basalt sequence. The presence of a disconformity at McKay Head with a thin (<1 m), weathered, veneer of angular blocks of amygdaloidal basalt in a silty matrix at the top of a MFU lava flow sitting immediately below McCoy Brook Formation sediments (field stop day 1). This relationship indicates neither a structural hiatus nor an extended period of uplift and erosion prior to deposition of the overlying sediments. Thus, it is possible that UFU basalts

were never present along this part of the Fundy Basin.

Having stated the above, we note that there are some problems with this interpretation when applied to the NMB on the north side of the Bay of Fundy, in particular the McKay Head area where three or four flows considered to be part of the MFU sequence (Fig. 5) are interpreted by Greenough et al. (1989a) as possible breakouts on top of UFU basalt. We will be visiting this locality on day 1 and this issue will be discussed.

Several cross-sections of the North Mountain were prepared by Kontak (2002) using the following geological constraints: (1) several exploration drill holes collared in the MFU provide the best constraints on regional dips of the basalt-sediment contact and dips between flow units (LFU-MFU); and (2) contacts between the LFU and underlying sediments and between the different units of the NMB, as inferred from field relationships. On these sections two dips have been used for extending contacts, 8° and 3°. The 8° dip represents a maximum for the range of 5-8° commonly quoted from observations of the flows themselves (e.g., Hudgins, 1960; Lollis, 1959; Mallinson, 1986), whereas the 3° dip is based on assumptions made from interpretation of the sections. One of these sections is shown in Figure 6a and the following features are highlighted.

1. The regional dip for the contact between the NMB and sediments and flow unit contacts is close to 2-3°, which is much less than what is observed locally for flows.
2. There is an inconsistency in the thickness of the LFU based on the exposure along the escarpment of the North Mountain (ca. 200 m) versus that determined from the drill holes (30-80 m). This inconsistency is apparent on the three sections constructed by Kontak (2002) who suggested that this thickness variation of the LFU is real. This change in thickness of the LFU has not been recognized previously.
3. The present relief of the North Mountain is attributed to the massive nature of the LFU basalt. Had the LFU been composed of multiple amygdaloidal flows similar to the MFU, then the North Mountain proper would not be a prominent topographic feature due to erosion, as has been the case for the MFU.

In order to accommodate the variation in thickness of the LFU, as inferred from the cross sections, an interpretation of one section is shown in Figure 6b. It is suggested that pre-eruption faulting created a topographic depression of ca. 100-120 m within which the LFU was deposited as a ponded flow or lava lake, thus accounting for its unusual thickness and obvious textural uniqueness compared to the MFU and UFU (i.e., dominantly holocrystalline with little or no mesostasis). The extent of this northeast-trending fault feature is not known and it is not manifested in the field, or at least nothing as yet noticed.

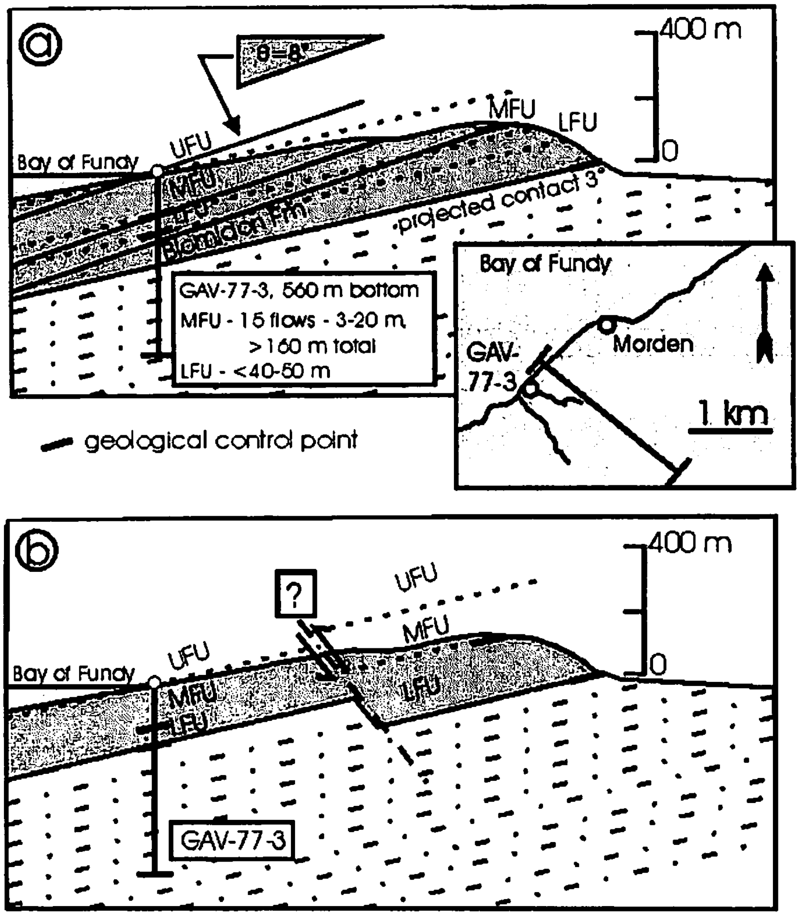


Figure 6. (a) Cross section from southeast to northwest (i.e., facing northeast) showing the constraints on the regional geology of the NMB. The extrapolated geology of the flow units and basal contact is inferred using a regional dip of 8°, which has been suggested for the NMB flows. However, this dip does not accommodate the geological constraints. (b) Interpretative diagram for the flows where a dip of 3° is used and, in addition, faults are inferred as a means to explain the variation in thickness of the LFU.

The integration of digital elevation models (DEM) using topographic data with field mapping allows general maps of the NMB to be made where access is difficult. Such a map is shown in Figure 7 for the area around Digby (from Kontak, 2002) and illustrates well the application of this technique. The method works because of differential weathering of the three flow units that relates to the friable nature of the flows of the MFU due to their enrichment in zeolites. Webster (2004) has since refined this method and extrapolated it to other areas of the North Mountain with similar success. Such maps are used in parts of the field guide to show the general geology of relevant areas.

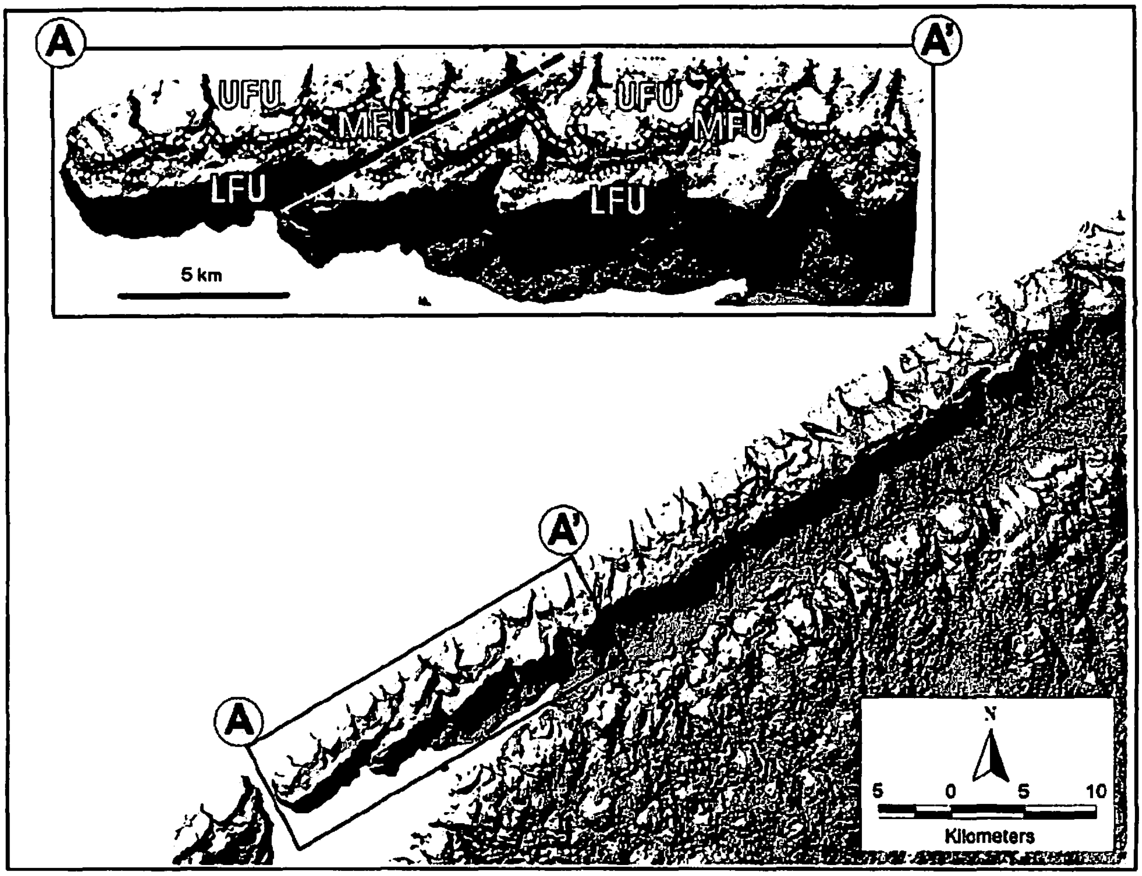


Figure 7. Digital elevation data for the Digby area (modified from Kontak, 2002) showing the inferred geology of the LFU, MFU and UFU of the NMB, as based on field checks here and in other areas. The integration of such data allows rapid mapping and extrapolation of the units on a regional scale.

VOLCANOLOGICAL FEATURES OF THE NORTH MOUNTAIN BASALT

In order to understand and appreciate the physical aspects of the NMB, a review of the current understanding of the generation of pahoehoe basalt flows is provided below. More detailed descriptions are found in the reference provided and a list of the volcanological terms used is provided in the glossary at the end of the guide for a quick reference. We note that the nomenclature can, at times, appear to be a bit confusing and beware that there is no consensus as to the terms that are used in the literature. Herein we use the terminology that Self and co-workers have been using for the past several years (e.g., Thordarson and Self, 1998; Keszthely et al., 1999).

Pahoehoe Flows: Overview of Formation

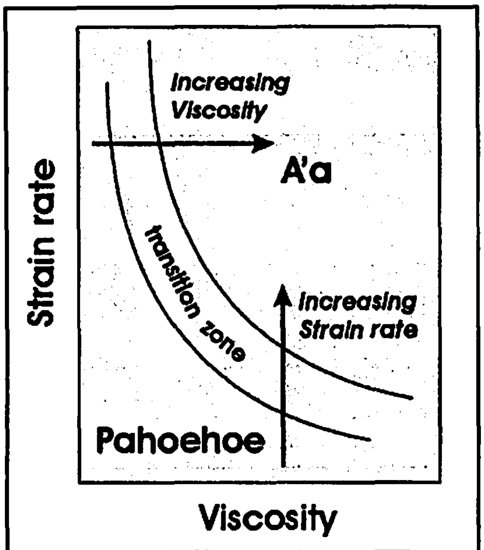
As noted in the introduction, subaerial basalt flows and their submarine equivalents are the most voluminous and aerially extensive volcanic rocks on earth; thus, it is important to understand their emplacement mechanism if, for example, inferences are to be made with respect to the impact basalts have on the atmosphere and climate change due to their emplacement. Among basalt flows, it is the sheeted, low-viscosity pahoehoe type that dominates over the channelized, faster moving and more viscous a'a flows. Thus, we discuss the features of the pahoehoe flows below based on recent observations.

The term pahoehoe refers to lava flows having a distinct distribution of structures and internal, three-fold subdivision consistently arranged vertically. As summarized elsewhere (Aubele et al., 1988; Self et al., 1997; Cashman and Kauahikaua, 1997; Thordarson and Self, 1998), these divisions are: (1) a chilled (i.e., hypocrystalline to hypohyaline) lower crust with vesicles; (2) columnar-jointed, massive, vesicle-poor to vesicle-free, holocrystalline lava core; and (3) vesicle-rich, hypocrystalline upper part or lava crust. The boundaries of these divisions are easily distinguished and relate to development of the flow, as discussed in some detail below.

The nature of pahoehoe flows relates to the rate and duration of effusion, and inclination and topography of the slope they erupt onto. For example, the general absence of tube structures, which reflect drainage of lava, implies long duration, sustained flows that did not have the opportunity to drain. Similarly, distal flows rarely deflate, since they require sustained input to be of such large magnitude. There are several features of lava flows, as based on observations of modern examples (e.g., Hawaii) that distinguished them as being pahoehoe:

- low viscosity and entirely coherent;
- "ropey"-smooth, glassy surfaces, but commonly altered in ancient flows;
- flow fronts of 10-30 cm thick; lobate to massive;
- flow interiors are massive to multi-lobate, m's to tens of m's thick;
- effusion rates are variable;
- lava can flow tens or more km through channel (near vent) to tube fed magma supply;
- source vents: fissures, central vents (e.g., CRBG);
- eruption styles: fire formation, effusive.

The features of the pahoehoe flows, of which the NMB are excellent ancient examples, contrast with a'a lava flows that are more viscous, rubbly or hackly with autobrecciation common, and have different eruption styles (point source). This said, and with reference to Figure 8, the following points are noted about potential transition from one basaltic flow type to another. As pahoehoe flows cool, crystallize and lose gas they become more polymerized and, therefore, viscous and may assume some features of a'a flows as they are distanced from their source. Similarly, advance down slope from their source with concomitant increase in shear due to topographic change may result in increasing strain rate.



Finally, a change in eruption rate to >5-10 m^3/sec can change the type of flow due to variation in shear.

Figure 8. Diagram showing relationship between strain rate and viscosity for basalt flows and illustrates how pahoehoe and a'a flows are related. Note that a pahoehoe flow may change to a'a type flow under certain conditions. (Diagram modified after figure at www.geology.sdsu.edu/how_volcanoes_work/Basaltic_lava.html.)

The inflation model discussed below, from excellent summaries in Hon et al. (1994), Self et al. (1998) and Keszthelyi et al. (1999) is based on the cited authors' observations of active flows of Kilauea Volcano, Hawaii, and well-preserved ancient flows (e.g., CRBG). These sheet flows were observed initially to propagate as thin (10-50 cm), fluid pahoehoe lava that later inflated (vertical growth) to ≥4 m. Initially, the lava flows as low-viscosity, Newtonian fluids with low-yield strengths (Shaw et al., 1968). However, the loss of heat results in formation of a thin (mm scale) crust and, as a result, non-Newtonian behaviour of the lava. The important consequence of crust formation is that the lava flow can build up hydrostatic pressure internally and inflate at the leading edge, this ballooning sensation causing formation of pahoehoe toes or lobes. The hot layer is viscoelastic and will allow the toe to swell before rupturing to form another toe via a breakout (see excellent photos of this phenomenon in Crown and Baloga, 1999).

Deformation of the outer skin is evident from the presence of flattened (i.e., sheared) vesicles of originally spherical shape (e.g., Walker et al.'s (1999) description of vesicles in the Birkett flow, CRBG). Where appropriate material is available in young or ancient flows, a progression to more spherical vesicles is observed inwards from the original margin. The outer skin is deformed by the continued flow of the interior lava and this shearing causes formation of such textures as ropy surfaces, one of the characteristic features of pahoehoe flows.

The growth, size and shape of pahoehoe flows depend on the slope of the erupted surface. Relatively steep slopes permit crustification of lobes before they come in contact with each other, whereas flows on shallower slopes have similar forward and lateral velocities and cause lobes to impinge on each other before crusts form and encourages coalescence. The progress of sheet advancement is ca. 0.5-1.2 m^3/sec. This process produces a continuous lava core beneath a similarly continuous crusty layer (note that in active flows billows outline the extent of earlier lobes and these eventually smooth out as spreading continues). In this manner, individual flow sheets of several 100's to 1000's m width and multi-km to tens of km length form (Self et al., 1996, 1997). It is critical to note that it is rare to see contacts between lobes and such contacts are texturally modified after lobe coalescence. Duration of active inflation can be estimated from the thickness of interior units (see below) due to thermal annealing.

The nature of a lava flow, sheet and field are shown in Figure 9; note that in the diagram the flows are being fed by tubes, that is underground flowage of lava beneath an overlying stationary crust. In this diagram there is a progression in the lava flow with the advance due to breakouts at lobe fronts. As the flow front is advancing, the original flow is growing vertically, that is inflating, as new lava is continually brought in from the source via the lava tube, which may be quite distal (i.e., km scale). The most important aspect of the formation of these lava flows is that the formation of the upper crust acts as an efficient thermal insulator which allows the central part of the flow to remain molten and retain its low viscosity. Another very important aspect in Figure 9 is the time scale, as it is hours in the case of breakouts (stage a), but days to years for inflation (stage b), to months and decades for the stagnation and final crystallization of the lava flow.

The nature of the lobes, either S- or P-type lobes, relate partly to their occurrence, with the former in flows with minimal inflation and the latter in inflated lobes. Spongy (S-type; Walker 1989) have spherical vesicles throughout with density increasing inwards. In contrast, dense interiors and more vesicular outer margins are typical of P-type (Wilmoth and Walker, 1993). Development, degree and distribution of vesicles in flows are complex due to changing pressure, the effect of which is to promote

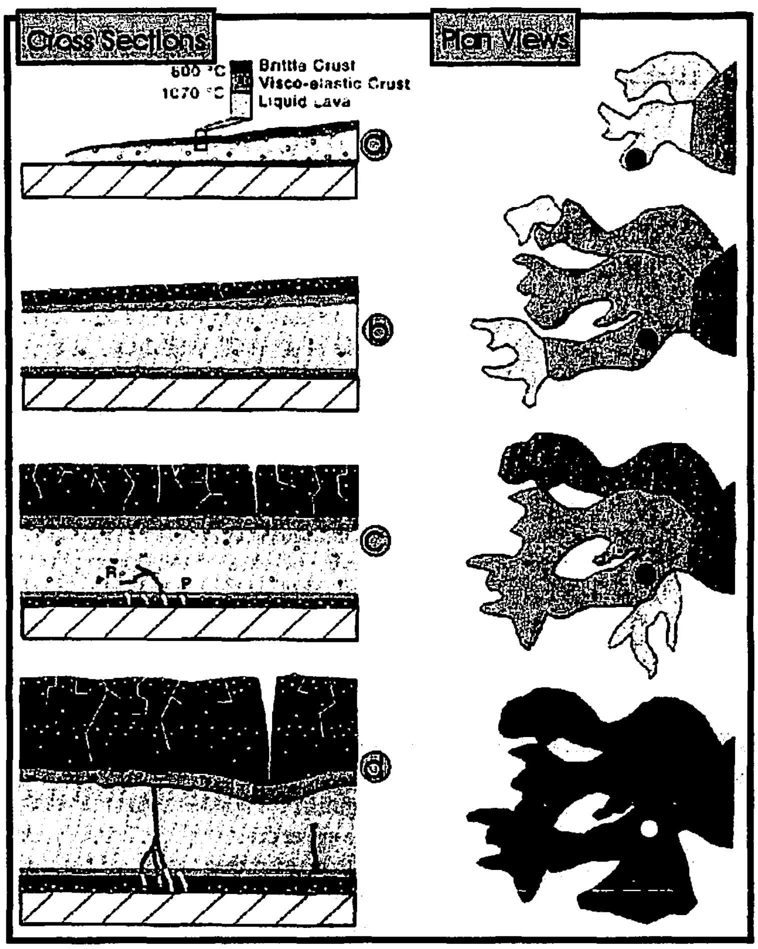


Figure 9. Schematic map illustrating the growth of an inflated pahoehoe sheet flow (from Self et al., 1998). On the left are cross sections with dots indicating their location in plan view on the right diagram, which are aerial views of the development of the flow field. These diagrams apply over a range of scales from 1-100 m thickness and <100 m to >10 km in lateral dimension and inflation can occur over days to years. The degree of darkening represents the degree of cooling, thus the darkest regions are the oldest part of the flow. Sequence of events: (a) new lobe advance from right to left resulting from breakouts; (b) lobe thickens due to inflation, bubbles from the new lava are trapped in the overlying crust forming vesicles, and upper crust grows faster than the lower part of flow; (c) inflation continues as new lava is injected from a distal source. Depressurization coincident with a breakout causes vesiculation of the lava, subsequent rise of the bubbles and formation of sheeted vesicle zones. Late-stage, residuum (R) of silicic

composition generated from the advancing, lower crystallization front is buoyant and rises into the overlying magma. Pipe vesicles(P) form in the lower crystallized zone; (d) the flow stagnates and last bit of residuum rises to form pipes and horizontal sheets at the base of the upper crust.

gas to dissolve back into the melt. A most important aspect of the pipe vesicles in the base of flows is that such features only form on shallow slopes, i.e., those of $\leq$2-4° (Walker, 1987; Hon et al., 1994) and thus have implications for paleotopography in paleo-flow fields.[Note: pipe vesicles are common in the basal parts of flows of the MFU of the NMB]

The endogenous growth or inflation of the flows occurs as the crust thickens and hydrostatic pressure builds up in the frontal parts of the flows, as lava replenishment continues. This pressure is dispersed equally within the flow and leads to generation of impressive plateau-like sheet structures. These features have been variably named "pressure plateaus" or "pressure ridges" (Note: Hon et al. (1994) discourage such terms unless lateral compressive stress can be demonstrated) by Wentworth and MacDonald (1953). MacDonald (1991) used the term "lava rises" for the smooth, flat-topped tumuli that are morphologically similar to inflated sheet flows, and hummocky pahoehoe for the topographically irregular sheets created by tube-fed pahoehoe.

The structures formed within the lava flows, sheets or fields can be complex because of the interplay of variables (i.e., effusion rate and volume, slope, topography, etc.). The margins of the sheets are monoclinal inflections and hinges may be marked by en echelon cracks (veins if later filled), the "lava-inflation clefts" of Walker (1991). These inflections may be a result of increased viscosity of flows towards margins and continued inflation of the core that leads to detachment of the inflated lava from stagnated margins (Fig. 10). Similarly, joint and fracture development will vary depending on the nature of the flows. Development of the fractures and related textures can be complex and the reader should see Hon et al. (1994, and references therein) for more details. Where flow margins have a sudden, steep change in slope or topography, folding of the flexible crust may occur. Changes in topography, especially depressions, can lead to formation of tumuli due to build up of pressure within constricted parts of the lava tube (Fig. 10a) or inflation pits where adjacent tumuli are present (Fig. 10a, stage c). Where there is active inflation, the flows may be bounded by scarps or clefts when the actively inflating lava core becomes isolated from the margin. Overhangs may result from subsequent, continued inflation. Shearing of the margins or interiors can occur, although rare, and where intense broken and slabbed crust (slabby pahoehoe) forms, so do ropy and groove textures that are generally perpendicular to flow movement. The increased viscosity of the flows with advanced crystallization and cooling can lead to development of features more akin to a'a flows (see diagram above). Some of the features described above are shown in

Figure 10.

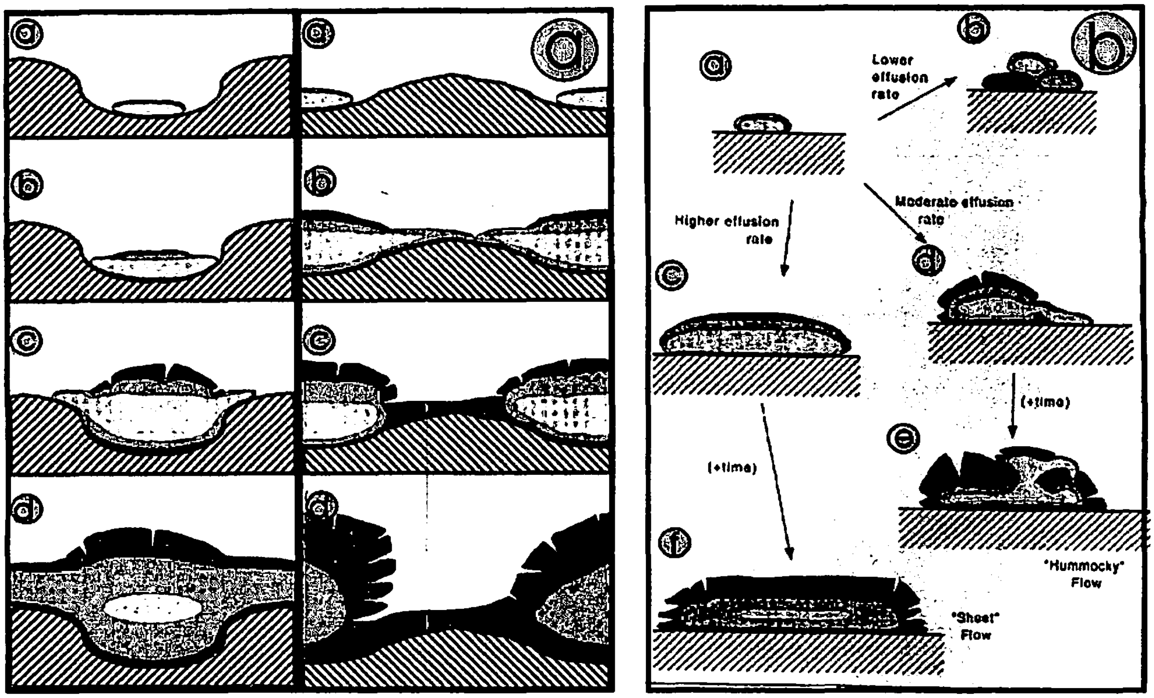


Figure 10. Schematic diagram (from Self et al., 1998) illustrating formation of tumuli (Fig. 10a), inflation pits (Fig. 10a stage d, 10b stage d), and inversion of topography during inflation (Fig. 10a). The key point here is to note that the thickest part of the flow will occur over the oldest part of the sheet, since this is originally where the lowest ground was. Once the depressions have been filled by the flows, breakouts can cover what was once the earlier higher ground. Note that the inflation pit widens with depth (Fig. 10b stage d), as the bounding lava lobes cool inward with time.

It is important to note that the distinction between the lobes, flows and flow fields can be difficult. Since the flows are generally active for long periods of time and there are many active flows, with each of these being compound in the sense of numerous breakouts, it is a difficult task to unravel the entire history of ancient flows. Thus, even the most simple or basic flow will likely be compound, as emphasized by Self et al. (1998). Examination of much of the NMB also attests to this, with rare preservation of lobes within the large sheet flows. In Figure 11 is illustrated what a compound inflated pahoehoe flow field might look like. The emplacement of large basaltic lava flows as sheet flows following the mechanism discussed above lead Self et al. (1998) to propose the SWELL model, that being the Standard Way of Emplacing Large Lavas as compound, inflated pahoehoe lava flows.

Pahoehoe Flows: Lobes, Sheets lobe, sheet flow, and lava field

The nomenclature of lobes, sheet flows and lava flow/field can be confusing, thus we clarify the usage here. The term lobe or flow lobe, as suggested by others (e.g., Self et al., 1997; Thordarson and Self, 1998; Keszthelyi et al., 1999), describes a discrete lava entity surrounded by its own chilled crust; these cases are rare and most commonly seen as relatively small (i.e., few m) surface breakouts at the tops of flows. Where lobes have flat tops that are much wider than thick, the term sheet lobe is used and when several of these may be stacked the term sheet flow is used. Lava flow is a more general term that would apply to the latter, that being a sheet flow, and is used to describe mappable units that are composed of sheet flows and represent individual eruptive events (i.e., the LFU, MFU and UFU). Lava field represents the final, collective or aggregate products of a single eruption that is recognized by distinct petrological features (i.e., the entire NMB).

Pahoehoe Flows: Late-stage Features and joint Development

Stagnation of the lava within an inflating flow will eventually occur, the consequence being final vesiculation of the lava, as solidification continues unabated without injection of new lava; this process can lasts for months to years depending on the size of the lava flow. In addition, during crystallization of the core, incompatible elements, including volatiles, will concentrate in the residuum. This latter material can rise as buoyant diapirs and even spread out laterally as sheets (vesicle sheets of Self et al., 1998) once the residuum overcomes the viscosity and yield strength of the melt. As these diapirs form late at the terminal stage of inflation when the flow is stagnant, they have subvertical orientations - ***this is an important feature as it permits rotation of tilted lava flows to their horizontal.*** A summary diagram of the aforementioned features that might be expected in an inflated pahoehoe flow is shown in Figure 12, which is based on observations in both young and ancient flows.

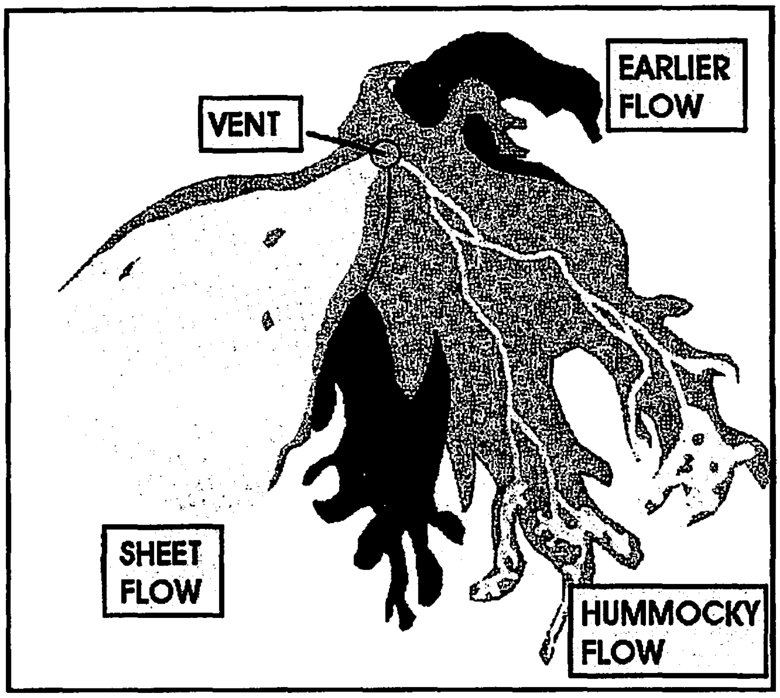


Figure 11. Schematic map of a compound inflated pahoehoe flow field (from Self et al., 1998) constructed from a number of separate flows, which may originate from different vents. Note that lava is transported via an anastamosing network of lava tubes and that the entire width of a lava flow is able to transport lava. The formation of the hummocky flow sometimes occurs near the front when the viscosity of the lava increases.

The recognition of the internal subdivision of lava flows and their construction over times is important since these zones are time and process dependent. Using the presence of the lower vesicle-rich zone and beginning of the dense core, often marked by presence of a vesicle sheet, one can estimate the duration of inflation via the following equation:

(1) $t = 164.8 * H^2$

where t=time (in hours), H=thickness (metres) of upper crust (see Figure 12). A simplified version of this diagram, using examples from the NMB and is applicable to MFU lava flows is shown in Figure 13 and details of this will be discussed in later sections of the guide.

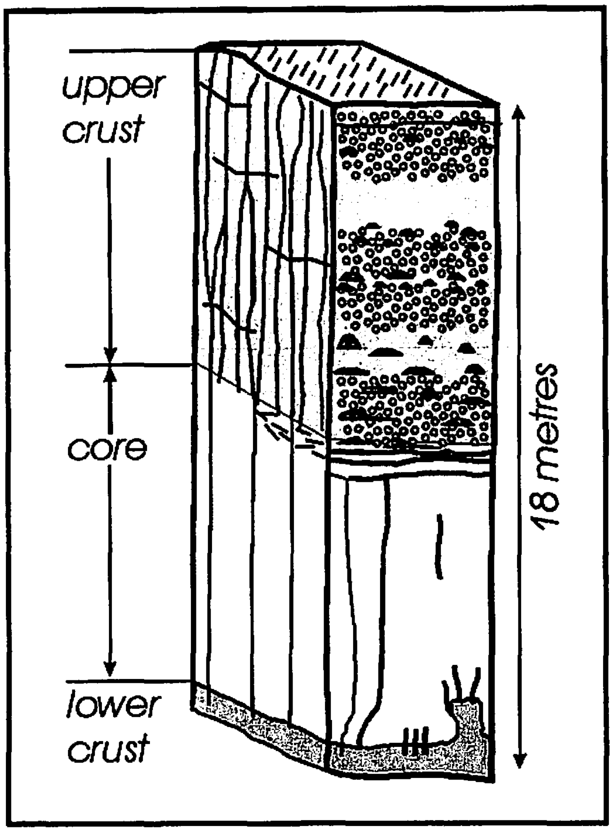


Figure 12. Cross section of an inflated pahoehoe lava flow that is typical of such flows in Hawaii, Iceland and the Columbia River Basalts (from Self et al., 1998). Note that the scale is variable depending upon the flow, thus the 18 m shown here is specific for a particular flow (Levering flow, CRBG). The three zones shown, the upper crust, core and lower crust, and the contained features are diagnostic of pahoehoe flows. Thus, although the thickness may vary, the three zones are always present.

After the lava crusts have solidified and begin to cool, commencing at 900-100°C, thermal stress builds up and this energy is released to form cooling joints (note that some joints may also form from differential subsidence), commonly referred to as columnar joints. Simplistically, these joints are generally perpendicular to the external surface of the lava flow and form a regular polygonal pattern in plan view. For thick, ponded flows or lava lakes this may be idealized as the thickening of the two crusts, the lower and the upper, as the solid-melt interfaces of each contract with time and the percentage melt in the core diminishes. Thus, the fracture front follows closely the solidification front of the magma. The fracture and pattern style is predicated by the type (i.e., convective, conductive) and rate of cooling, thus the surrounding environment.

As summarized in Ryan and Sammis (1978), studies of cooling lava lakes in Hawaii has placed the crust-melt interface at 1070 ± 5°C, that the crust grows at a rate of 1.3 cm/month, and that tensile cracks begin to form in the upper crust before a thickness of 0.5 mm is achieved. The rate of cooling will determine if a widely spaced (i.e., colonnade, 40-200 cm; ≤ 1°C/hr)) or closely spaced (i.e., entablature, 20-40 cm; ≤ 10-1°C/hr) jointing pattern is developed (summary in Degraff et al., 1989).

Although the images of regular, six-sided polygons are often used to represent the formation of the cooling joints, more irregular patterns are known because of formation of multi-generation joints (e.g., Peck and Minakami, 1968) and superimposition of entablature on colonnade patterns. An additional complication of the jointing pattern is created by introduction of water, this affects the upper part of cooling flows and may generate chaotic patterns (Long and Wood, 1986). The effect of such influx of water is to change the rate in different directions and thus isotherms need not necessarily parallel the surface of the flow. Since columnar joints generally form perpendicular to lines of surfaces of equal cooling (i.e., isotherms), inclined columnar jointing may occur and this is commonly observed in the LFU of the NMB.

The nomenclature used to describe the distribution of cooling joints within flows is that of Long and Wood (1986), modified slightly after that originally proposed for the famous columnar-jointed basalts of the Giant's Causeway, Ireland (Tomkeieff, 1940). Although use of the term columnar jointing is often considered to represent six-sided columns, such is not always the case. For example, in tabulating data for famous localities globally, Beard (1959) noted that the number of sides varied from 3 to 8. In addition, although the frequency was greatest for five- and six-sided columns, only at the Giant's Causeway did six-sided columns dominate (51% vs. 35%). As noted already, colonnade and entablature are used for widely and closely spaced jointing (40-200 and 20-30 cm, respectively; Fig. 14). Entablature joints have the added complexity of being irregularly curved or radial (Fig. 14a), often related to an irregular cooling history. The layers of the lava flow with these characteristics are referred to as tiers. Sometimes horizontal or flat jointing may develop and is referred to as platy jointing.

The petrographic features of the rocks (i.e., grain size, percentage mosostasis, grain morphology) correspond well with the nature of the jointing, thus confirming that cooling rate is the dominant control on the nature of jointing (see Long and Wood, 1986; Degraff et al. 1989). However, an important observation made in examination of both historical (CRBG; Long and Wood, 1986) and modern (Degraff et al., 1989) flows is that interlayering of colonnade and entablature require models other than simple conductive cooling to account for the distribution of joint patterns. As noted by other workers, infiltration of large volumes of surface water in large volumes can promote formation of the jointing patterns.

Finally, with respect to jointing, we note that Self and co-workers do not recommend use of the terms colonnade and entablature used in the sense of Long and Wood (1986) because they carry a genetic implication. Instead, they use columnar and crustal zones for widely- and closely- spaced jointing, respectively. Although this terminology works to a certain extent in the MFU lava flows, it is not applicable for the thicker LFU and UFU flows and, therefore, we retain the

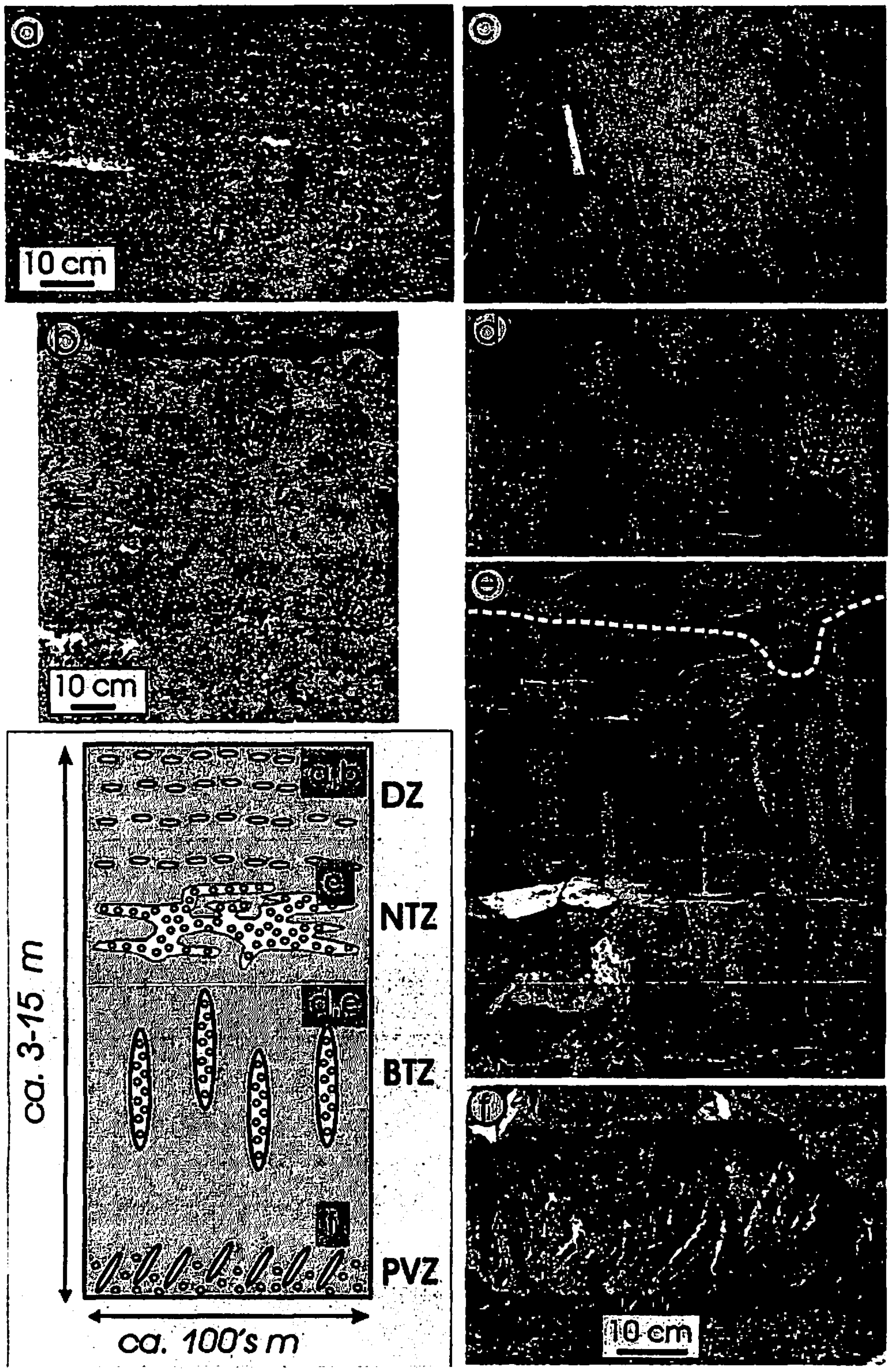


Figure 13. Schematic profile through a pahoehoe lava flow (modified after Aubele et al. (1988) and Kontak (2001)), showing the types of vesicle zones in a sheet lobe or flow of the MFU of the NMB. Importantly, this systematic pattern is repeated in all lava flows within the MFU. Pen knife for scale in

photos is 9 cm long. (a, b) Upper vesicle-rich zone, referred to as the Disseminated Zone (DZ), with ≤50-70% amygdules arranged in either a random pattern or horizontal vesicle-rich layers. In the latter case, sequential depressurization events in the core of the lava flow reflect breakout events and lead to degassing and formation of the vesicle layers. (c) Net-textured Zone (NTZ) that equates to the horizontal vesicle sheet zone of Self et al. (1998) which shows continually connected amygdaloidal zones between areas of non-vesiculated basalt. (d, e) Plan and cross-sectional views, respectively, of the Bubble-Train Zone (BTZ) showing individual vesicle cylinders with abundant contained amygdules. The width and length of the cylinders can vary, as discussed in the text. Note in the top of Figure 13e the BTZ merges with the NTZ (dashed white line). (f) The basal Pipe Vescile Zone (PVZ) with inclined mega-vesicles indicating dextral shear and, hence, movement direction of the flow (view of photo to southeast). Note that smaller amygdules occur between the larger pipe vesicles.

terms mentioned above. In the NMB there is exceptional development of jointing with megacolumns (i.e., ≥2 m width) often seen in the UFU. There is also development of multiple tiers or layers within both the LFU and UFU, an excellent example of which is seen in the UFU at East Ferry, Long Island (Fig. 14b).

VOLCANOLOGY AND DISTRIBUTION OF THE FLOW UNITS OF THE NORTH MOUNTAIN BASALT

Lower Flow Unit (LFU)

The LFU outcrops extensively on the south face of the North Mountain along the length of the Annapolis Valley and is easily accessible along road cuts and stream sections. However, past Digby area there is a marked change in topography and the LFU actually occurs along the southern coastline of Digby Neck and contiguous Long Island. In these areas the prominent *cuesta* is defined not by the LFU, but instead by the UFU.

The LFU is a massive, dark greenish to dark grey-green basalt with microcrysts of plagioclase and pyroxene (augite >> pigeonite) with minor amounts of mesostasis (5-15%) sometimes present. The upper and lower contacts are chilled, as observed in drill core, and both are vesiculated to varying degrees. The lower contact has a thin (<10-15 cm), chilled zone with amygdules amd rare pipe vesicles, both containing zeolites. In contrast, the upper contact is vesiculated over a wider zone (≤1-2 m). An excellent exposure of this contact, but very precipitous to ascend, is at the top of Kane Quarry (located at base of North Mountain near Glenmont, Fig. 25a). At this locality, several, thin (10-20 cm), parallel layers of highly vesicular basalt occur and the host basalt is intensely altered.

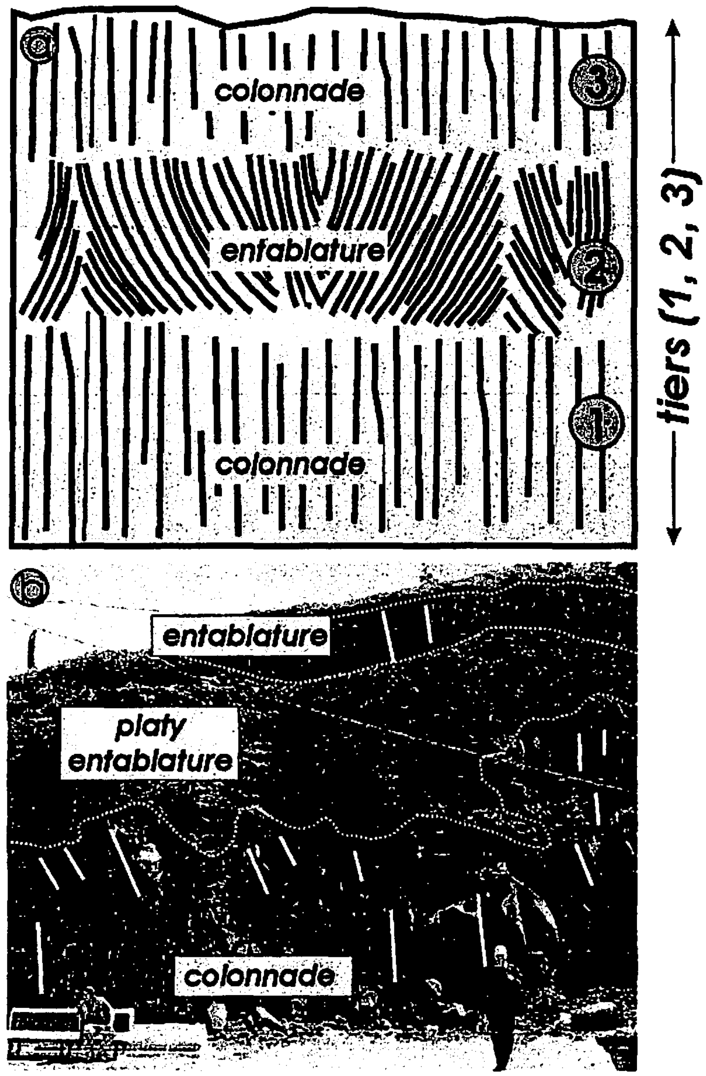


Figure 14. (a) Schematic cross section showing the nature of colonnade and entablature jointing in homogeneous basalt. Note that there is a single flow unit represented here, not three successive flows. (b) Outcrop of UFU basalt at East Ferry, where a similar style of jointing as that shown in Figure 14a is present. The chaotic nature of the entablature reflects differential cooling and relates to the infiltration of water as the basalt was cooling (e.g., Long and Wood, 1986). The orientation of the columns in both the lower and upper colonnade parts of the flow are of variable orientation, also consistent with differential cooling due to the influx of water.

The most significant feature of the LFU is layering of near horizontal mafic pegmatite (cm, but rarely ≤2 m) with or without thin (≤ 1-2 cm) rhyolite bands that occur mainly in the upper (i.e., top 30-50

m) part of the flow, although at one locality (Beamans Mountain, see later) it is in the lower part of the flow. This layering in the LFU, first noted by Lollis (1959) along the section exposed at Petite Passage between Digby Neck and Long Island, has since been recognized as other excellent exposures have become known, such as Mt. Pleasant and Beamans Mountain quarries (Baldwin, 2004), and McKay Head (Greenough and Dostal, 1992b, c). The layering is also noted in drill holes that penetrated the LFU (our observations). These pegmatites locally have comb-textured megacrysts (≤15-20 cm) of Fe-rich augite in a leucocratic matrix (i.e., granophyre). The pegmatitic layers are considered to be a product of extreme fractionation of the residual melt and may, in part, represent immiscibility. The origin of the McKay Head occurrence, discussed extensively by Greenough and Dostal (1992b, c), relates to immiscibility. Occurrences of similar pegmatites in the ENA magmatic province are described by, among others, Puffer and Horter (1993) and Puffer and Volkert (2001).

Jointing is well developed in the LFU with columns of variable widths observed, that is both colonnade (Parker Mountain Quarry) and entablature (e.g., East Sandy Cove). In some places where there is considerable exposure of the unit (e.g, Parker Mountain quarry near Annapolis Royal) planar columnar jointing is seen throughout the vertical exposure of the unit, whereas in other localities (e.g, Little Harbour, Freeport) the lateral continuity of joint development can be followed out over great lateral distances (i.e., several km). However, there are also excellent examples (e.g., Kane and Burlington road quarries) of multi-tired sections with both colonnade and entablature and variably inclined orientations for the columns. Development of platy entablature is also observed at the Kane quarry and East Ferry, both recommended stops.

A common feature in the LFU is the presence of thin silica veins lining the columnar joints along with ridges outlining this jointing due to differential weathering of the basalt, with the silicified areas around the silica-filled joints more prominent. This aspect of fluid infiltration into the NMB has not been noted before and remains to be studied. Rare cases of sedimentary dykes penetrating the LFU have been seen (e.g., Parker Mountain quarry).

Rare cases of circular structures have been observed in the LFU by many workers based on air photo interpretations or outcrop distribution (e.g., Lollis, 1959; Hudgins, 1960; Koskitalo, 1967; Stevens, 1980; G. Prime, pers. Commun., 2002). More recently, the use of digital elevation imaging (DEM) has revealed many more such structures (e.g., Lawrencetown area; Webster, 2004) and Long Island (our observations). Although some have suggested these textures may be artifacts of the exposure and erosion (Koskitalo, 1967), others have suggested an origin related to primary volcanological processes, such as spiracles (steam from heated ground water blasting through the flow; Webster, 2004; Webster et al., submitted) or volcanic vents. Similar structures, but more abundant, occur as elliptical to round lakes on the top of the North Mountain (e.g., Ramsay Lake) and these are not considered to have formed as a result of a recent process such as glacial erosion (I. Spooner, personal communication, 2005) and require investigation.

Middle Flow Unit (MFU)

The MFU outcrops extensively along the coastline, particularly northeast of Margaretsville, and underlies much of the flat topography areas of the North Mountain proper. The MFU is easily recognized where there is abundant outcrop due to the presence of numerous, thin (≤ 10-20 m) sheet lobes with all the features of pahoehoe flows, as discussed above (lobes, tumuli, pipe vesicles, vesicle zonation, vesicle cylinders, etc.).

The lava flows are internally zoned from base to top, as follows: (1) chilled base (≤ 10-20 cm) with disseminated, round- to irregular-shaped amygdules and vesicles, and inclined pipe vesicles; (2) a core zone (≤ 1-4 m, rarely 8-10 m) with massive texture void of macroscopic vesicles and having colonnade jointing; (3) zone (≤ 1-3 m) containing vertical vesicle cylinders, termed bubble train zone (BTZ) here; (4) net-textured zone (NTZ; ≤ 1-2 m) of amygdules (vesicle sheets of Self et al., 1996, 1998); and (5) an upper crust zone of fine-grained basalt with disseminated amygdules (≤50-70%; disseminated zone, DZ) that becomes red-brown (i.e., oxidized) in the upper 1-2 m. Locally breakouts occur above the upper crust zone and are recognized as well-preserved flow lobes.

The vesicle zonation described for flows of the MFU is common in pahoehoe flows (Abule et al., 1988) and is a feature in both modern and ancient flows (Self et al., 1998). In many cases the upper zone 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). 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 on found in pahoehoe flows proximal to their vent sites (e.g., CRBG; Swanson and Wright, 1980), and an overall regular, low-slope topography.

Importantly, the MFU contrasts markedly with the LFU and UFU, thus it is easily traced out within the NMB permitting the three-fold subdivision of the NMB to be traced laterally. Internally, individual flows are rarely seen to have lobes or toes, the vestiges of breakouts at the advancing front of pahoehoe flows (Hon et al., 1994), and buildup to form sheet flows. More common is the presence of surface breakouts with stacked lobes on the tops of sheet lobes. Complex architecture in areas (e.g., Morden, Margaretsville; see below) reflects the local presence of tumuli structures, a feature common in the CRBG (e.g., Thordarson and Self, 1998). The planar tops of flows are rarely seen due to the nature of exposure along cliff faces, but in rare instances where appropriate surfaces were exposed (e.g., St. Croix Cove) ropy textures are observed. Finally, it is very common for both the number and thickness of flows to vary along coastal sections, reflecting a combination of features during flow effusion (i.e., volume, rate, local changes in topography, etc.).

Jointing in the MFU is not as regular or well developed as in the LFU and UFU. Platy jointing is common in the upper parts of sheet flows, but columnar jointing is not common. However, exceptions do occur and one such case is at Ross Creek, one of the field stops, where well developed, subvertical, columnar jointing (entablature type) occurs in the lave core, which is characterized by a medium-grained texture and locally 20% mesostasis.

The presence of abundant pipe vesicles in bases of sheet lobes of the MFU indicates a generally southwesterly flow direction, as summarized for several sites in Figure 4. However, we do note that locally contradictory directions can be indicated from overlying or underlying flows, which probably reflects flows being fed by different lave tubes. In addition, pipe vesicles may be rotated (e.g., Point Prim, Digby area) which suggests a change in shear or flow movement of the flow. Also shown in Figure 4 are flow directions based on magnetic anisotropy measurements (Ernst et al., 2003), which indicate flow in a generally NE-SW direction, but the technique cannot distinguish more precisely which way the flows traveled (i.e., NE or SW).

The MFU is fine-grained, dark grey to grey-green, and massive except where intensely vesiculated. It is rare to see coarse phenocrystic phases, as in the LFU and UFU. The internal, massive part of lava flows of the MFU commonly weathers to show a nodualr texture and such features may reflect balling of flows or internal brecciation; this feature requires further studies. The presence of columnar jointing, either colonnade or entablature, in the massive lava core is not well developed. An additional feature of the flows is that in the massive core areas are flat, lens- or sheet-shaped areas of discoloration that are considered to reflect fracture-controlled alteration.

Almost exsclusive to the MFU is the presence of sedimentary dykes ($\leq$1 cm to 1 m width) within the upper few m of individual flows. These dykes are red-brown, very siliceous (90-95 wt. % SiO_2), indurated, and commonly contain angular fragments of altered basalt, but rounded or subrounded pebbles and cobbles also occur. Exceptional examples of sedimentary dykes filling extensional opening parallel to columnar joints occur at McKay Head. A structural analysis of 680 filled fissures in the NMB by Schilshce (1993) indicated a preferred northwest extension direction, similar to orientation of the 200 Ma Shelburne dyke of southern Nova Scotia. The sedimentary dykes are rarely cut by veins composed of silica $\pm$ zeolites, which is an important observation often repeated since it provides an important relative constrain on the timing of fluid flow related to zeolite formation.

Upper Flow Unit (UFU)

The UFU is best observed in coastal exposures along the length of the south shore of the Bay of Fundy, from Cape Split to Brier Island; however, the UFU is apparently absent along the north shore of the Minas Basin along the Parrsboro coast (Note: this aspect is not well established and will be discussed on the first day of the field trip at McKay Head east of Parrsboro). Along coastal areas east of Digby the vertical exposure of the UFU is minimal, as most of the flow unit has been eroded. In contrast, the coastal area from Digby Gut to Port George offers nearly continuous exposure of the UFU and it is everywhere similar; more isolated outcrop areas occur further east towards Cape Split. West of Digby, the UFU dominates the topographic ridge that runs along Digby Neck and Long Island, and considerable vertical exposure is seen in many of the coves along this coast (e.g., Gullivers Cove, Upper Point, Whale Cove).

The UFU basalt is massive and medium-grained with ≤30-40% mesostasis and variable amounts of pyroxene and plagioclase microcrysts. Columnar jointing is well developed with variable widths of columns, from 0.3 to 2 m (exceptional examples at Canada Creek-Black Rock, Parker Cove). Locally, multi-tiered layers with colonnade and entablature occur and zones of chaotic jointing are present with variable inclinations of columns, as seen at East Ferry for example (Fig. 14b). As with the LFU, thin silica veins commonly outline the columnar joints.

A feature unique to the UFU is the presence of segregation pipes (Kontak and Dostal, 2002; Kontak et al., submitted), a feature that is well documented in pahoehoe flows (e.g., Anderson et al., 1984; Goff, 1996; Self et al., 1998). These pipes, of 1-60 cm width and to ≤1.5 m length, are located near the base of the MFU and have only been seen in a few localities. The pipes are of mixed felsic-mafic composition and Kontak and Dostal (2002) considered them to represent mobilization via filter pressing of late-stage, highly-fractionated residual melt that is developed on a microscopic scale in the NMB via immiscibility (Kontak et al., 2002). In this sense, the felsic pipes are similar to the rhyolite bands associated with the mafic pegmatites in the LFU noted above.

GEOCHEMISTRY OF THE NORTH MOUNTAIN BASALT

Whole rock geochemical studies of the NMB and its significance has been addressed by many authors over the past thirty years (Sinha, 1970; wark and Clarke, 1980; Dostal and Dupuy, 1984; Papezik et al., 1988; Greenough et al., 1989a; Greenough and Dostal, 1992b, c), with regional overviews and syntheses also having been contributed (Dostal and Greenough, 1992; Greenough and Dostal, 1992a; Pe-Piper et al., 1992; Pe-Piper and Piper, 1999). These data indicate the following features regarding the chemistry of the NMB:

- quartz-normative tholeiitic basalts of continental character;

- within-plate chemical affinity, but with possible oceanic-chemical characteristics, which may reflect a transitional nature due to contamination via eruption through a thinned continental crust. This is borne out by an assimilation-fractional crystallization model;
- crustal contamination of the basalt magma occurred within the lower crust where homogenization occurred, rather than during emplacement (i.e., as feeder dykes ?). Consequently, the flows have a moderately uniform chemistry.

The general features listed above have been well-demonstrated for the NMB over a large area by many workers, also including the peripheral settings on the north side of the Bay of Fundy (e.g., Greenough and Papizik, 1987; Greenough et al., 1989a; Pe-Piper and Piper, 1999). However, what remains unanswered is whether there is a regional-scale change in the nature of the chemistry (sse below), as a consequence of *in situ* fractionation of the flows during lava transport. This has been noted also from the mineralogy, whereby pyroxene phases are both coarser and more abundant towards the southwest and orthopyroxene is also present compared to the central and eastern parts of the NMB. The interpretation of these observations is that relatively more mafic lava may be expected to dominate the southwestern part of the NMB if this area is towards the source area. Another issue is whether the Shelburne dyke (Fig. 3) may have been a feeder for some of the NMB.

In order to address these issues of source area and relationship of the Shelburne dyke to the NMB we present in Figure 15 a summary of the geochemistry of these units for the area from Cape Split to Digby Neck-Briar Island. The samples are subdivided into the LFU, MFU and UFU and the following points are noted.

- The data base is not complete and additional, systematic sampling is required to properly assess the regional flow variation with the LFU and UFU;
- There appears to an overlap of data for the Shelburne dyke and NMB samples in general, thus suggesting a first order relationship, but at the same time more detailed comparative studies may preclude a simple genetic relationship between these two;
- To a first approximation it appears that all the flows are chemically related and their differences relate to simple processes of fractional crystallization;
- The data clearly indicate that the most primitive samples lie in the western part of the NMB, that is the Digby area and west, as these samples have higher mg# and are more enriched in Ca and Cr. We note that the Ni data are anomalous and may relate to analytical problems, as the elevated values are for samples analyzed by Sinha (1970), but other than this data there is also a trend of

elevated Ni in the westerly samples;

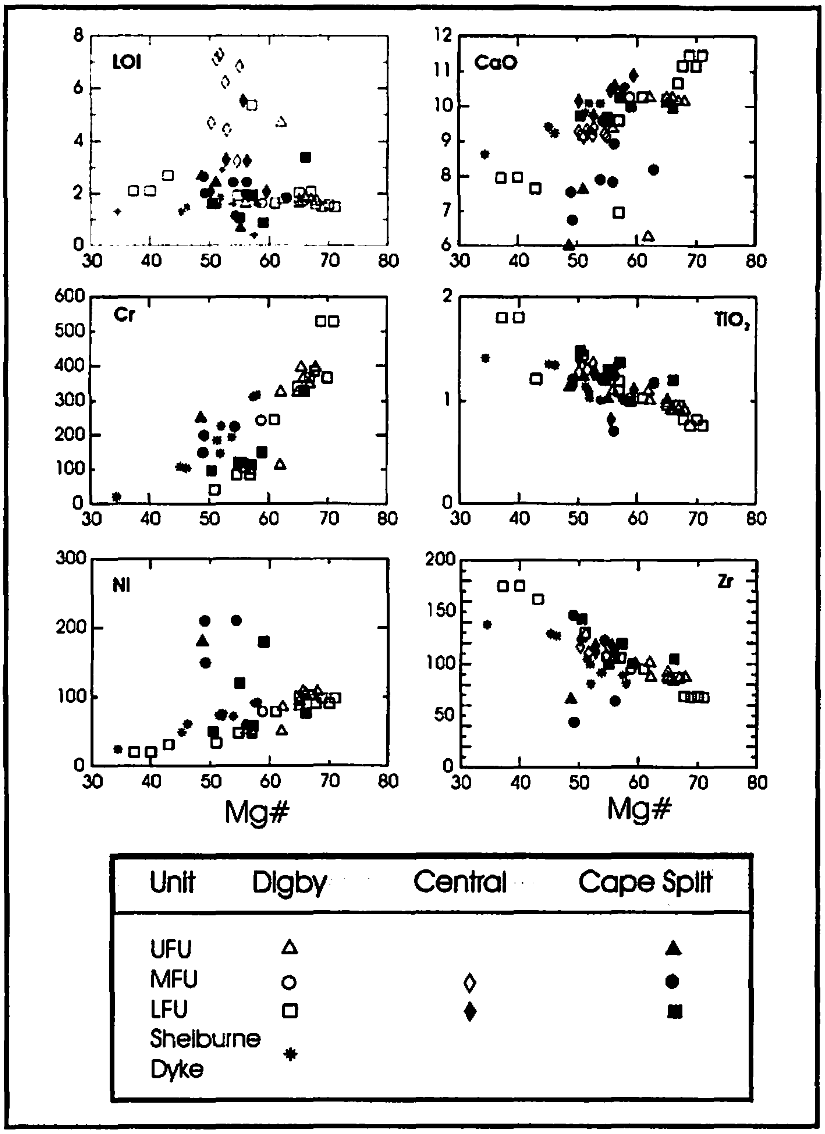


Figure 15. Binary plots of chemical data (wt. % and ppm) for the NMB and the Shelburne dyke with data subdivided into the flow unit (LFU, MFU, UFU) and geographical setting. Note that only data on the southern side of the Bay of Fundy have been used. Mg# is magnesium number (atomic Mg/(Mg+Fe)). Sources of data are from Sinha (1970), Wark and Clark (1980), Papezik et al. (1988) and Dostal and Durning (1998). Note that for the Sinha (1970) data set we have

assigned flow A to the LFU, B and C to the MFU, and D to the UFU. The elevated Ni contents for the Cape Split samples are from the Sinha (1970) data set and may indicate an analytical issue.

- The chemical range for LFU from the western region spans the entire data set, thus indicating that within the LFU there was considerable fractionation. Is it tempting, therefore, to speculate that there is in fact a relationship between this degree of fractionation and the presence of the layered mafic pegmatite and rhyolite seams in the LFU.

In summary, we note that whereas the chemical data set is incomplete it does highlight some interesting points, the most relevant being the source of the flows. Assuming that the more primitive chemistry acts as a vector towards the source, this suggests that the flows originate from the southwest. However, this is at odds with the inferences based on pipe vesicles (Fig. 4) and requires explanation. Any suggestions regarding this matter would be appreciated!

QUESTIONS: THE REGIONAL DISTRIBUTION AND VOLCANOLGY OF THE NORTH MOUNTAIN BASALT

Many outstanding issues remain regarding many aspects of the NMB, which are summarized below in order to generate, perhaps even provoke, debate during outcrop stops and evening discussion.

1. What is the source of the NMB? Are these large fissure fed flows that have traveled large distances (i.e, 100's km), as in the case of many historical flows (e.g,, Columbia River Basalts; Thordarson and Self, 1998), or produced by more local vents?

2. Do the three units, namely LFU, MFU and UFU, have a common source or are multiple sources involved? This is particularly relevant given: (1) the LFU contains coarse, partially resorbed orthopyroxene phenocrysts that are absent in the MFU and UFU; (2) there is a notable difference in the initial $^{87}Sr/^{86}Sr$ ratios for the LFU and UFU basalts (Jones and Mossman, 1988); and (3) the difference in the eruption styles and possibly volatile contents of the three units, in particular the vesicle-, now amygdule-rich MFU.

3. What is the origin of the basal flow? Although it has been referred to as a ponded lava (e.g., Papezik et al., 1988), are alternative origins likely and is a single outpouring of lava represented? Is the regional variation in thickness related to pre-flow faulting as a consequence of crustal extension? As indicated in the cross-sections (Fig. 6), there appears to be good reason to infer the presence of a northeast-trending fault within the basement to the NMB that may run parallel the length of the valley for an unknown

distance.

4. What is the origin of the UFU in the context of the above question regarding the origin of the LFU?
5. As with the LFU, the MFU is laterally variable with regards to its thickness, which is reflected in the number of flows present and their aggregate thickness. This is most clearly demonstrated in the McKay Head-Parrsboro area where only 4 lava flows are present, in marked contrast to the 15 or more in the Annapolis Valley area. Does this indicate separate vent sites or another controlling factor?
6. The UFU thins dramatically towards the northeast, being absent in the Ross Creek/Scots Bay area where Scots Bay Formation sediments rest disconformably on the MFU, although it reappears again towards Cape Split. However, the UFU is completely absent on the north side of the Minas Basin and then reappears on Grand Manan Island to the west. What are the factors that control this distribution?
7. What is the cause of the chaotic jointing and tiered jointing in the LFU and UFU? Is this related to sudden influxes of large volumes of surficial water?

FIELD TRIP STOPS

North Mountain Basalts, North Shore of Minas Basin, Bay of Fundy

General geology, stratigraphy and structure

The locations of areas underlain by the NMB along the north shore of the Bay of Fundy are shown in Figure 16 and more detailed maps of the relevant areas are shown in Figure 17. The general references on these Mesozoic rocks include Donohoe and Wallace (1980, 1982; general geology), Greenough (1995; overview, Mesozoic rocks of Atlantic Canada), Klein (1962) and Olsen et al., (1987; sedimentary stratigraphy), Greenough et al. (1989a; basalt stratigraphy), and Hubert and Mertz (1980; 1984 aspects of the sedimentology), Olsen and Schlische (1990) and Greenough (1995; structural geology).

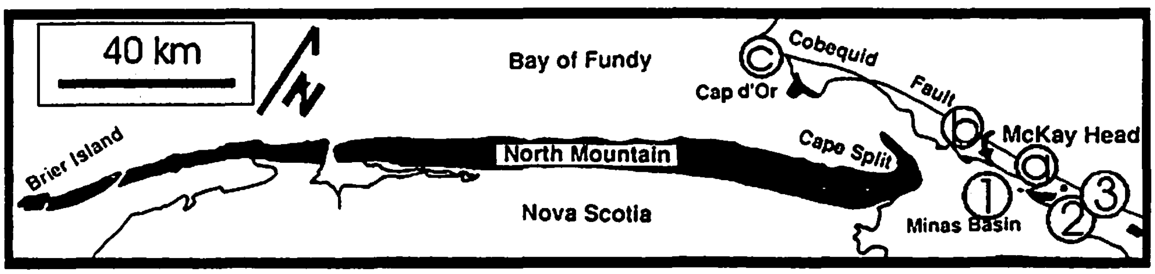


Figure 16. Outcrop of the NMB around the Bay of Fundy. Areas of the NMB along the north shore that are discussed in more detail are indicated as a, b, c and field stops are also shown (1, 2, 3). Note the presence of the east-west - trending Cobequid Fault Zone in the Cap d'Or - McKay Head area that causes structural complexities.

The stratigraphy of the sequence in this area is as described above for along the south shore of Bay of Fundy. The lower-most Mesozoic rocks belong to the Wolfville and Blomidon formations, composed of red Triassic siliciclastic rocks of alluvial-fan, braided-river, playa-mudflat and eolian origin. Above these, the 202 Ma NMB occurs very close to the Triassic-Jurassic boundary. As noted in the introduction, the NMB has been subdivided into the LFU, MFU and UFU based on superposition and geochemical data, but the upper part of the NMB, this being the UFU, is not readily apparent in this area, which may relate to structural complexities as discussed below. The McCoy Brook Formation, a unit only recognized on the north shore of Minas Basin, overlies the NMB and represents a continuation of sedimentary conditions that produced the Blomidon Formation. However, eolian deposits are more common and movement along the Cobequid Fault produced talus deposits of basalt agglomerate at the base of the McCoy Brook Formation (Olsen and Schlische, 1990).

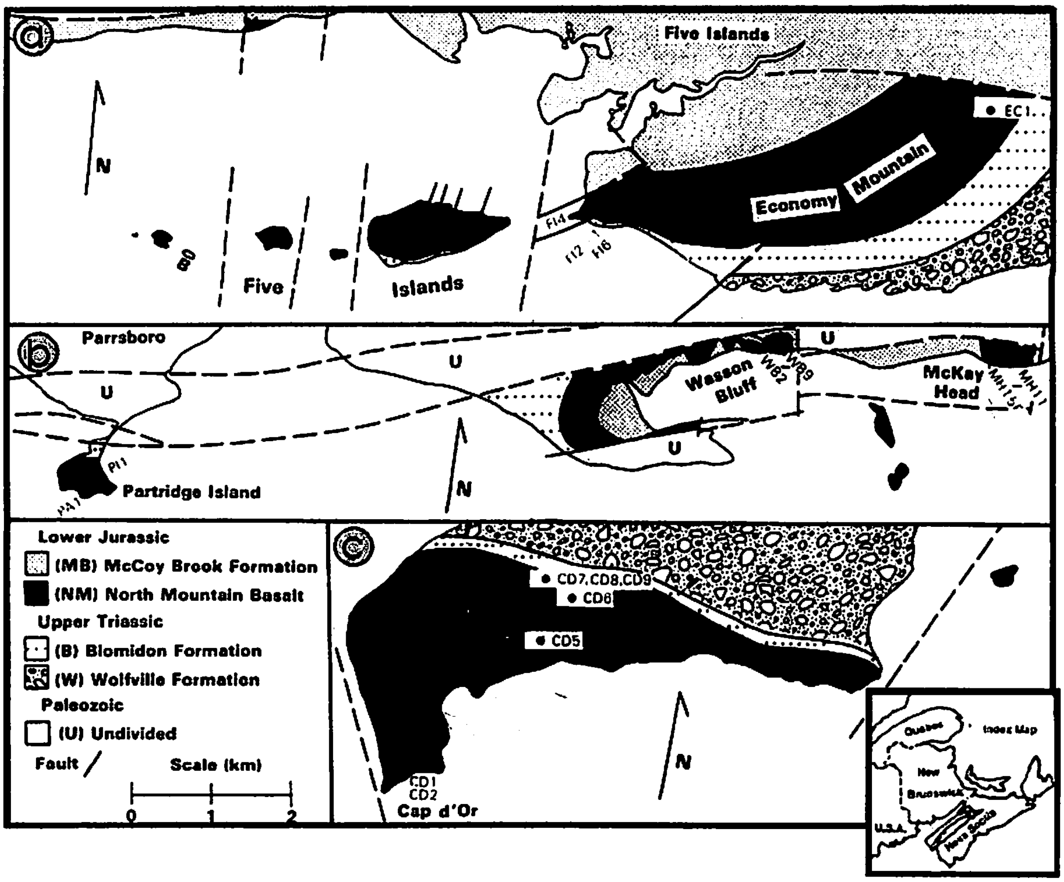


Figure 17. Geology maps of the three field areas discussed in the field guide. Diagram from Greenough et al. (1989a).

The stratigraphy of the NMB flows in this area is summarized in Figure 18; note the apparent discrepancy compared to the relatively simpler stratigraphy noted earlier along the North Mountain (Fig. 5). In this diagram, the LFU is represented by a basalt flow referred to as the Lower Unit, the MFU by the Middle Unit, and the UFU by the Upper Unit, which is then overlain by the Overlying Unit in the McKay Head area. The more complicated interpretation shown is based on the fact that at McKay Head the Sr isotopic signature (data in Greenough et al., 1989b) of the massive flow of the Upper Unit has a signature more consistent with that of the UFU (data in Jones and Mossman, 1988) rather than the LFU, as might have been expected from field relationships. If this is in fact the case, the thin flows of Overlying Unit may represent surface breakouts from the massive, underlying Upper Unit. Alternatively, and a geologically simpler interpretation, is that the thin flows of the Upper Unit at McKay Head equate to the Middle Unit of Cap d'Or and collectively they equate to the MFU of the NMB. In support of this interpretation is the fact that there are a similar numbers of flows in the two areas and they have similar volcanological features suggestive of an inflated pahoehoe sheet lobe origin. The participants can decide for themselves which model is more reasonable! The upper part of the massive Upper Unit at McKay Head is host to spectacular layers of pegmatite and rhyolite seams that will be seen on the field stop to this locality.

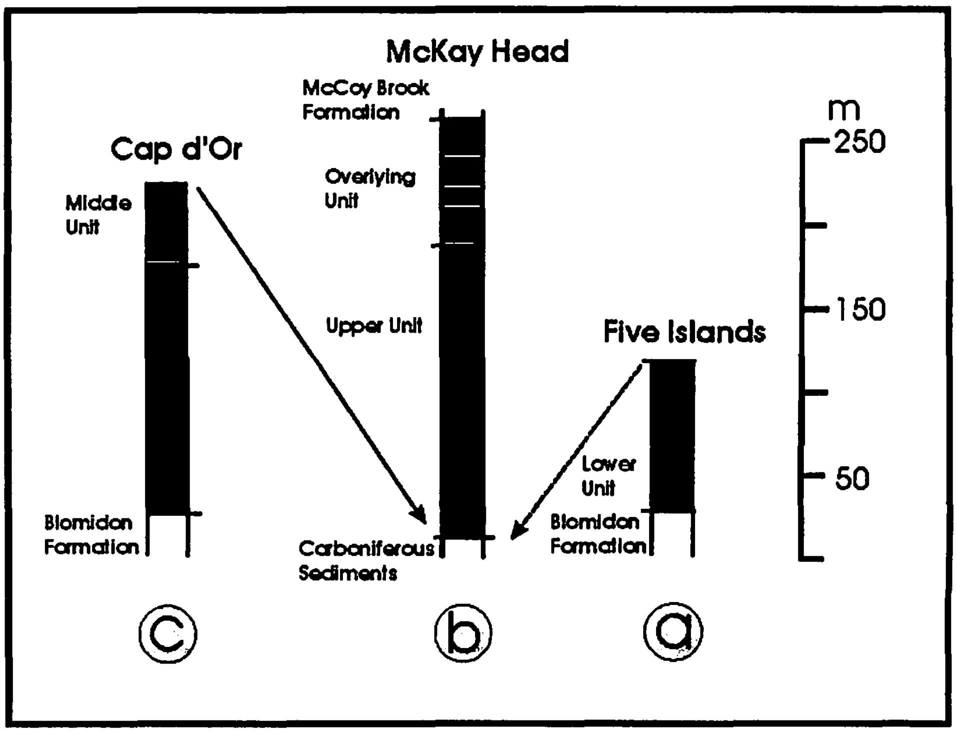


Figure 18. Important stratigraphic sections through the NMB on the north shore of the Bay of Fundy going from east to west. See Figure16 for the locations of the sections (a, b, c). Modified from Greenough et al. (1989a). See text for discussion of comparison to LFU, MFU and UFU terminology.

The Mesozoic rocks in the Bay of Fundy form a large, asymmetrical, plunging syncline (Figure 1) that dips more-steeply on the northern side. The northern boundary of the basin is demarcated by a major south-dipping fault with a prolonged (Paleozoic to present) history of movement; this fault is the western extent of the boundary between the Meguma and Avalon terranes and initially was dominated by sinistral displacement. Normal movement associated with Triassic-Jurassic opening of the North Atlantic created a graben similar in shape and scale to the present-day Bay of Fundy. However, unit displacements, such as along the Economy Mountain Fault, provide evidence for right-lateral movement (Donohoe and Wallace, 1980) and Olsen and Schlische (1990) suggest left-oblique displacements. A significant point to keep in mind is that between Five Islands and Parrsboro, the shoreline approximately follows the trace of the terrane bounding fault (i.e., Cobequid Fault of Fig. 16) and locally house-sized blocks of uncertain origin are enclosed in fault breccia.

Stop 1: McKay Head

Use the map in Figure 19 to locate the field stops discussed below. It is recommended that visitors to these sites visit the Fundy Geological Museum in Parrsboro where more detailed information on the area may be obtained, in particular with respect to the stratigraphy and information relevant to why this area is so important with respect to dinosaur excavations.

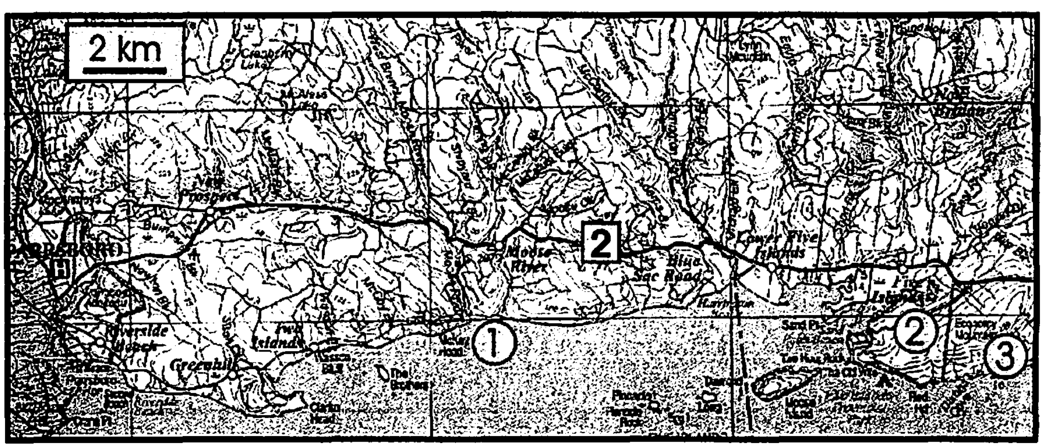


Figure 19. Topographic and road map of the Parrsboro - Five Islands area showing field stops.

Directions (see Fig. 19)

With reference to Figure 19, follow the paved road eastwards from Parrsboro along the coast towards Wasson Bluff and continue past here for ca. 2 km where one must park and hike to the coast. Alternatively, if time permits access the beach at Wasson Bluff and hike along the coast from here to McKay Head. Excellent exposure of brecciated NMB at Wasson Bluff has been described by, among others, Stevens (1980, 1987), in field guides of this and adjacent areas (e.g., Five Islands).

HAZARDS: The cliffs are locally steep. Indiscriminate approach from above can result in a fatal fall. There are overhead hazards at the base of the cliffs at McKay Head. Strictly adhere to the hiking instructions of the leader and avoid approaching the cliff. Rocks along the shoreline can be slippery. ***Exercise extreme caution.*** In the Bay of Fundy, the tides rise rapidly and can prevent safe return around the McKay Head cliff. Stay close to the group and make sure that you start back toward the vehicles when instructed to do so. Read the general health and safety precautions above.

Preamble

Powers and Lane (1916) brought the evidence for differentiation in North Mountain Basalt to the attention of Bowen (1916) who used it in support of his arguments for differentiation in mafic magmas. Perhaps one of the most spectacular exposures of differentiation-related layering in the NMB occurs on the north side of the Bay of Fundy, at McKay Head. Due to a steep dip, a walk along the McKay Head shoreline provides a traverse down into the flow, which shows remarkable layering. Even more incredible is the chemical variability produced by rapid, *in situ*, differentiation processes that apparently involved crystal differentiation, silicate-liquid immiscibility and elemental transport via volatile complexing.

In discussions of the field stops we will use the nomenclature of LFU and MFU in the sense of the NMB, realizing that the observations of Greenough et al. (1989a) may in fact be correct. This usage is done in order to be consistent when referring to units of the NMB throughout the field guide.

Highlights

Stratigraphy and field Relationships

On approaching McKay Head from the Parrsboro side, one first walks through a section of fine-grained, red-brown sedimentary rocks of the McCoy Brook Formation, which can be seen resting on intensely weathered basalt of the MFU of the NMB (but see below for further discussion). In fact, there are fragments of highly vesiculated upper crust zone fragments in the sediments at the contact.

There is some confusion still as to how many flows make up the MFU or Overlying Unit of Greenough et al. (1989a) here because of a structural zone that cuts the underlying massive basalt containing the layered pegmatites and the interpretation of what this flow represents – is it the LFU or another massive unit that is not recognized elsewhere in the NMB? If it is part of the massive, LFU - type basalt this would leave three flows to comprise the MFU. These three flows are considered to be sheet lobes and they all have excellent characteristics of inflated pahoehoe flows with:

- Vesicle-rich, upper crust zone (red-brown oxidized);
- Well developed NTZ or horizontal vesicle zones;
- Large and abundant vesicle cylinders of the BTZ;
- Entablature to colonnade jointing in the massive base (i.e., core) of the flows

In addition, abundant sedimentary dykes fill extension zones perpendicular to the original eruptive surface and penetrating a few m into the flows.

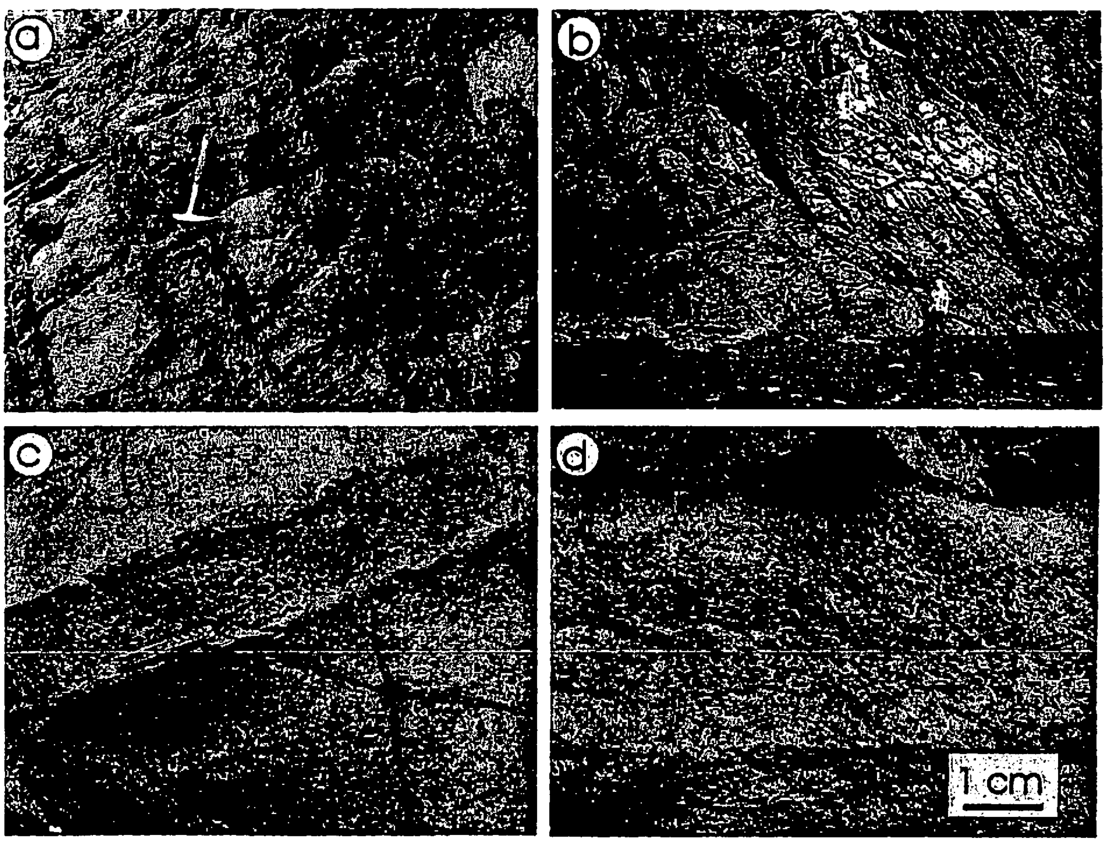


Figure 20. Outcrop photographs of rocks at McKay Head. (a) Sedimentary dykes filling extensional openings parallel to columnar jointing (colonnade type) in LFU (?). (b) Pegmatite layering in the upper part of the LFU or Upper Unit. Note the person for scale. (c, d) Close up of the pegmatite layers and vesicle-rich zones between these layers in the basalt. Knife for scale in Figure 19c is 9 cm long.

The massive basalt under the thinner flows contains abundant layering that is anything but subtle (Fig. 20b, c), and it changes in character with depth in the flow (Fig. 21). The upper contact of the massive flow has a thick (i.e, 4-5 m) red, oxidized top and it also contains absolutely spectacular sedimentary dykes in a colonnade-jointed section of the flow (Fig. 20a). These sedimentary dykes deserve many pictures and certainly come discussion regarding their significance! At a depth of ~ 6 m in the thick layered flow, indistinct, vesicle-rich layers appear inside less-vesicular basalt. These layers tend to be about 30 cm thick, are coarser grained than surrounding basalt, have vesicles (Fig. 20d) filled with dark green (Fe-rich mica ?) and white secondary minerals, and tend to preferentially weather out of the cliff face. Layers are traceable at the scale of the outcrop, and tend to be separated by about 1.5 m of basalt. With depth the layers become less vesicular, coarser-grained, and show more-distinct boundaries, though there is a zone at 15 to 20 m depth that is clearly layered, but where distinct 30-cm-thick layers are less obvious. Below this (~ 20 m), layers occur as mafic pegmatites within basalt. Some of these show comb-textured pyroxenes forming 15 cm long sheaths emanating from a moderately well defined boundary with the enclosing basalt. The sheaths end abruptly in the middle of the pegmatite and abut a fine-grained, lighter-colored, vuggy rock that forms a thin (2 cm-thick), continuous (many m) band down the centre of the pegmatite. These banded rocks have rhyolitic compositions (see below)! The base of the layered section is faulted off and past the fault the basalt is notably different in terms of its fracture pattern (much narrower).

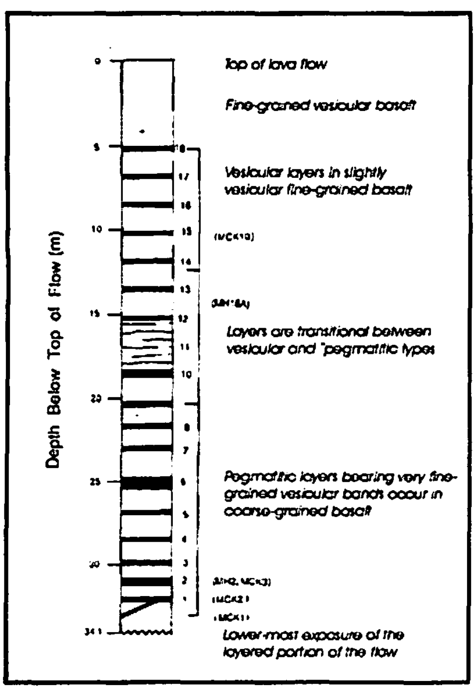


Figure 21. Stratigraphy of the upper 34 m of the thick, layered flow at McKay Head (right column. Numbering on layers (1-18) is schematic. The column marked "Time" gives estimates of the number of years it took the upper crust, growing downward, to reach various levels in the flow. Diagram and information modified from Greenough et al., (1989a) and Greenough and Dostal (1992b).

Petrography and geochemistry

Assessment of textures, whole rock geochemistry (data in Greenough et al., 1989a; Greenough and Dostal, 1992b) and mineralogy led to interesting hypotheses for differentiation in the thick flow at McKay Head. The lower layers show the most extreme pegmatite textures. These pegmatites contain polygonal patches of quartz - feldspar and stilpnomelane - skeletal Fe-Ti oxides surrounded by large zoned augite and plagioclase crystals. The fine-grained, vuggy band in the middle of the pegmatite layers forms a sharp boundary with the pegmatites, as shown by truncated zoning in plagioclase and augite crystals. The mafic pegmatites may be the most texturally striking rocks at McKay Head, but they do not show the most extreme chemical compositions. The average mafic pegmatite from layers 1 and 2 is similar in composition to basalts sampled adjacent to the pegmatites (McKay Head, Upper Unit basalt), which are similar in immobile elements to the more altered basalts from the Overlying Unit. The fine-grained rhyolite bands exhibit the most extreme compositions in the flow, though replicate electron microprobe analyses of the fine-grained, felted, quartzo-feldspathic mesostasis forming polygonal patches in the mafic pegmatites indicates even higher silica concentrations. Replicate electron microprobe analyses of the near-isotropic polygonal masses of stilpnomelane associated with large skeletal Fe- Ti oxides in the pegmatites show Fe-rich compositions. Despite the extreme compositions of the rhyolite bands, in some respects the vesicular layer rocks (layers 14-18 in the stratigraphic diagram above) show the most unusual compositions including the highest Na, P, Fe and Ti in the flow, and high K, Ba, Th, Zr, Hf, Nb, Y and the REE but low Ni and Cr relative to all other mafic rocks. Note that mass balance calculations show that it is impossible to mix mafic pegmatite + rhyolite back together to get a composition anything like the vesicular layers.

Origin of layering and differentiation

Drilling of Hawaiian lava lakes (e.g. Helz, 1987) indicates that all of the "layers" at McKay Head, vesicular to pegmatitic, are segregation veins, but the McKay outcrops show that segregation veins are continuous and traceable for at 10's, if not 100's of m. Although observed forming during drilling in Hawaii, the physical processes responsible for the formation of segregation veins are not well understood. Horizontal segregation veins in North Mountain Basalt apparently formed at somewhat regular spacial vertical intervals due to repeated tearing of the crystal mush at the base of the downward growing upper crust of the lava flow (i.e., crystallization front). As a horizontal crack opened, interstitial liquid in the underlying crystal mush was siphoned into the opening crack, or forced into the crack by gas overpressures. High volatile contents in this liquid led to coarse-grained, vesicular textures in the uppermost segregation veins and pegmatitic textures in the lowermost veins.

The origin of the rhyolite bands is more controversial. It has been argued that they represent silica-rich immiscible liquids squeezed into a second segregation vein formed in the middle of the mafic pegmatites (Greenough and Dostal, 1992a). Evidence for immiscibility includes the polygonal patches of felted, microcrystalline, interstitial, Si-rich minerals and analogous patches of Fe-rich stilpnomelane surrounding skeletal Fe-Ti oxide grains. In most respects these have bulk chemical compositions, relative proportions and total modal percentages consistent with their representing Si-rich and Fe-rich liquids (respectively). The rhyolite bands have compositions consistent with an immiscible origin, the bulk composition of the pegmatites is typical of tholeiitic rocks that produce immiscible liquids, and mineral compositions and temperature estimates for pegmatite minerals all support an immiscible origin. What is not preserved at McKay Head is a Fe-rich liquid with high P_2O_5 content, though the work of Kontak et al. (2002) for other parts of the NMB appears to confirm the potential for immiscibility as a rock-forming process.

Clearly the vesicular layers have very different compositions from underlying pegmatitic layers. Mass balance and trace element modeling show that crystal fractionation can, to a first approximation, explain the composition of these rocks (Greenough and Dostal, 1992b). However, some elements, in particular elements likely to be transported by volatiles (alkali metals), do not fit well with the crystal fractionation model. Work on other lava flows such as in Hawaii (Helz et al., 1989) and Taiwan (Greenough et al., 1999) indicates that low-density residual-magma can form plumes, in some cases buoyed by vesicle formation, that rise from lower crystallization front at the base of a flow. These plumes bring a compliment of volatile-complexed elements to high levels in the flow (i.e., melt) that ultimately becomes the interstitial liquid that is incorporated in segregation veins. Of economic importance, some of the elements most likely to be enriched in vesicular layers by these processes include the platinum group elements (Greenough and Fryer, 1995).

McKay Head: summary and conclusions

Unlike layered intrusions, the processes for layering and differentiation in lava flows must be rapid, and the time-frame for their operation can be constrained by the reasonably well known cooling regime for flows. Thus the most differentiated mafic rocks at McKay Head, the vesicular rocks, formed after only 6 months of cooling. Coarse-grained textures, vesicularity, and the chemical composition of these rocks imply a role for volatiles in their formation and indicate that rapid movement of volatiles affects the early differentiation of mafic magmas. Similarly, rapid cooling has preserved evidence for the formation of the rhyolite bands by immiscibility, and this supports the idea that granophyres in layered mafic intrusions may be due to silicate liquid immiscibility.

Stop 2: Five Islands Provincial Park

Directions (see Fig. 19)

Access to this popular tourist site is via Highway 2. If Stop 1 was visited it is necessary to first return to Parrsboro to access this highway, or if coming from Bass River-Economy area then follow directions to the park area.

Highlights

The rocks atop Economy Mountain and exposed in cliffs and sea stacks at the southwestern tip of the Five Island Provincial Park belong to the Lower Unit of NMB (Greenough et al., 1989a), or LFU in sense of Kontak (2002; and Fig. 5 in the guide). The contact between the basalts and underlying Blomidon Formation will be examined, as well as the suggested evidence that a feeder dyke for the NMB is exposed in the sea stacks.

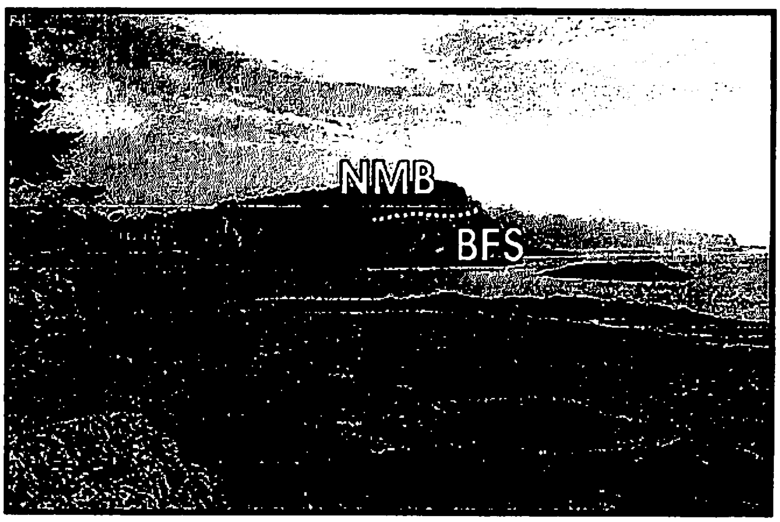


Figure 22. Photograph looking northeast toward cliffs on the "back", or southwestern side, of Five Island Provincial Park. Sea stacks in front of cliffs may represent feeder dykes to the flows. Contact (dashed white line) between NMB and underlying Blomidon Formation sediment (BFMS) is marked by a thin layer of light-colored sediment that has been reduced by some process involving the overlying basalt.

Sea stacks creating a linear series of outcrops from the westernmost tip of Economy Mountain toward the five islands in Minas Basin contain angular blocks of vesicular basalt surrounded by non-vesicular columnar basalt. These contact relationships led Powers (1916) to suggest that the outcrops expose a feeder-vent system, a conclusion supported by Stevens (1987). If so, this is the only known vent for the basalt in this area.

On rounding the point at the end of the park, there are spectacular cliffs revealing the lower portions of the Lower Unit where it is in contact with the normally red, Blomidon Formation (Fig. 22). However, rocks immediately below the basalt are white. It is unknown whether the reduction is related to baking at the time of extrusion, or due to prolonged reaction with groundwater that was reducing as a result of contacting the basalt.

Stop 3: Economy Mountain

Directions

From Stop 2 at Five Islands return to the main Highway (#2) and go right (east) and follow the road to the top of Economy Mountain. Alternatively, if coming from the east stop at the top of Economy Mountain.

HAZARDS

The road represents the most important hazard at this stop. Local traffic regularly tops the hill at illegal speeds. Be extremely careful crossing the road. Avoid approaching the roadside cliff face as falling rocks represent a hazard.

Highlights

This stop at the roadway-top of Economy Mountain provides another chance to sample the LFU of the NMB and to discuss the origin of this unit in the context of the stratigraphy of the NMB. The basalts here are massive and holocrystalline with prominent jointing and without diagnostic features that permit easy classification as LFU or UFU flows. Although it is not clear at what height these rocks occur at in the basal flow, we note that their chemistry is very similar to basalt from between pegmatites at McKay Head (Greenough et al., 1989a). The average for samples from the cliff at the "back" of the Five Islands Park, and therefore from low in the LFU or Lower Unit of Greenough et al. (1989a), is somewhat more mafic. However, this raises an important point; Lower and Upper Unit rocks can be chemically very similar and this is true along North Mountain as well (Papezik et al., 1988). Thus, the relevant question is how does one unequivocally distinguish among massive flow units of the NMB, because major and trace element geochemistry is not a reliable indicator. (Note: along the North Mountain the LFU can be distinguished form the UFU on the basis of the presence of orthopyroxene and lack of abundant mesostasis, but evidently such is not the case along the north shore area of the Bay of Fundy.)

Jones and Mossman (1988) tackled this problem of chemical similarity and showed that the LFU along North Mountain has a consistently lower initial $^{87}Sr/^{86}Sr$ ratio than the Upper Unit (Table 2). Greenough et al. (1989b) extended the flow units to the north shore of the Bay of Fundy, but scatter in the isotopic ratios for McKay Head make the conclusion that it represents the Upper Unit (Fig. 18) less than certain. Nevertheless, a Rb-Sr isochron based on 7 rhyolite-pegmatite samples gave a scattered initial ratio that confirms an Upper Unit assignment (J. Hodych, personal communication, 1988).

Table 2. Initial $^{87}Sr/^{86}Sr$ ratios for North Mountain Basalt.

	Lower Unit	Upper Unit
North Mountain	0.70591-0.70609	0.70676-0.70687
Five Is., Economy Mtn.	0.70609-0.70610	
McKay Head		0.70637-0.70688, *0.70671 ± 0.00013
Cap d'Or	0.70567-0.70595	

Notes: North Mountain = Jones and Mossman (1988); Lower and Upper units equate to the LFU and UFU of Kontak (2002) and in this guide. Other data = Greenough et al. (1989a) except * = isochron initial ratio J. Hodych, personal communication, 1988).

The Lower Unit and problem of North Mountain Basalt Stratigraphy

After having seen the geology of the flow units in the Parrsboro-Five Islands area, it is now appropriate to discuss the problem of the stratigraphy and nature of the flows in the area. In summary the problem is whether one can correlate the massive flow units beneath the thinner pahoehoe sheet lobes as being part of the LFU of the NMB or, alternatively, if there are two massive units represented in this area that equate to the LFU and UFU, respectively, as seen along the North Mountain proper on the south side of the Bay of Fundy. The former interpretation is the simplest, but is at odds with some of the chemistry, in particular the Sr isotope data, whereas the latter requires that sheet lobes occur above the UFU in this area, which are not seen in the North Mountain area. The occurrence of thin sheet lobes on top of the UFU is not a problem in terms of volcanic processes and can be explained as breakouts through the upper crust of the UFU. Not only have such features been described from ancient and modern settings, but recently McHone

(2005) has suggested such an origin for the MFU sheet lobes of the NMB on Grand Manan Island! Clearly, more work is required before this problem can be fully and satisfactorily resolved.

WOLFVILLE-BLOMIDON AREA

The next part of the field trip occurs on the south side of the Bay of Fundy, thus there is a drive required from the last field stops along the north shore of the Bay of Fundy-Minas Basin to the present area. One can arrive here via three routes from the Truro area after leaving Parrsboro-Five Islands. Past Truro about 20 km there is turn off (Exit 12) at Brookfield for Highway 89 that goes west to the Noel Shore and follows route 215 along the coastline; this is a scenic drive on a paved road, but it is slower. Alternatively, remain on Highway 102 to Exit 9 and go along Highway 14 through the Rawdon Hills, which leads to Windsor, or continue towards Halifax and take Exit 4, which leads to Highway 101 and takes you to the Annapolis Valley-Wolfville area.

Stop 1. Kingsport

Directions (see Fig. 23)

Take Exit 11 off Highway 101 heading north to Wolfville/Greenwich and get on Highway 358 going north to port Williams/Canning, etc. Alternatively, take Highway 1 at Exit 10 and go through the lovely town of Wolfville until coming to Highway 358.

Proceed on Highway 358 to Canning and go east on Highway 221 to Kingsport, where there is a parting lot on the right side of the road.

Highlights

There are many things to see in the Wolfville area and the interested traveler is encouraged to do their homework prior to planning a trip. Include the Tangled Gardens, just past Exit 10 and further on Grand Pre Wineries. On the way to Kingsport, there is a winery, open for tours and business, on the right side of the road 4-5 km past Canning. In the spring (i.e., March) this area is a favourite place for eagles and dozens can be seen overhead. The power of the tides of the Bay of Fundy is evidenced in the exposed cliffs that are continually eroded and pushed back at an alarming rate. The strong tides here are generated because of the constriction caused by Cape Split (Fig. 16) at the head of the Minas Basin. However, at present the tides continue to erode the cliff and the cottage dwellers have been forced to move back their residences or be carried away with the tides!

The section along the beach here towards the north provides an excellent opportunity to walk out strata of the lower part of the Wolfville Formation. The rocks display many well-preserved sedimentary structures.

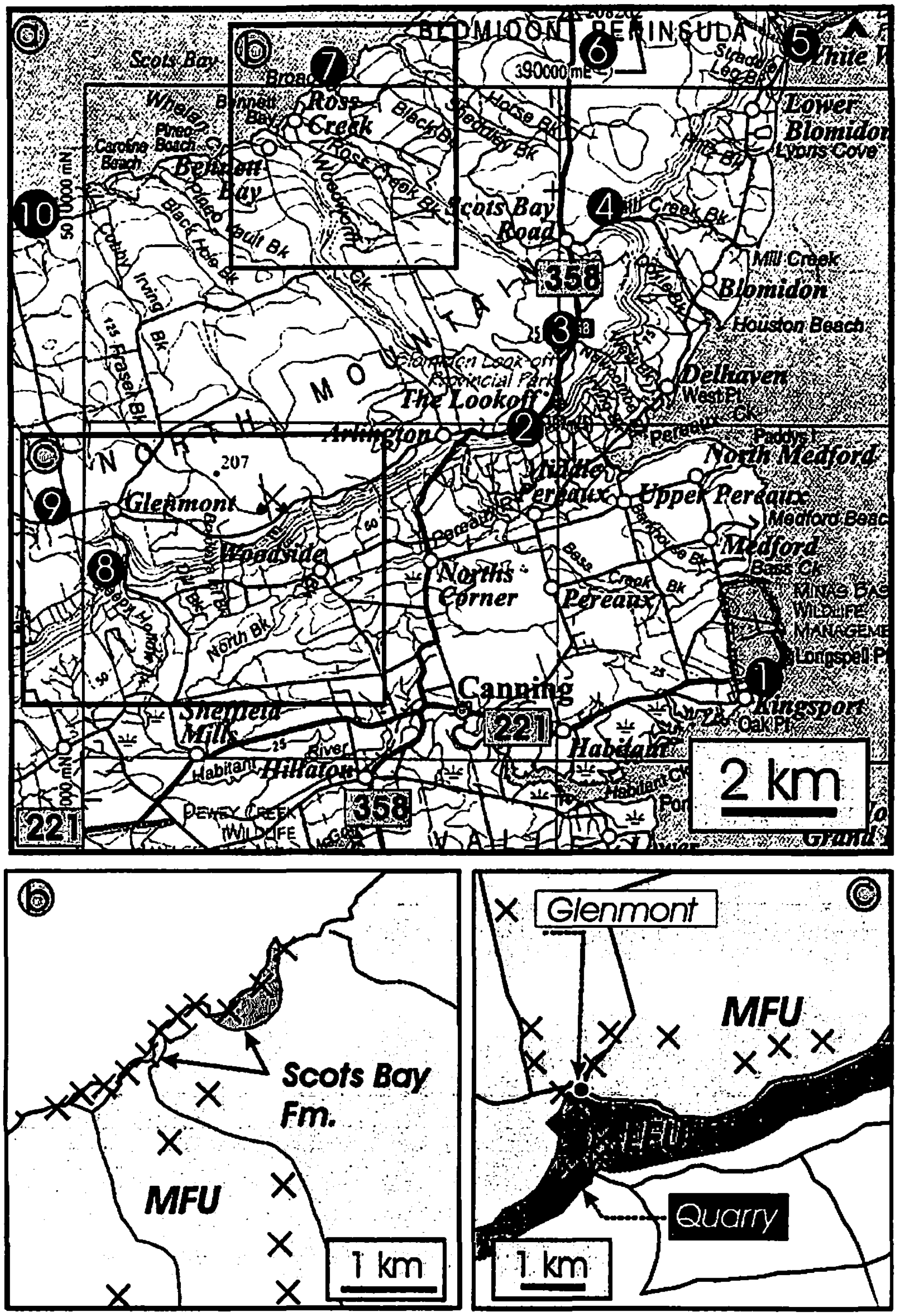


Figure 23. Topographic, road and geology maps for the eastern part of the Annapolis Valley area near Wolfville. (a) Topography and road map with locations of field stops in the region of The Lookoff and surrounding area. (b) Map of the Ross Creek area showing outcrop locations of the Scots Bay Formation. (c) Map of Kane quarry area south of Glenmont.

Stop 2. The Lookoff

Directions (see Fig. 23)

Continue along Highway 358 north from Wolfville (or return to Canning if Stop 1 was made), proceed through Canning (note that signs in the middle of the town point in the right direction) and continue along the road to the top of the steep hill, turn right after ascent and continue to The Lookoff, where there is a parking area on the right side of the road. An overnight campground and a small restaurant are located across from here.

Highlights

The road takes you along the gently inclined Triassic red bed strata of the Wolfville and Blomidon formations that have generated the rich agricultural land you drive through. This area is well known for its fruits and more recently vineyards. Note the abundant, centuries-old dykes built to prevent flooding of the farmlands from the tides.

The base of the North Mountain marks an important contact between these Triassic sedimentary rocks and overlying, 202 Ma NMB (note that the contact is not exposed). Rarely the contact is recognized by a white alteration zone, as seen at the Five Islands locality, and in some instances magnetite veining occurs. As you drive up the steep hill, note the massive nature of this holocrystalline basalt with well-developed colonnade jointing.

Standing at The Lookoff, you are ca. 300 masl, providing an excellent view of the Annapolis Valley. You have just gone through the LFU of the NMB and now are close to the contact with the overlying MFU, which defines the gently dipping surface to the north. Note that the topography of this area is geologically related, reflecting the resistant nature of the LFU versus the friable nature of the zeolite-rich MFU - the face of the valley extending to the west exists because of this phenomenon.

There is excellent exposure of the LFU just below The Lookoff or, alternatively, back at the turn where you ascended the North Mountain. ***If you excellent to descend and examine outcrop at The Lookoff exercise extreme caution, as there is abundant loose rock and the climb can be challenging for some.***

Stop 3. Top of the LFU

Directions (see Fig. 23)

Continue northwards for ca. 1.5 km on Highway 358 from The Lookoff until you come to a small farm on the north side of the road across from a large field with a pond on the south side of the road. Pull over to the side and be careful parking vehicles and crossing the road. Note there is a large outcrop in front of the small barn., which is what we are here to see.

Highlights

The outcrop here consists of fine-grained, red-brown, hypocrystalline basalt with 5-20% vesicles and amygdules; note that some vesicles may be considered to have segregation material. Given the nature of the rock and the absence of typical features of sheeted pahoehoe flows (e.g., lobes, vesicle sheets, abundance of vesicles) this outcrop is considered to represent the vesiculated, upper part of the LFU. What do you think?

Stop 4. Stewart Mountain Road

Directions

Continue along Highway 358 northwards towards Scots Bay and turn right on the Stewart Mountain Road, a well-maintained dirt road 3.5 km past The Lookoff or 2 km from the last outcrop at Stop 3. Continue down this road for about 0.5 km until you come to a stretch of continuous outcrop on the north side of the road. Part along side the road and be careful here because of traffic on this narrow road.

Highlights

This outcrop is within the LFU and exhibits several interesting features. It is a very fresh, dark green-grey to black, holocrystalline basalt with variably developed jointing. Walk along the outcrop noting both the size and orientation of the columns, as there is both colonnade and entablature developed and the inclination varies from subvertical to near horizontal. What is causing such a sudden change in the nature of jointing in such a massive, thick basalt flow?

At the east end of the outcrop occurs an abrupt change in the nature of the basalt. Note the change in jointing characteristics (size, orientation), basalt color, and the presence of abundant vesicles and amygdules. This outcrop is part of the LFU and represents a very unique condition in this flow. May this be a spiracle within the bottom part of the flow? If not, what other suggestions are possible?

5. Cape Blomidon

Directions (see Fig. 23)

For those interested in going here, either follow the road from Canning through Pereaux-Delhaven or continue down the Stewart Mountain Road from stop 4 until you come to the northerly trending road that leads to Blomidon. A provincial campground at Cape Blomidon where the road ends is open from May till October.

Highlights

This site is one that decorates many post cards that can be purchased in local stores in the Annapolis Valley. The view shows the Triassic red beds of the Blomidon Formation overlain by the LFU of the NMB. A beautiful section exposed along the coast is a favourite hiking area and mineral collecting site (e.g., Amethyst Cove) for locals, but it is imperative to time the tides as there is no escape once the tide begins to roll in.

Stop 6. Scots Bay

Directions (see Figs. 23, 24)

Return to Highway 358 from outcrop Stop 4 and continue northwards to near its termination (Fig. 24a). There is a wharf area on the south side of the road, which is the destination for this field stop. The paved road continues to a parking lot, which is the beginning point for a popular hiking trail that leads to famous Cape Split, which decorates many postcards.

Highlights

The drive down towards Scot Bay is along a gently inclined surface that is close to the general dip of the NMB. Note that westwards the UFU has been removed, or possibly was not deposited (field trip Stop 7, Ross Creek), but it reappears in this area. The overall shape of this area defines a synclinal structure with a fold axis dipping shallowly towards the Bay of Fundy. Across the other side of the water, one can see the north shore of the Bay of Fundy, where the NMB outcrops in the Parrsboro area (north) and Cape Chignecto (west) and was part of day 1 field stops.

The best features to be seen along here occur at the wharf area (Fig. 24b), where the contact between the UFU and MFU is well exposed on the south side of the wharf; note the inclined dip between the two flow units. As summarized in Figure 24c, the MFU is represented by a vesiculated, amygdaloidal-rich flow with a red-brown, oxidized, and chilled top. The top part of the MFU consists of flow lobes, a consequence of breakouts and a ca. 0.5 m wide, non-vesiculated green-grey feeder dyke is exposed cutting intensely vesiculated, red-brown, lava of the upper crust zone of the main inflated pahoehoe sheet flow (Fig. 24f). In contrast, the UFU is a dark, grey-green to dark grey, massive, hypocrystalline rock with plagioclase and pyroxene microlites and variable amounts of mesostasis.

Well-developed jointing in the UFU is seen in all the exposures and polygonal structure is seen on top sections (e.g., Fig. 24e). The jointing pattern in the UFU basalt is interpreted by some workers (e.g., Sinha, 1970) to be related to pillow basalt features, thus indicating subaqueous deposition. Note that the dips of the columns vary from south to north (Fig. 24e) and this change in dip is easily seen in the sections along the coast.

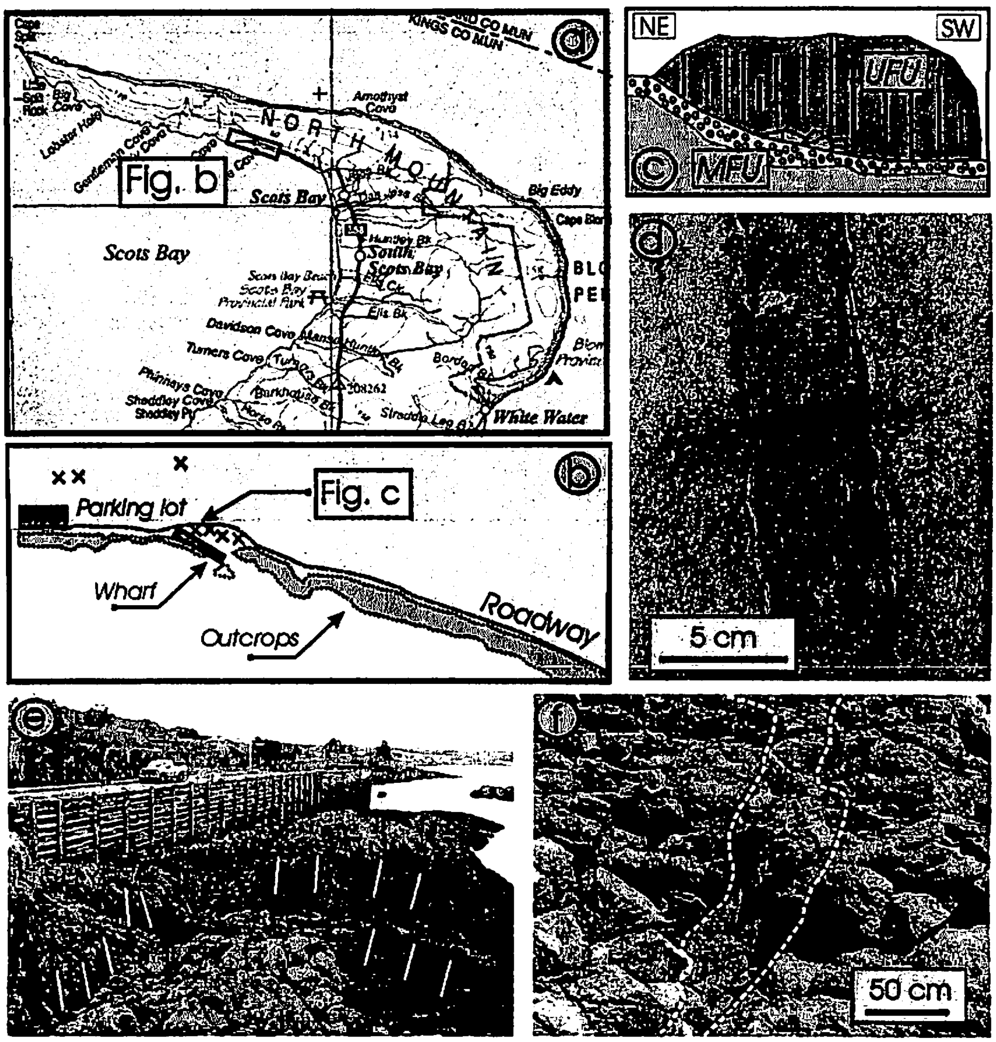


Figure 24. (a) Topographic and road map of Scots Bay area. (b) Map of the wharf area at Little Cove. Most of the outcrop in this area is UFU, but see cross section in Figure 24c for exception. (c) Sketch of sectional view of the outcrop to the north of the wharf area showing the relationship

between the UFU and MFU. The disseminated zone in the fine-grained, red-brown, oxidized top of the uppermost lava flow of the MFU marks the contact with the UFU that has pronounced colonnade-jointing.(c) Dyke material cutting UFU basalt in outcrop exposed at low tide just east of the wharf. Note the thin silica veins at the margins. (e) View (facing east) of the columnar-jointed UFU basalt just south of the wharf. Note the change in the inclination of the columns from left to right. This jointing pattern in this same outcrop was interpreted by Sinha (1970) to reflect pillow texture. (f) Feeder dyke (outlined in dashed white line) leading to surface breakouts of flow lobes on top of a inflated pahoehoe sheet flow just below contact with UFU basalt.

Other features to be noted here:

- Rare cases of dark grey, aphanitic dykes cut the UFU; they can be seen in shoreline outcrops just east of the wharf;
- Veins (≤ 1-5 cm wide) of silica (± zeolites) with general E-W and N-S orientations cut the UFU; these veins may have an *en echelon* array style in some case;
- Fine-grained, red-brown sedimentary dykes in the UFU (Fig. 24d);
- Topographic maps of the area show several embayments (i.e., coves) along the coastline to the northwest where the UFU has been breached and MFU rocks underlie the area.

Stop 7. Ross Creek Area

Directions (see Figs. 23, 25a)

Easily accessible off Highway 358; a sign indicates the turnoff just west of the intersection of the road that leads up the mountain to The Lookoff (Stop 2). Follow the well-maintained dirt road running north to the coast. Note that there are cottages along the waterfront at the end, so beware of traffic and pedestrians. It is best to park near Ross Creek where there is a turn around point in the road. ***Outcrops here are only accessible at low tide, so plan accordingly.***

Highlights

Firstly, along the dirt road there is an outcrop as part of a small quarry in MFU basalt; the outcrop is about 1.5 km from the turnoff from the paved road.

At Ross Creek there are several places (i.e., stations) that are worth visiting and the stations are numbered in Figure 25a and discussed separately below.

Station 1. Continuous outcrop of massive, columnar-jointed basalt outcropping along the coast to the north and west. The basalt is characterized by:

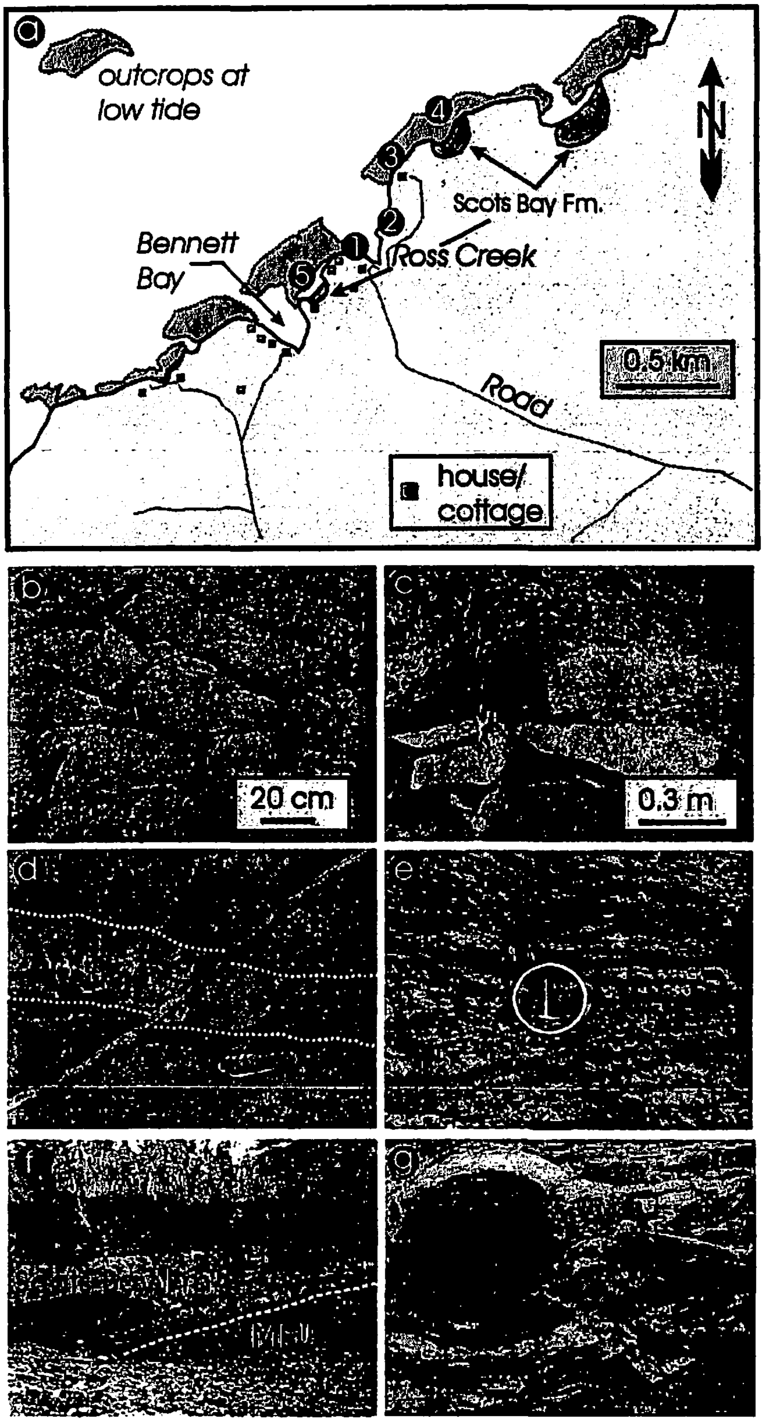


Figure 25. Ross Creek map area and outcrop photos. (a) Map of the Ross Creek area with locations of suggested stations for viewing. Area is underlain by flows of the MFU and Scots Bay Formation rocks. (b) Massive, columnar-jointed basalt of the lava core of a MFU flow; note the variety of shapes and sizes for the columns (Station 1). (c)

Sedimentary dyke cutting MFU lava flow. Note the entrained fragments of altered basalt in the dyke and also the late cross-cutting silica-zeolite vein (Station 2). (d) Silica-zeolite vein cross-cutting an offset sedimentary dyke (outlined with dashed white line) which cuts lava flow of the MFU (Station 3). Knife for scale is 9 cm. (e) Intensely vesiculated, now amygdaloidal, lava flow of the MFU (Station 3). There are numerous horizontal vesicle zones shown in the photo, which reflect multiple depressurization events in the core of the lava flow. Geological hammer is circled for scale. (f) Contact (traced with dashed white line) between basalts of the MFU and overlying sediments of the Scots Bay Formation (Station 4). View is facing southwest. (g) Close up of a petrified tree in silicfied limey sedimentary rocks of the Scots Bay Formation (Station 4). Knife for scale is 9 cm.

- Subvertical jointing with columns of variable size (≤40-70 cm) and shape (Fig. 25b);
- Distinct mesostasis (20-30% locally) of dark material;
- Plagioclase microphenocryts and pyroxene grains with no preferred orientation;
- Series of *en echelon* silica/quartz veins of 035° cutting the basalt;
- Rare amygdules in the UFU, more than normally seen.

The basalt at this station has features that are more akin to UFU basalt than MFU, but yet one can follow out the basalt upwards (i.e., to the west) into intensely vesiculated, hypocrystalline, red-brown to dark grey-green basalt that is more typical of the upper crust of an inflated pahoehoe sheet flow. Thus, this is part of the MFU and the unusually fresh, massive and medium-grained texture of the flow is considered to represent a well preserved lave core of a pahoehoe sheet flow.

Station 2. Outcrop of MFU flow at beach level with massive, honeycomb-textured (columnar jointed) basalt in basal part of the flow (i.e., lava core) with vesicle- and amygdule-rich upper crust overlying this zone. It is most unusual to see such well- developed columns in the MFU flows. Note presence of silica-zeolite veins (040-070/60-90 dips) and fine-grained, red-brown sedimentary dyke rocks and cavity fills (Fig. 25c). Dyke rocks, consisting of fine- to very fine-grained siliceous sand (loess material) and rarely containing zeolite- bearing basalt, are cross cut by banded silica-zeolite veins (Fig. 25d), which provides important time constraints on zeolite formation.

Station 3. Exceptional example of horizontal vesicle sheet or layering in outcrop of MFU (Fig. 25e); note that locally megavesicles occur here. This vesicle rich zone can be walked out for some distance along the coastline here. The flow here contains alternating layers of massive basalt and a more friable, material resulting in a distinctive pseudo-bedded texture to the flow. Note that the amygdules are of very irregular shape and often flattened. These layers represent repeated pulses of degassing of the once underlying core to the lava flow, which underwent depressurization when breakout events occurred. Note that we do not see breakouts locally, but infer their existence from the nature of vesiculation in the lava flow.

Stations 4 and 5. Unconformity between the MFU of the NMB and the younger Scots Bay Formation (Fig. 25f) at both localities, but site 4 is more impressive. The sedimentary rocks are finely laminated limestones (wackestones, lime mudstone) and the sequence has been extensively silicified due to hot spring activity. There are excellent examples of well-preserved petrified logs present (Fig. 25g). The stratigraphy, geology and paleo-environmental setting of the Scots Bay Formation have been discussed by De Wet and Hubert (1989). Note that to the northeast, the UFU appears again at Little Cove area of Scots Bay (Stop 4, Fig. 24a).

At the west end of station 5 one can see the extremely vesiculated nature of the upper part of this sheeted pahoehoe flow and at low tide walk down into the massive core of the flow. Contrast the low-density distribution of the amygdules in the ower part of the flow here with their total absence at station 5, which is at a similar stratigraphic level.

In summary, this area is an excellent example of a single, inflated sheeted pahoehoe flow where a well preserved lave core is present and the overlying, intensely vesiculated upper crust zone is exposed along the coast for the entire area in Figure 25a (i.e., 2-3 km exposure). In addition, we again emphasise the unique character of the lava core to the pahoehoe flow in this area, with its well-preserved columnar jointed texture.

Stop 8. Glenmont - Kane Quarry

Directions (see Fig. 23)

One can travel here along the bottom or top of the North Mountain, but it is quicker and easier to go along the top if Stops 2-7 were visited and along the base if coming from Wolfville area or Stop 1. Along the top of the mountain, continue west past The Lookoff, through Arlington to Glenmont, and then go down to the foot of the mountain where there is quarry on the west side of the road. Alternatively, travel along the base of the mountain through Woodside and turn right at the T-intersection and go north towards the mountain to the quarry.

The quarry is informally referred to herein as Kane quarry after the owner, and parking is available at the entrance. Note that the quarry is intermittently worked, so if men and equipment are present, stop and ask permission and then examine the rocks in the area while respecting the presence of the workers.

Highlights

The quarry, shown as a panorama section in Figure 26a, is developed in the LFU basalt (Fig. 23c) where there is an abundance of excellent exposure displaying tremendous variation in the texture of the basalt, the frequency and inclination of jointing, alteration and development of vesiculation, which is uncommon in the LFU. This area was a stop in the Guidebook for the 1980 GAC-MAC meeting, reproduced here as Figure 26b, where Stevens (1980, p. 16-17) suggested that "...at least five 'stratigraphic' zones can be delineated by contrasts in style of fracturing, prism development, degree of column tilt, and possibly texture". However, Stevens (1980) also noted that some zones might represent internal bands developed due to differential movement and cooling rate. Examine the outcrops and decide for yourself if this represents a single or multiple lava flows, bearing in the mind the nature of jointing in flows reviewed in the introductory section.

It is recommended to start observing the outcrops in the north end of the pit where fresh basalt with large, subvertical columns is exposed (Station 1). Note that the texture of the basalt here is medium-grained and holocrystalline. Traverse up the slope carefully to the ledge area to see the change in the inclination of the jointing (Station 2; Fig. 26c). From this point one can look southwest and see the upper part of the working face and note the alternating layering of massive and highly vesiculated basalt (Station 3, Fig. 26d). The vesiculated, now amygdule-rich, material is altered (hematite, green celadonite, chlorite, silica veins) and rich in zeolites (Station 3). This material can be also seen in boulders along the talus slopes (**Note: use of binoculars here would reduce the need to climb the slopes**). The amgydules and vugs in the basalt are flattened, thus recording strain and indicating a high yield strength in the basalt when vesicles formed. The amygdule-rich zone is considered to reflect proximity to the upper contact of the LFU with the MFU.

Moving along the pit, Station 4 has basalt that where jointing is intensely developed and very chaotic. The entablature-jointed basalt is, in places, interlayered with more massive basalt. Further to the south (Station 5; Fig. 26e) one sees large, steeply inclined columns that are overlain by smaller, shallowly inclined columns. At the top of the section at this end are exposed large, subvertical columns.

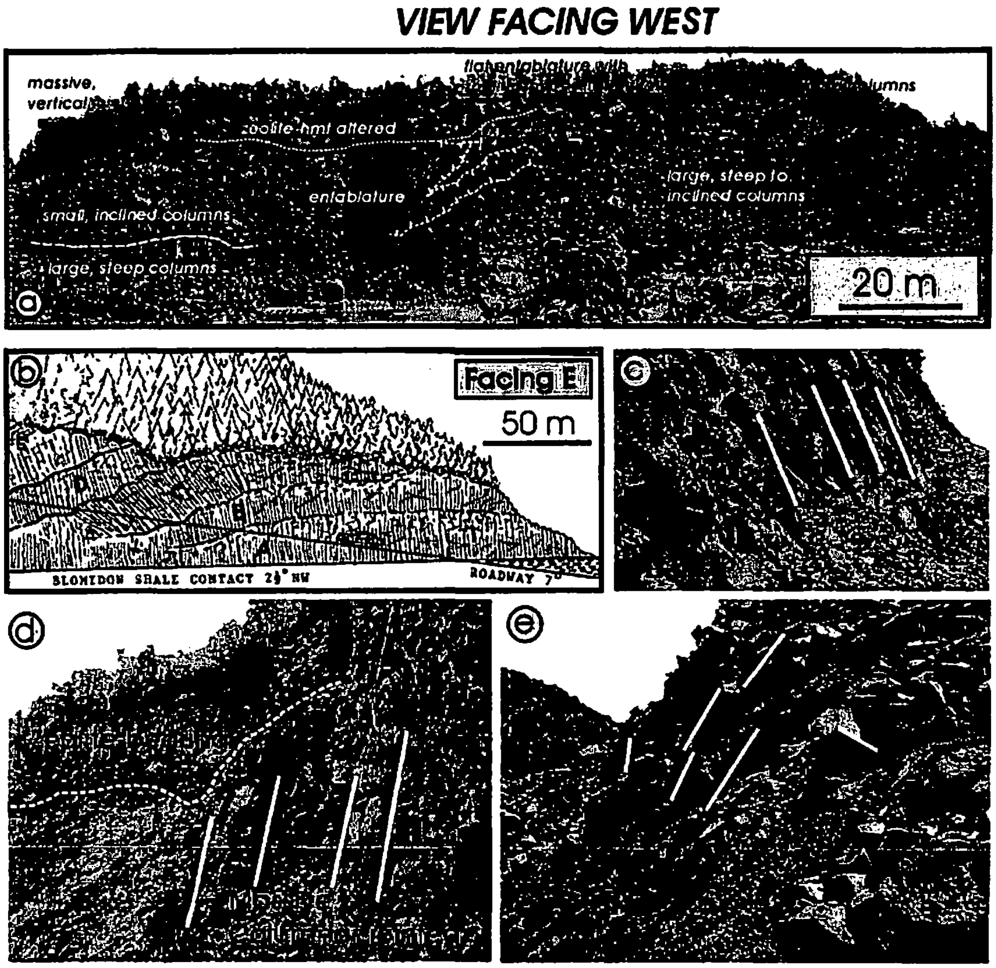


Figure 26. Photos of Kane quarry in LFU basalts. (a) Panorama view of the quarry showing the main features and site locations, as discussed in the text. (b) Inclined columns at station 2 in the quarry. (c, d) Upper part of quarry wall (stations 2, 3) showing subvertical colonnade- to entablature jointing that is overlain by amygdaloidal-rich upper part of the LFU with platy jointing. (e) Station 5 in quarry showing inclination of columns above area of vertical columns.

Before leaving this stop, exit the quarry area, turn left and proceed along the road northwards in order to see excellent exposure of the LFU on the east side of the road; this is the location of Stevens' (1980) section reproduced in Figure 26b. Note again the change in the size of the columns, their inclination (subvertical to 40-50°) and plunge.

So, the question for discussion is if this represents a single flow sheet or multiple flows based on the jointing observed?

Stop 9. Glenmont

Directions (see Fig. 23)

Exit the quarry area at Stop 6 and proceed to the top of the North Mountain along the paved road at Glenmont. It is best to park at the top where it is flat, rather than along the steep hill.

Highlights

The contact between the LFU and MFU is not exposed, but the upper part of the LFU outcrops at the top of the mountain on the west side of the road by a yellow house and in the river valley just off the road to the west. Note the grey nature of the basalt and lack of features typical of pahoehoe flows, hence the interpretation as the upper part of the LFU.

On the south side of the E-W road west of the intersection at the top of the mountain is exposed the lower part of the MFU. The MFU is fine- grained, red-brown and amygdule-rich, thus contrasting with the color and texture of the LFU. Looking off to the north, note the gently dipping topography that essentially parallels the contact between the two flow units.

Stop 10. Baxters Harbour

Directions (see Fig. 23)

From Glenmont area go west and turn right at the next intersection. Head north along the paved/gravel road that leads to the coast. The short drive of about 5 km brings you to a very picturesque embayment where there is a small fishing village. There is parking at the end of the road.

Highlights

The drive down follows the low-lying topography of the MFU. It is not until the last km or so that the UFU is reached. Excellent exposure of the UFU is found here along the shoreline at low tide and also under a spectacular waterfall (Fig. 27a) a short walk from the parking area along the stream that flows into the bay. A short walk across the stream to the east will bring you to a large, isolated blocks, *in situ*, of the basalt - is it possible that this is the result of later structural features, such as those which have controlled the localization of the silica veins at this and other localities. The areas between the blocks contain some exceptional exposure of the silica veins, thus plan to visit during low tide in order to access these areas.

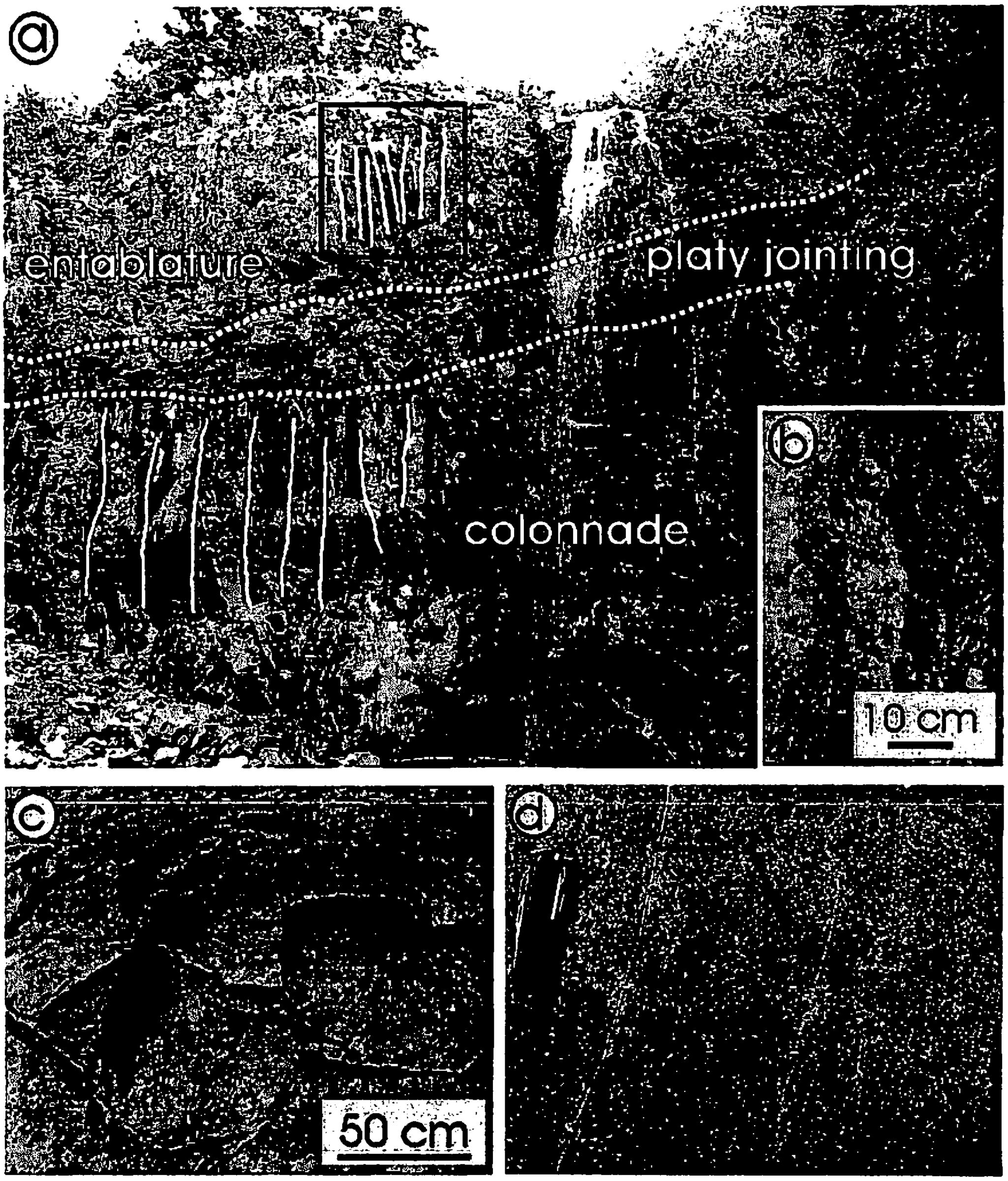
Notable observations at this locality follow:

- Abundant silica veins, some containing zeolites, flooding the basalt with strikes of 10, 40, 80° and steep to subvertical dips; these veins are sometimes cut by flat, zeolite-bearing veins. The vertical veins are up to 10-15 cm width and pinch and swell (Fig. 27b), and have an *en echelon* arrangement. These veins cause incipient alteration of the basalt within 1-2 cm of the fractures;
- Thin silica veins outline the columnar jointing pattern in the basalt (Fig. 27c); also see that veins appear to cross cut the columnar jointing (Fig. 27d);
- Well-developed colonnade and entablature jointing is best seen in the section along the southeast face, where the waterfall is (Fig. 27a). There is a change in the size, and also some change in the dip, of the columns across the entablature zone. Of note here, also, is that veins are present in the lower part of the flow, but do not cross the area with flat fractures (!);
- Rock face on the west side of the stream exposes basalt with a well-developed orthogonal joint pattern with spheroidal weathering. The weathering features have been interpreted by some workers to represent pillow-textured basalt and, therefore, to indicate subaqueous deposition, however, we know that this is not the case!

The jointing pattern in the UFU basalt here varies up section and might be interpreted by some to reflect different lava flows, such as at the Kane quarry area (Stop 8). However, such diverse jointing can occur within a single flow unit due to differential cooling, as is the interpretation for this area. Towards the west from here about 3 km is McLeod Point where the MFU is well exposed beneath the UFU along the beach. Typical exposures of the MFU illustrate the presence of flow lobes, vesicle zonation, and tumuli structures. The UFU has columnar jointing in very fresh basalt with columnar jointing local development of the nodular texture in discrete zones.

Figure 27. Outcrop pictures of UFU basalt at Baxters Harbour. (a) Waterfall area showing the nature of the fracture patterns with both vertical and horizontal sets. Inset box shows the entablature jointing, which is intensely developed across the top face of the cliff. (b) Subvertical

silica vein of ca. 10-15 cm width in basalt. This vein is typical of many in the area. (c) Silica veins outlining columnar jointing in basalt.(d) Closeup of alteration rinds about the columnar joints in basalt. Note the alteration about the later cross-cutting silica veins also.



HALLS HARBOUR-HARBOURVILLE AREA

These field stops cover the area from Halls Harbour in the east to Victoria Harbour in the central to western part of the Annapolis Valley-North Mountain area and focus on the nature of the MFU lava flows and the contrasting nature of the relatively massive UFU. All areas are easily accessible and, in addition, the stops and both Halls Harbour and Harbourville provide very scenic tourist sites worth visiting in their own right. See Figure 28 for a topographic and road map of the area with the field trip stops.

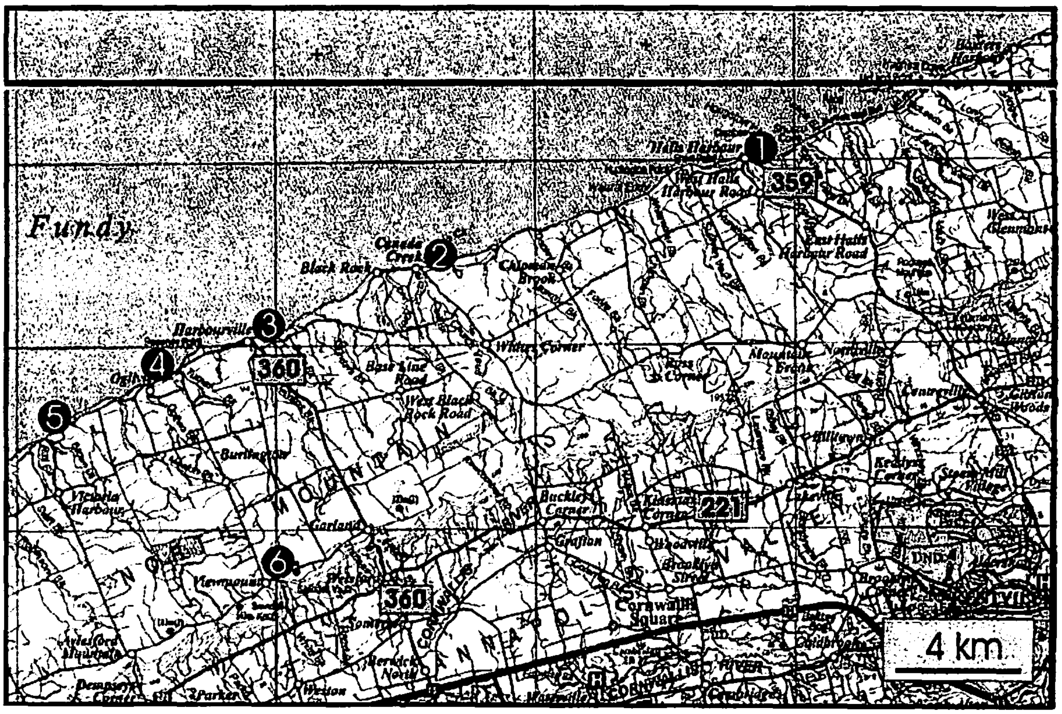


Figure 28. Topographic and road map of the central Annapolis Valley area for stops between Halls Harbour and Victoria Harbour.

Stop 1. Halls Harbour

Directions (see Fig. 28)

Continuing from Baxters Harbour, Stop 10 in the previous section, return towards Glenmont and go west at the intersection, which will lead to Highway 359 that goes north to Halls Harbour. Alternatively, if coming from another direction, Highway 359 can be accessed from either Highway 221 to 101 further to the south. ***It is necessary to be at this locality during low tide.***

Highlights

This is one of the areas along the Fundy Basin that prides itself in having the highest tides. Some agree, as it appears in an IMAX nature film. For those who have not witnessed the extremities of 55 foot tides, plan to visit at the appropriate time. While waiting for the tide to either rise or fall, enjoy freshly-cooked lobster that can be selected to satisfy your appetite at the local lobster pound on the recently upgraded wharf area. There are also many artisan shops for your enjoyment.

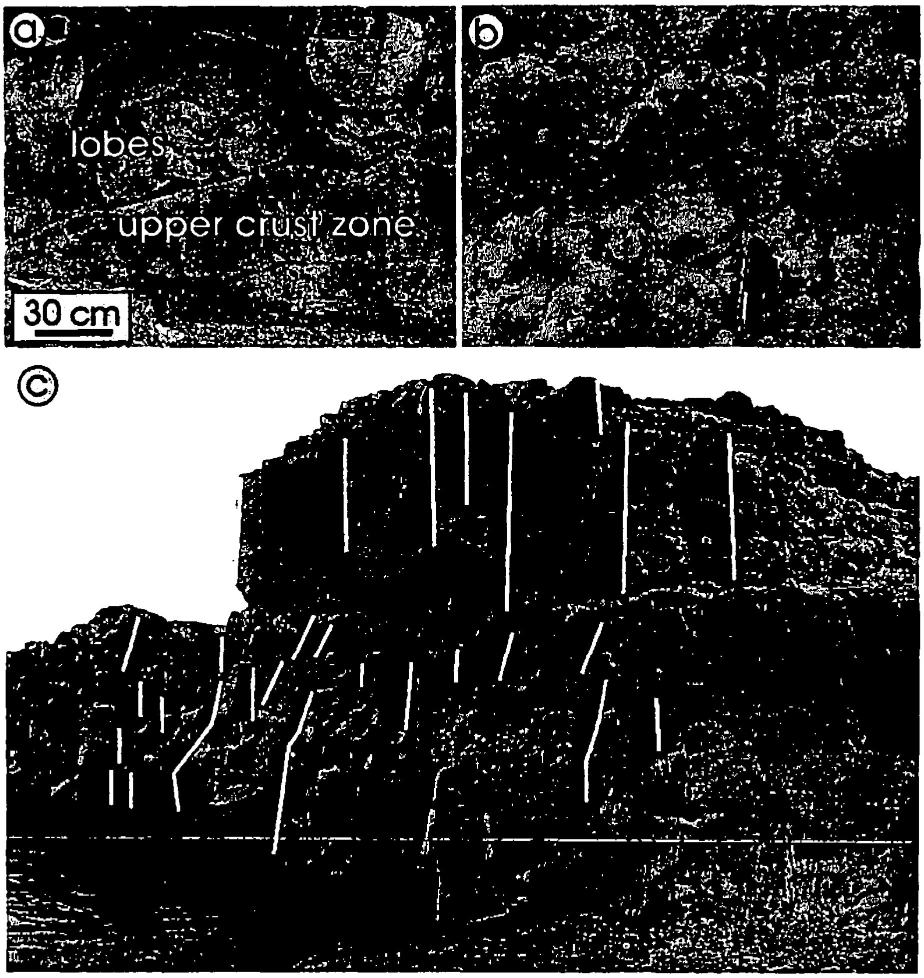
At this locality there is again convergence of the UFU and MFU, which can be seen on a short hike just east of the wharf area of the village. Examination of the topographic map shows a promontory at beach level to the northeast due to the presence of the resistant UFU. Further eastwards past the point occurs MFU, which also outcrops along the coast and to the west of the wharf area until the point seen in the distance where UFU outcrops.

Towards the prominent point to the northeast are exposed several contacts between the MFU and UFU. The uppermost, exposed lava flow of the MFU shows its typical red-brown, oxidized top with abundant vesicles and some well-developed flow lobes (Fig. 29a); the presence of the lobes above the upper crust of the sheet lobe suggests these are surface breakouts. The overlying UFU basalt is very fresh, forms the promontory to the northeast and consists of massive, columnar jointed material. Along the way, some of the UFU overlying the MFU has entablature jointing, which shows exfoliation and development of pseudo-pillow textures (Fig. 29b).

Going along the beach southwest of the wharf area, there is a single sheet flow of MFU basalt with typical internal zonation of the vesicles (i.e., DZ, NTZ, BTZ, etc.) that is overlain by the basal part of the UFU that has well-developed jointing of both colonnade and entablature types. Zeolites occur within the vesiculated MFU and also along subvertical fractures cutting UFU basalt. The contact between the two lava flow fields is uniform along here, contrasting with the irregular contact (i.e., wavy) seen elsewhere where tumuli structures are developed.

Figure 29. Outcrop photographs east of the wharf area at Halls Harbour. (a) Flow lobes, possibly surface breakouts, on top of an inflated sheet lobe (upper crust zone) of the MFU about 80 m east of the Old Lighthouse Wharf. The exposed flow is enriched in amygdules. (b) Exfoliation of well jointed (entablature type) UFU basalt giving pseudo-pillow texture. Knife for

scale is 9 cm. This is just past the previous outcrop photo. (c) Outcrop at promontory of massive UFU basalt with columnar jointing. Column orientations are indicated by the white lines. Note person in foreground for scale.



Stop 2. Canada Creek - Black Rock

Directions (see Figs. 28, 30)

Exiting from Halls Harbour there is a fork in the Highway 359, with one road going southwest for about 6 km where it hooks up with the east-west trending road you have been on before. Head west on this road for about 11 km, go pass Ross Corner and continue to a T-junction and here take a right, heading north to Canada Creek.

Highlights: Canada Creek

This location (Stop 1 in Fig. 30) is intended for those who wish to see exceptional development of columnar jointed basalt, which is displayed in this area in the basal part of the UFU. Along the coast just east of the brook entering the bay the contact between the UFU and MFU is exposed, with several volcanological features well displayed in the MFU, including tumuli, inflation ridges, lava lobes, and vesicle zonation in the flows. Continuing eastwards a promontory ***exposed at low tide*** is underlain by black basalt with mega-columns (i.e., 2-3 m width) that can be viewed from on top of the cliff, as shown in Figure 31a. Note that there is a prominent ridge developed along the margins of many of the columns, this again is attributed to silica alteration along the joints and subsequent differential erosion.

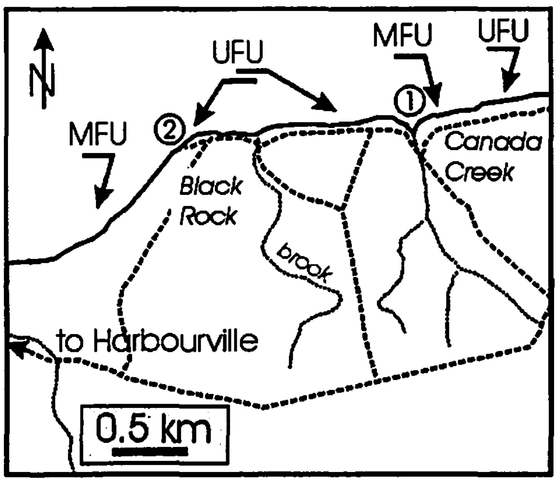


Figure 30. Map of the Canada-Creek to Black Rock area. Note that the coastline is dominated by UFU basalt, but that west of Black Rock MFU appears, hence the change in the shape of the coastline.

One can hike at low tide along the coast from Canada Creek to Black Rock and see UFU basalt with variable development of columnar jointing, both with regards to the width (i.e., colonnade and entablature) and inclination of the columns, along with silica veining. Alternatively, one can drive the short distance along the coastline to the next stop. If you drive you will not see the excellent jointing in the UFU basalt (Fig. 31b) that shows tier development within subvertical colonnade jointing underneath an inclined entablature pattern.

Highlights: Black Rock

Access this area (Stop 2 in Fig. 30) is along the dirt road just off the paved road as it turns southwest. Drive in and park at the end of the road. A short hike along the coast to the west towards a promontory of UFU basalt provides access to abundant outcrop with entablature jointing, which contrasts with the colonnade pattern seen at Canada Creek, possibly reflecting different levels of exposure in the UFU. Note again here the differential weathering causing the columnar jointed basalt to take on the appearance of pseudo-pillows. The columns here are variably inclined, in some cases approaching near horizontal. Just past this promontory a little embayment, ***accessible only at low tide***, exposes the contact between the UFU and underlying MFU that is quite irregular due to the presence of breakout lobes in the upper part of the MFU. Just past here the MFU outcrops along the coastline to Harbourville with a thin layer of UFU along the top of the cliff face.

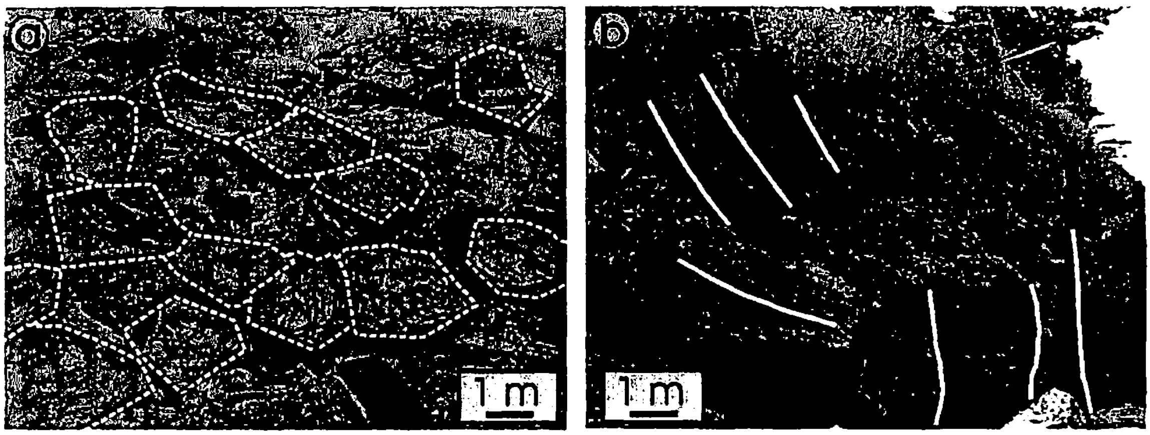


Figure 31. (a) Mega-columns in very fresh UFU basalt at Stop 1 of Canada Creek. The dashed white lines show the outlines of the columns, some of which have very prominent ridges due to silica alteration along column margins. (b) Tier jointing developed in UFU basalt along coast west of Stop 1 at Canada Creek. Note the colonnade jointing in the lower part of the outcrop and inclined orientation of the entablature jointing in the upper part of the exposure.

Stop 3. Harbourville

Directions (see Fig. 28)

From Black Rock-Canada Creek proceed southwest for about 1.5 km, take a right turn and continue for about 3.5 km until you intersect Highway 360, which leads northward to Harbourville along the paved road. A small restaurant and convenience store here provides supplies and nourishment.

Highlights

There are two short traverses here, one to the southwest of the wharf area and the second to the northeast. The former offers the following features:

1. UFU overlying the MFU which is rich in zoned vesicles; three flows are exposed here with the lower two part of the MFU and the lowermost one has tumuli structures;
2. A large variation in the shape, size and vertical extent of the vesicle cylinders in the MFU lavas; at low tide the BTZ is well seen in the lowermost exposed flow (i.e., sheet lobe);
3. Superb examples of red-brown sedimentary dykes of multi-cm width;
4. Development of nodular-texture in the massive, core part of sheet lobe of the MFU;
5. Silica veins cutting MFU lava flows.

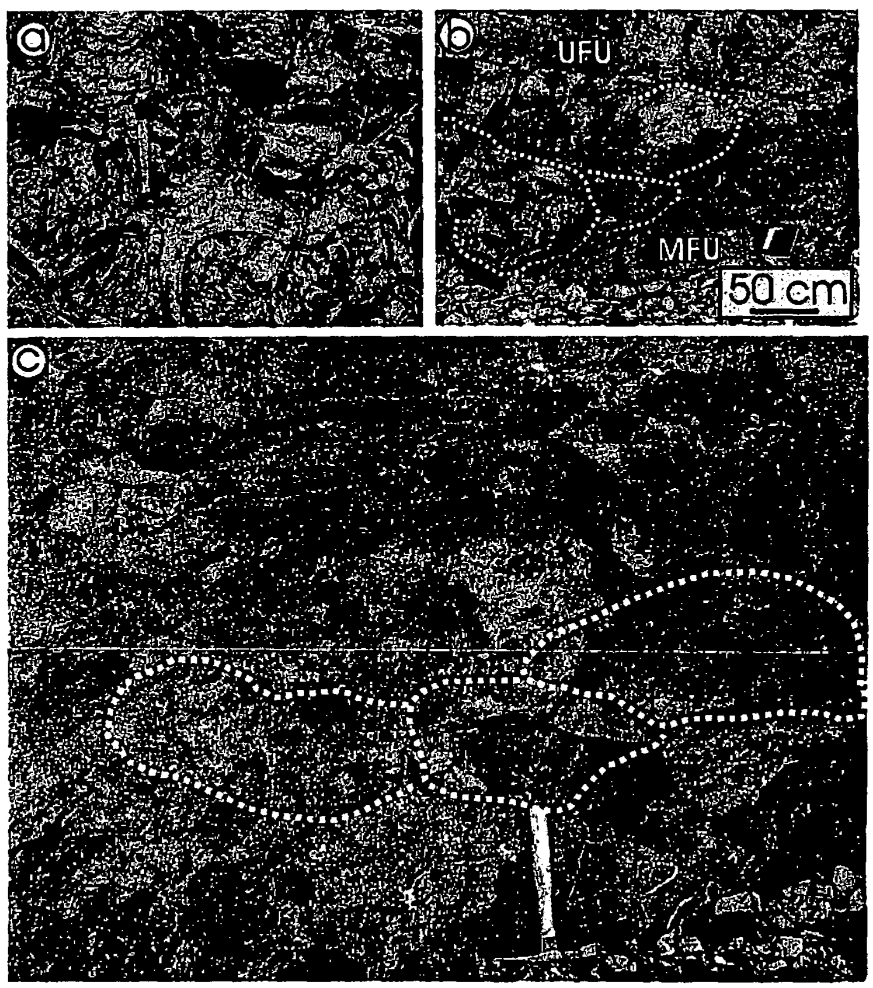


Figure 32. Photos of outcrops northeast of the wharf area at Harbourville. (a) Exfoliation features in the UFU basalt where columnar jointing is well developed. Note that these are not pillows, as some have interpreted to infer a subaqueous origin for part of the NMB. (b) Flow lobes (outlined in dashed white line) occurring on top of the vesicle-rich upper crust zone, which

suggests that these are breakouts on top of the sheet lobe. Overlying is the base of the UFU lava. (c) Flow lobes in the upper crust zone of a sheet lobe, which are rare in the interiors of pahoehoe flow, as contacts are usually annealed.

A traverse to the northeast of the wharf area offers more spectacular features, so if time is a factor this is suggested. Again, the UFU is seen resting on MFU lava flows with irregular contact. The point at the far right forming a promontory is underlain by the more massive and resistant UFU basal. Points to note follow:

1. The contact is very irregular and is marked by exceptional development of lava lobes, in some cases with vesicles outlining the shape of the original lobe (Fig. 32b, c); these are S-type lobes of MacDonald (1991);
2. Excellent red-brown sedimentary dykes (≤20 cm width) are seen in the upper part of the MFU, just below the contact with UFU basalt;
3. The columnar joints are subvertical to inclined in their orientation;
4. Nodular textures are present in the UFU along with vesicle cylinders, a rare occurrence in the UFU.

Stop 4. Sweeney Point

Directions (see Figs. 28, 33)

Continue along the paved road westwards from Harbourville going along the coast for about a km before taking a right turn, as indicated by the sign, and follow to the coast for field Stop 1 in this area. Proceed further along the same road westwards for about 0.6 km until the road turns up a hill towards the south and park at the beach area for field Stop 2.

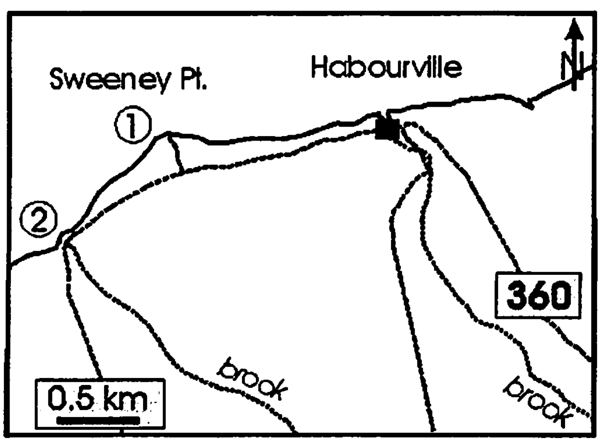


Figure 33. Map of the Harbourville-Sweeney Point area with field stops indicated.

Highlights: Stop 1

At the beach area where you have parked are outcrops of massive UFU basalt with plagioclase microlites and mesostasis texture. The following features can be observed in the basalt:

1. Large (1 m width), 4-6 sided columns; the boundaries of the columns are defined by ridges due to positive relief (alternatively the cores have negative relief), which relates to silica alteration along the joints, a feature seen already;
2. Development of intense fracturing of the basalt along NW orientations with silica flooding; sometimes the veins are zoned with several generations of silica;
3. Local development of a radial fracture pattern in the basalt, referred to as spindle-like pattern;
4. Black, aphanitic, ameboid-shaped blebs with some vesicular texture (Fig. 35f) and silica material; this material contains ≤30-70%, dark red-brown glass, as observed in thin section and imaged using the electron microprobe

Continuing along the beach eastwards from the above stop the coastline turns inwards due to the presence of the MFU outcropping which provides an opportunity to see the contact between the UFU and underlying MFU; excellent field relationships are observed:

1. Basal part of the UFU contains 30 cm vesiculated zone with zeolites and above this some vesicle cylinders, which are generally rare in the UFU
2. Nodular texture in the base of the UFU, a feature that requires further work to understand;
3. Well-developed disseminated zone in upper part of MFU with easily discerned layers reflecting pulses of new lava into the core of the pahoehoe flow and subsequent degassing accompanying breakouts at lobe fronts;
4. Contact between the UFU and MFU is curved or bulbous due to local irregular inflation of the flow lobes of the MFU prior to emplacement of the UFU.

Highlights: Stop 2

At the east side of the beach a cliff face exposes two sheet lobes of the MFU (see Fig. 34 for sketch of this exposure) and further to the northeast the UFU is seen to overlie the MFU at beach level. The promontory to the northeast is due to the UFU outcropping. Proceeding along the coast to the northeast for a few hundred metres, towards the point where the UFU forms a promontory, the following features are noted:

1. Excellent examples of lobes and toes in the MFU lava flows exposed in many places along the coastline (Fig. 35a, c). These probably represent surface breakouts as they lie above the upper crust layer of the sheet lobe;
2. Colonnade jointing in the massive core of some lava flows (Fig. 35b);
3. Interflow sediment and sedimentary dykes in the MFU flows;
4. Mega-columnar joints in colonnade jointed UFU (Fig. 35e), which is places is adjacent to inclined entablature jointing

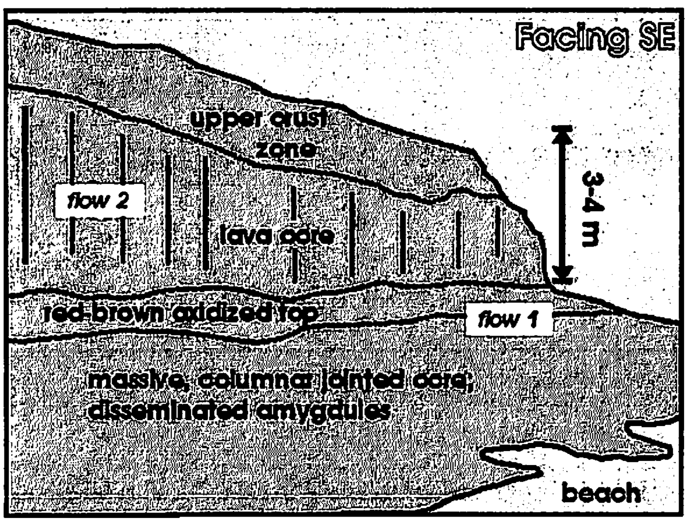


Figure 34. Sketch of outcrop showing the relationship between two sheet lobes of the upper part of the MFU at beach, Stop 2 of Sweeney Point. Drawing is from photo taken at low tide.

Continuing past the promontory a small embayment exposes the contact between the UFU and MFU. This is a good example to illustrate that the shape of the coastline is determined by the nature of the NMB rock that outcrops - the embayments reflect the presence of recessive flows of the MFU.

Returning to the parking area at Stop 2, continue past here along the coastline to the southwest for a short distance to see excellent exposure of MFU flows. A short hike away are exposures of interflow sediments and sedimentary dykes filling joints in MFU basalt (Fig. 35d) and many examples of flow lobes.

Figure 35. Photographs of outcrops in Sweeney Point area. (a) Breakout lobes (outlined by dashed black lines) on the surface of a sheet lobe, as marked by the dashed white line. Outcrop along beach northeast of parking area at Stop 2. (b) Columnar jointing, colonnade type, in the core zone of a sheet lobe near previous outcrop photo. Note the presence of disseminated amygdules in this part of the flow. Note the large column outlined by the dashed white line. (c) Flow lobes in top of a sheet lobe of the MFU that is overlain by the basal part of the UFU (contact marked by dashed black line). Outcrop near the promontory where UFU outcrops and

northeast of parking area for Stop 2. (d) Flow lobes (outlined by dashed white line) in upper part of a sheet lobe with later filling by red-brown sediment; fractures cutting the lobes are also filled by red-brown sedimentary material (indicated by white lines). Outcrop is southwest of parking area along beach from Stop 2. (e) Mega-column in UFU basalt that underlies the promontory for traverse northeast of Stop 2; the UFU basalt is very massive and fresh here. (f) Irregular-shaped bleb of hypohyaline material that is dominantly intermediate glass with microlites of skeletal, Fe-rich augite, as seen in thin section and analyzed on the electron microprobe. Note presence of silica blebs in the middle of the dark, fine-grained material. Outcrop located at Stop 1.

Stop 5. Victoria Harbour

Directions (see Fig. 28)

This stop is accessed from Stop 4 at Sweeney Point by continuing south, up the hill for about 2 km towards Burlington and turning right, towards the west at a sign indicating Victoria Harbour. Note, however, that the next stop at the Burlington Road quarry south of Viewmount is further south on this same road, so plan accordingly.

Access to Victoria Harbour is also from the south from Highway 221, or Highway 101 by taking Exit 16 and heading north, following the signs towards the coast.

Highlights

This locality provides an exceptional example of development of the zoned, vesicular horizons in the MFU flows that are locally overlain by the UFU. Upon driving to the locality there is an open field on the left (west) side of the road just before it steepens towards the coast. There are several outcrops here and one can locate the contact of the UFU and MFU; the large flat area of the field owes its existence to the fact it is underlain by relatively resistant UFU basalt. Once reaching the coast, which must be accessed at low tide (***plan ahead accordingly***), there are excellent sections both east and west from the beach that show the upper part of the MFU beneath the UFU.

For those that wish, this is an excellent area to camp for the night, as others use it on a regular basis in the summer. It is a sheltered cove and there is a fresh water stream feeding into the ocean here.

Stop 6. Burlington Road Quarry

Directions (see Fig. 28)

The quarry is found along the west side of the Burlington Road leading north from Highway 221 about 4 km west of Welsford. If coming from the north after Stops 3, 4 or 5 then drive along the top of the North Mountain to Viewmount and go south to Highway 221. If coming from elsewhere, then follow Highway 101 to Exit 15 and proceed north towards Burlington-Viewmount. ***This is an active quarry at times and the road it is along side has regular traffic, thus be careful at this stop.***

Highlights

The quarry is located near the top of the LFU and the large exposed face shows exceptional development of columnar jointing with variable development of both the width of the columns (colonnade and entablature) and their orientation; hence, there are several tiers to the flow here. It is suggested that the traverse start at the south end of the working face where the jointing is subvertical and columns the largest. Progress northwards noting the change in the nature of both the size and orientation of the columns. At the far north end the columns are inclined to near horizontal and relatively narrow. Also note the massive nature of the rock and its freshness - this is why it is being used as aggregate material.

Now, walk along the paved road up the hill past the quarry ***(be careful of the traffic on the road)*** to the outcrops on the west side of the road and follow the change in joint orientation and style from near horizontal entablature to subvertical colonnade over the next ca. 100 m. At the end of the stretch of outcrop where subvertical jointing is dominant, note the presence of very discrete horizontal layers in the basalt. This material is coarser grained and vesiculated compared to the host basalt and represents late-stage pegmatite layers in the LFU. Note that we are near the top of the LFU at this point.

MORDEN TO PORT GEORGE AREA

This section provides excellent exposure to many of the volcanological features that charactertize the MFU as pahoehoe flows, all spectacularly displayed, and some unusual petrological features, namely segregation pipes, in the basal part of the UFU. The trace of the coastline here illustrates well the relationship between geology and coastal erosion. For example, at both Morden and Margaretsville the promontories are underlain by UFU basalt, whereas away from here the MFU occurs. Another excellent example of this occurs at St. Croix Cove west of Stop 4, Port George, where the UFU gives way to the more easily eroded lava flows of the MFU, the erosion of which resulted in formation of the cove. ***All of these stops require accessing at low tide for maximum viewing pleasure.***

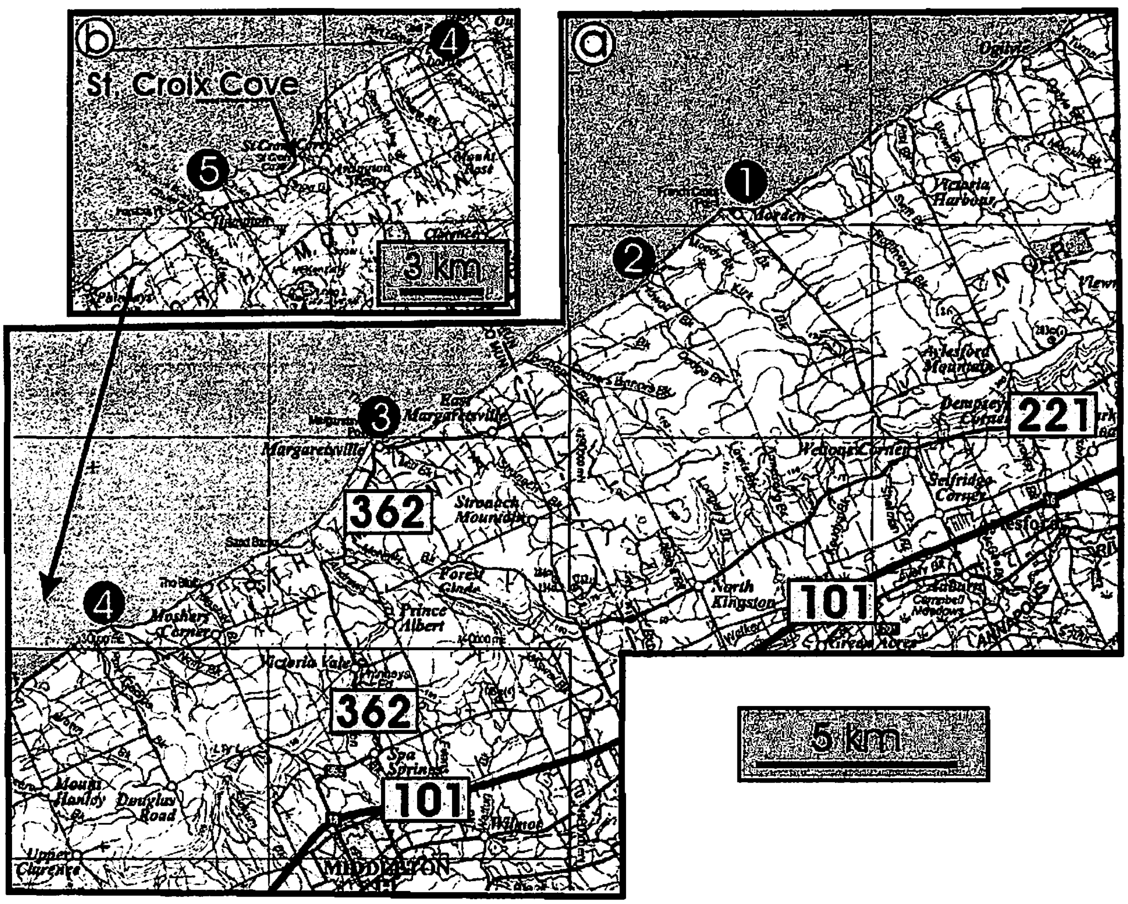


Figure 36. Topographic and road map for field stops from Morden to St. Croix Cove.

Stop 1. Morden

Directions (see Figs. 36, 37)

The directions to Morden depend on the last field stop made. If Victoria Harbor was visited, then return up the hill and take the cross-land dirt road to Morden, which is clearly marked. Alternatively, if one is coming from further away it may be best to follow Highway 221 westwards along the base of the North Mountain to Weltons Corner and the go north. This road is paved the entire way to Morden.

Upon arriving at Morden go through the village to the water and stop at the small parking area by the French Cross - a monument erected in memory of those who perished as a result of a perilous journey during the winter a few hundred years ago, thus stop and read the very interesting commemorative plaque to appreciate the hardships of the early settlers!

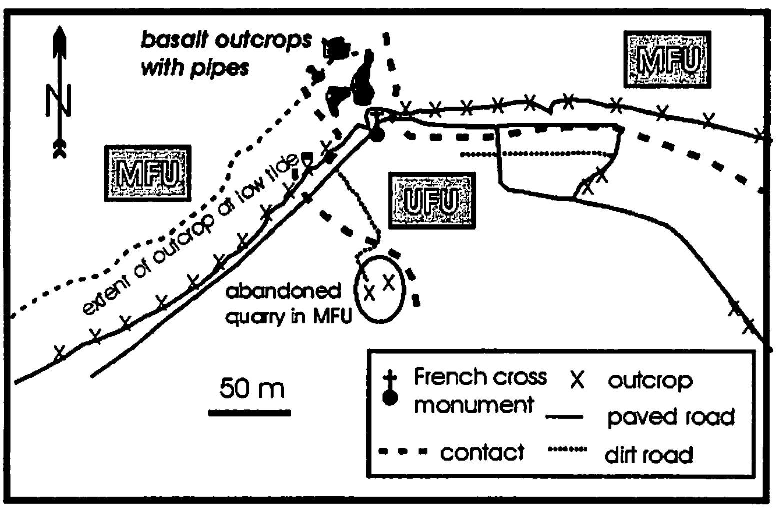


Figure 37. Map of Morden area showing extent of the MFU and UFU. Note extent of outcrop area at low tide on west side of map area.

Highlights

Firstly, there is a well-known zoo in the town of Aylesford that is worth a visit if this trip includes young family members, or those young at heart. There is an array of interesting animals including exotic wild cats (lions, tigers), birds, monkeys, etc.

The road to Morden travels over MFU basalt flows that should be easily recognized now after having visited several outcrops; note the fine-grain size, the red-brown oxidized character, and presence of zeolites. As you approach Morden UFU basalts are exposed - try to recognize the features that distinguish these from the MFU basalts.

At French Cross the tip of a tongue-like protrusion of UFU is exposed and the contact with underlying MFU flows is seen just to the east (Fig. 37). Again, note that the relief here is clearly an expression of the relative freshness of the rock types with the headland area underlain by fresh, massive UFU, forming the promontory. The UFU basalt is characterized by a medium-grained texture, abundance of mesostasis and, most importantly, the presence of some very spectacular and unusual petrological oddities. Walking around the large UFU outcrop you will notice round- to elliptical-shaped features, some of which are shown in Figures 38a, b, c. The unusual material is composed of the following three components:

- Dark grey to black, fine-grained to aphanitic, basaltic (?) material;
- Red-brown, aphanitic material bordering the dark material;
- Variety of siliceous material that includes crystalline quartz, multi-colored agate, and massive, fine-grained cloudy silica.

The exposure here does not provide a very good 3D view of these features, but there are essentially pipe- or cigar-like in the third dimension based on observations elsewhere. The pipes at this locality contain the highest proportion of siliceous component, either the agate or crystalline quartz, out of all pipe localities so far observed in the NMB. The proportion of igneous- versus silica-rich pipes in this outcrop area is 68% versus 32%, respectively, based on 103 pipes observed.

The nature of the MFU and UFU at this locality can be observed via several traverses in this area, two from French Cross and one from east of the town of Morden to Black Point.

Black Rock Point: access the area by the road east of French Cross that leads to the old wharf area (Fig. 37). From hear traverse along the beach to the promontory of dark UFU basalt that extends into the water. After about 300 m outcrop exposes two sheet flows of MFU basalt with very irregular thickness - these are probably tumuli structures. The well-defined nature of the upper crust in these two flows of the MFU here permits you to approximate the time of emplacement - compare the answers using the equation provided earlier (i.e., $t=164.8 * H^2$). These flows are overlain by massive UFU basalt.

Further towards Black Point the two MFU flows flatten out with more regular, uniform thickness and have exceptional development of internal zonation of amygdules (i.e., the DZ, NTZ and BTZ discussed earlier). In the upper part of the top sheet lobe of the MFU are well-preserved examples of flow lobes (Fig. 39). These lobes are immediately below the contact with overlying massive basalt of the UFU.

The UFU underlying the point has well developed columnar jointing (i.e., colonnade zone of lower part of flow) and is very fresh. The very prominent nature of the outcrop, its overall

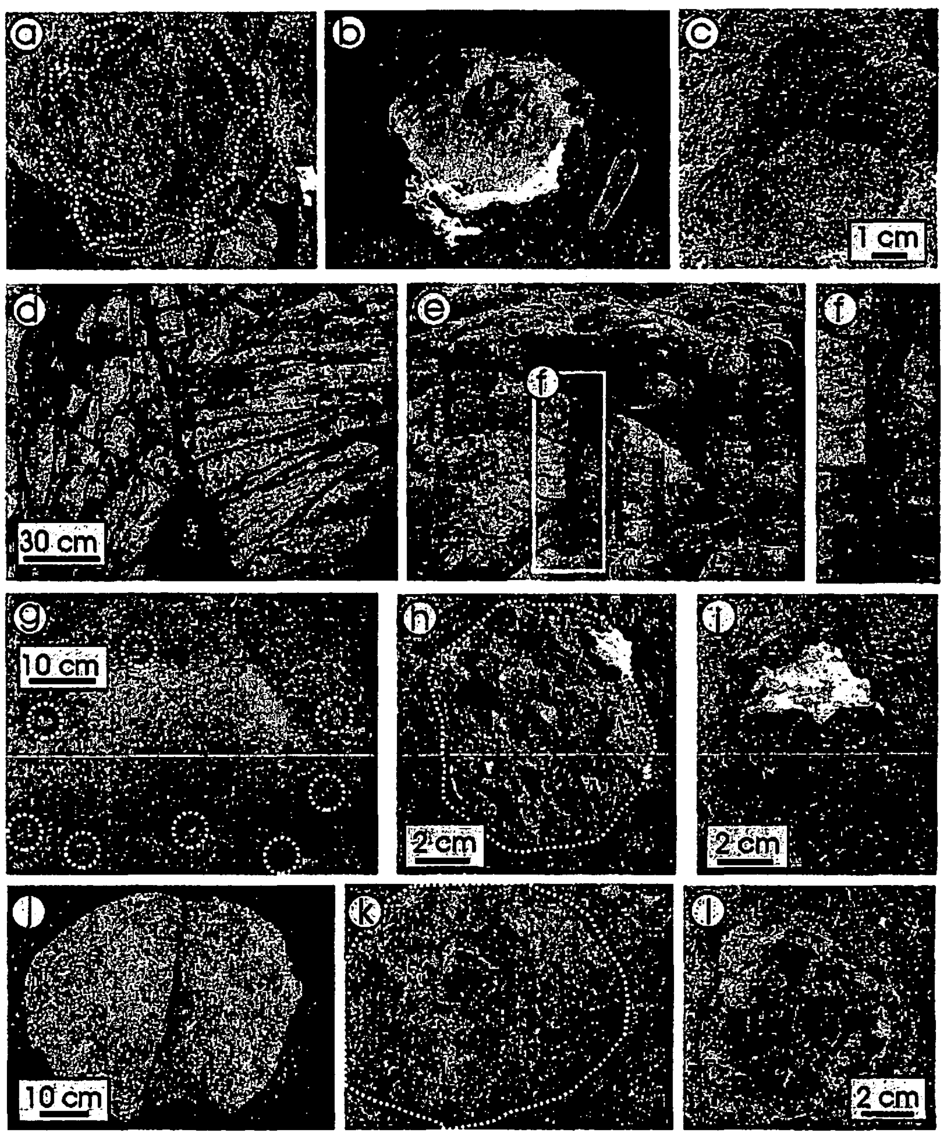


Figure 38. Outcrop photos of UFU basalts and their features at Morden (a, b, c), Margaretsville (d,e, f, g, h, i) and Port George (j, k, l). (a, b, c) Segregation pipes (e.g., Anderson et al. (1984), Goff (1996), Self et al. (1998)) showing uniform to composite features (C=core, R=rim in Fig.

38a), including mafic and felsic components (in Fig. 38a R is felsic) and agate cores. (d) Plan view of spindle-fracture pattern in UFU basalt near lighthouse (traverse 2) at Margaretsville. (e) Segregation pipes in cross-section (traverse 2 at Margaretsville) in basal part of the UFU. (f) Close up of segregation pipe in the previous photo. Note the massive nature of this pipe, in contrast to the amygdaloidal nature of others in the previous photo. (g) Plan view of segregation pipes at site in traverse 2, Margaretsville (area mapped in Fig. 45). (h) Close up of a pipe showing amygdaloidal nature. (i) Ovoid-shaped pipe with crystalline quartz material in the top part. Note the presence of vugs in the dark material. (j, k) Mega - segregation pipes at Port George field stop. Note the agate core in Figure 38k, which is enlarged in Figure 38l.Knife for scale is 9 cm long.

circular shape and the development of columns have been used by some to infer this site to be a volcanic neck or plug, a relict vent site for the flows. You may wish to discuss this on the outcrop! Contrast the nature of this very fresh flow with the much finer grain size and the altered, vesiculated nature of the MFU basalt just seen. Around the point, **only accessed at low tide**, is an excellent exposure of the contact between the UFU and MFU with some good examples of sedimentary dykes at this contact and pipe vesicles at the base of the UFU indicating variable shear sense. Within the UFU basalt are some vesicle cylinders and zones dominated by nodular textures.

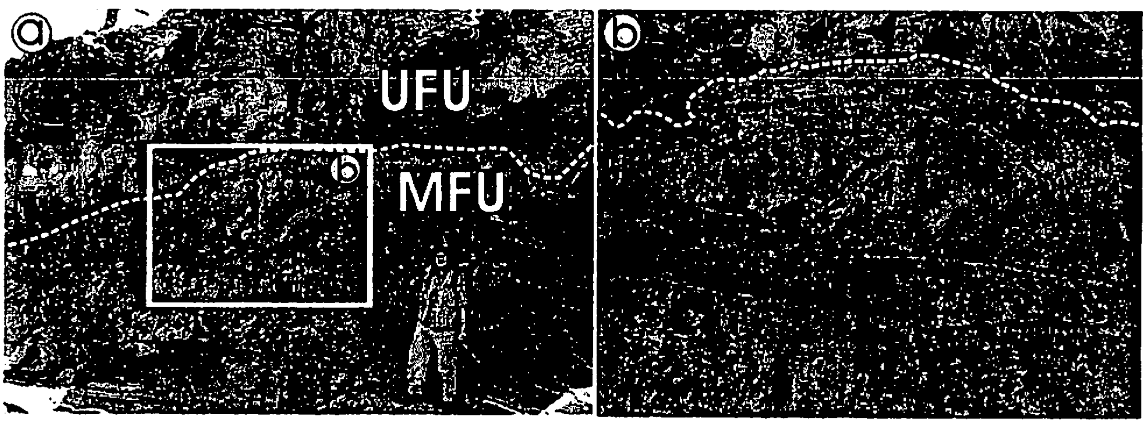


Figure 39. Outcrop of upper most sheet lobe of the MFU near Black Rock Point. (a) Contact between lava flows of the MFU and the UFU with area in next picture outlined by the box. Note person for scale.(b) Flow lobes(outline by dashed black lines) at top of a an inflated pahoehoe

sheet lobe, probably originating as breakouts on the top surface of the flow. Contact between MFU and UFU is marked by dashed white line.

French Cross - northeast: going northeast from the French Cross is a ca. 200 m section showing the middle (lava core) and upper part (crust zone and lobes) of a single sheet lobe in the uppermost part of the MFU, which is overlain by the basal part of the UFU. The top part of this sheet lobe contains some of the best flow lobes seen in the MFU any where in the NMB and well-preserved vesicle zonation (BTZ, NTZ, DZ); hence, it provides an excellent opportunity to discuss the proposed inflated sheeted pahoehoe flow origin for these lavas. Abundant zeolite-bearing veins of variable orientation are also present. The eastern part of the exposed section is in the upper part of the sheet flow; thus, the flow lobes are seen. As one traverses westwards the middle part of the flow is exposed, which reveals the zoned vesicles (NTZ, BTZ) and massive core of the flow - thus, classic zonation of an inflated sheeted pahoehoe flow.

French Cross - southwest: going southwest of French Cross is a section of MFU for which a map has been provided (Fig. 40). Along this section volcanological features are seen, in particular, the development of tumuli, which reflect localized pressure build up in the flow and subsequent inflation. Importantly in these structures the vesicle cylinders are vertical, thus there has been no post-emplacement folding of the flows to create the appearance of these pseudo-folds (i.e., antiforms and synforms). Also along here are zonation of vesicles, nodular-textured basalt, silica-zeolite veins, and sedimentary dykes.

Stop 2. Kirk Brook

Directions

Continue along the coast on the dirt road west of Morden for ca. 2.5 km until you come to a bridge just after a steep hill. There is parking at the bottom of the hill and a nice beach, for the Fundy Basin at least, to use for a lunch stop or just to relax.

Highlights

Basalts of the MFU are well exposed along the coast here and many excellent features are seen just to the northeast (i.e., right) of the parking area, as shown in Figure 41. In particular, this is an area where many of the features that support an inflated pahoehoe origin for the MFU can be observed. Features to be seen are summarized below:

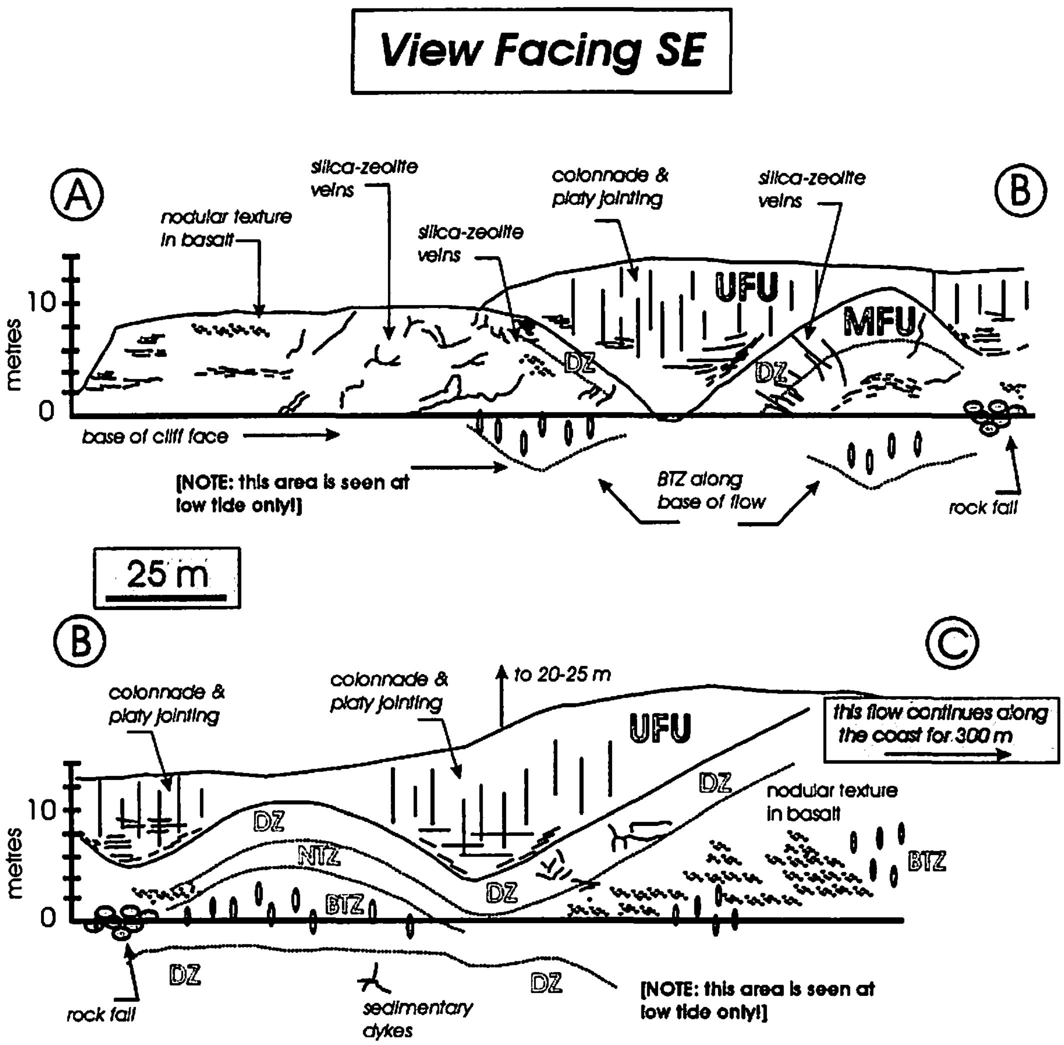


Figure 40. Longitudinal section commencing just past the brook to southwest of French Cross showing irregular nature of the contact between UFU and underlying MFU. The uppermost sheet lobe of the MFU contains several tumuli features. Note that at low tide you can see the upper crust zone or top of another sheet lobe. There is excellent development of vesicle zones in the sheet lobe of the MFU.

- Multiple sheet lobes of 8-15 m thickness, easily recognized by their red-brown, oxidized upper crust zone, fine-grained textures at the tops and bases, disseminated vesicle zone at the top, several subparallel vesicle layers (Fig. 41e), vesicle cylinders, massive interiors, and basal pipe vesicles (see Fig. 41a). The horizontal vesicle layers in Figure 41e represent periodic depressurization and concomitant degassing within the lava core during breakouts;Architecture of flow 2 may reflect the merging of two flow lobes with inflation ridges between the two, subsequently filled by flow 3;

- Note how flow 3 contains several flow lobes, but the contacts are discontinuous and cannot be traced out laterally, a feature not uncommon in pahoehoe flows;
- Rare examples of lava lobes in the upper crust zone of the sheet lobe (Fig. 41d). As noted earlier, such excellent preservation of lobes is unusual in inflated pahoehoe flows since contacts are usual annealed, but these represent well-preserved cases and among the best seen in the MFU;
- A most unusual flow lobe inset in Figure 41a is shown for purposes of discussion;
- Feature in Figure 41b, c (seen at the beginning of the traverse) is interesting and may be interpreted as a squeeze up or conversely infilling of a fractured (i.e., cleft) lower flow lobe by the overlying flow, depending on how one interprets the contact relations;
- Nodular textured areas in the massive parts of flows that may be autobreccias formed as the flow 2 advanced on itself. This feature is fairly common in flows of the MFU.

This is a good area to contrast the vesicle cylinders, characterized by their highly vesicular nature, consistent vertical orientation, uniform width within a group, with the pipes just observed at Morden. Petrological studies suggest that, whereas the latter reflect mobilization of a late-stage, evolved and volatile enriched-felsic melt, the former reflect ascent of a less evolved, but also volatile-rich melt generated as the flow solidifies after having inflated to the observed thickness. Note that the densities of the melt forming the vesicle cylinders, also the pipes at Morden, are considered to reflect the nature of the source reservoir.

Stop 3. Margaretsville

Directions (see Figs. 36, 42)

This locality is easily accessible from south, east and west depending upon the previous field stop. If leaving from Kirk Brook, continue south along the dirt road that goes up a hill past the bridge and continue for about 1.5 km. At this point turn west (right) and continue for 3.5 km, at the T-junction turn left and go along the Bishop Brook road south for 3.5 km, turn west (right; note Margaretsville sign) and continue for 2.5 km until you come to a T-junction with a paved road. Turn right here and continue to East Margaretsville, then continue through here to Margaretsville.

Alternatively, one may access this stop from Highways 362 or 221. If you are going west along Highway 221, continue through North Kingston to the point that 221 turns south and head up the mountain. At the top of the mountain, take the left fork to go to Margaretsville; the right fork goes to East Margaretsville.

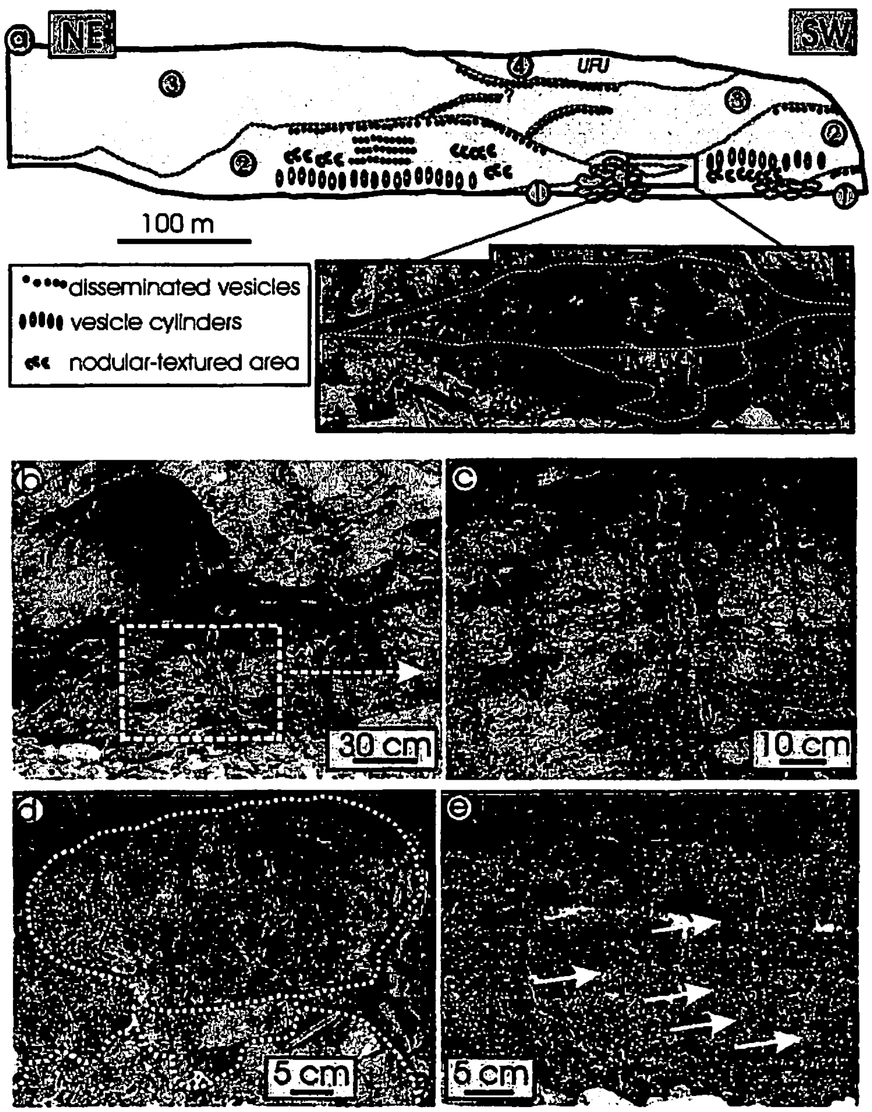


Figure 41. Longitudinal-section and outcrop photos at Kirk Brook. Photos b, c, d and are from the southwest end of the cross section. (a) Cross-sectional map facing southeast showing sheet lobes of the MFU and base of the UFU lava flow. Inset photo of the cross-section shows complex shapes of small lava lobes. Note that the contacts between flows are easily discerned because of

the presence of the vesicle-rich zones, chilled contacts and pipe vesicles. (b, c) Contact between two sheet lobes (flows 1, 2) of MFU showing fine-grained basalt material (dyke like) cutting the vesicle-rich zone of upper crust of flow 1. This may have originated by the younger flow infilling a cleft that formed post deposition of the lower flow. (d) Flow-lobes, outlined by dashed white lines, in upper crust zone of sheet lobe of flow 1. (e) Horizontal vesicle horizons in the fine-grained, oxidized, red-brown upper crust zone of flow 1.

Enter the town of Margaretsville and park at either the wharf area (don't forget to visit the little art store here with painting by locals decorating the walls), or at the parking lot nearer the lighthouse (Fig. 42) and take either the path or dirt road to the shoreline.

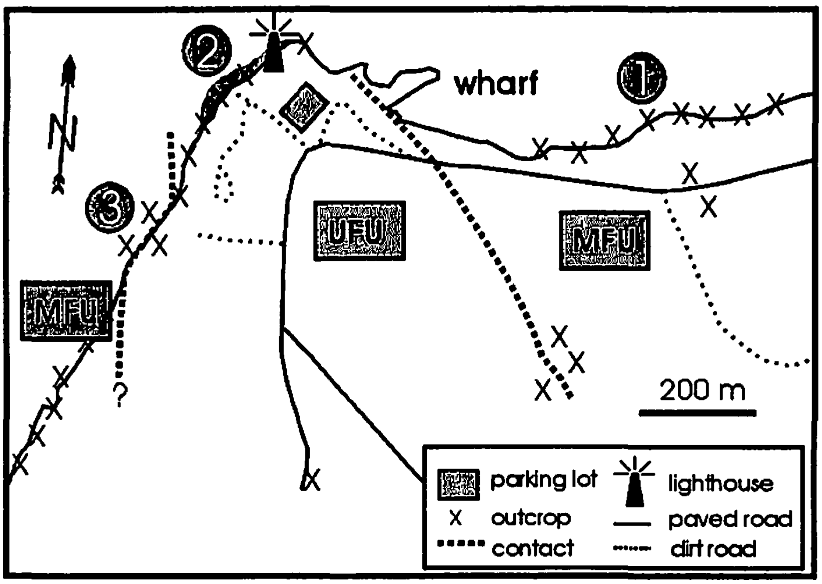


Figure 42. Road and geological map of Margaretsville area showing the extent of MFU and UFU basalts and location of the suggested field traverses (1, 2, 3).

Highlights

This area is excellent because the MFU and UFU are well exposed and full of many interesting volcanological features. The geology map of the area (Fig. 42) is revealing in that it shows that the promontory, Lighthouse Point, is underlain by UFU basalt that is more resistant than the zeolite-rich MFU basalt, an important feature that has been emphasized many times, as it permits inferences about the distribution of the flow units. In cross section, it is evident that the tongue of UFU basalt fills a topographic depression or channel-like feature in the MFU.

Three sites of interest here, discussed below as three traverses: (1) walk out the sections east of the wharf area to see complex architecture of flow lobes within the MFU flow field; (2) examine the UFU that locally contains abundant segregation pipes of differentiated material; and

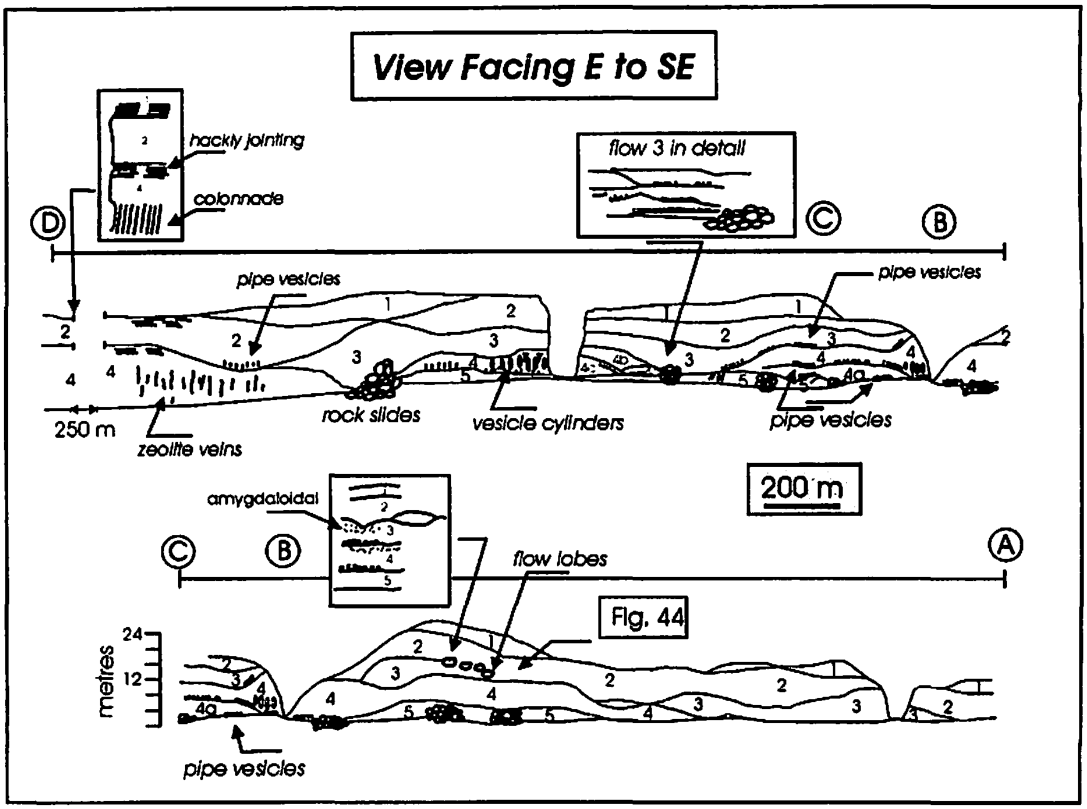
(3) walk out the section of MFU to the southwest to see the contact between the UFU and MFU lava flows and excellent examples of zoned, vesiculated sheet lobes within the MFU flow field.

Traverse 1:

The area of coastal exposure east of the wharf area was mapped by Kontak (2002) and the long section is reproduced here as Figure 43. The section is dominated by sheet lobes of the MFU with the basal part of the UFU exposed at the top of the cliff face. Contrast the massive, medium-grained textured UFU basalt, in places with colonnade jointing, with the fine-grained and vesciculated nature of the MFU basalt. The MFU consists of multiple sheet lobes and contacts between lava flows are easily seen using the crusted nature of tops and internal vesiculated zones as indicators. It is an excellent section to walk out and see the architectural complexity of the MFU and physical volcanology, including the number of flows and their internal features. Several hours could be dedicated to this area! Features to be noted are:

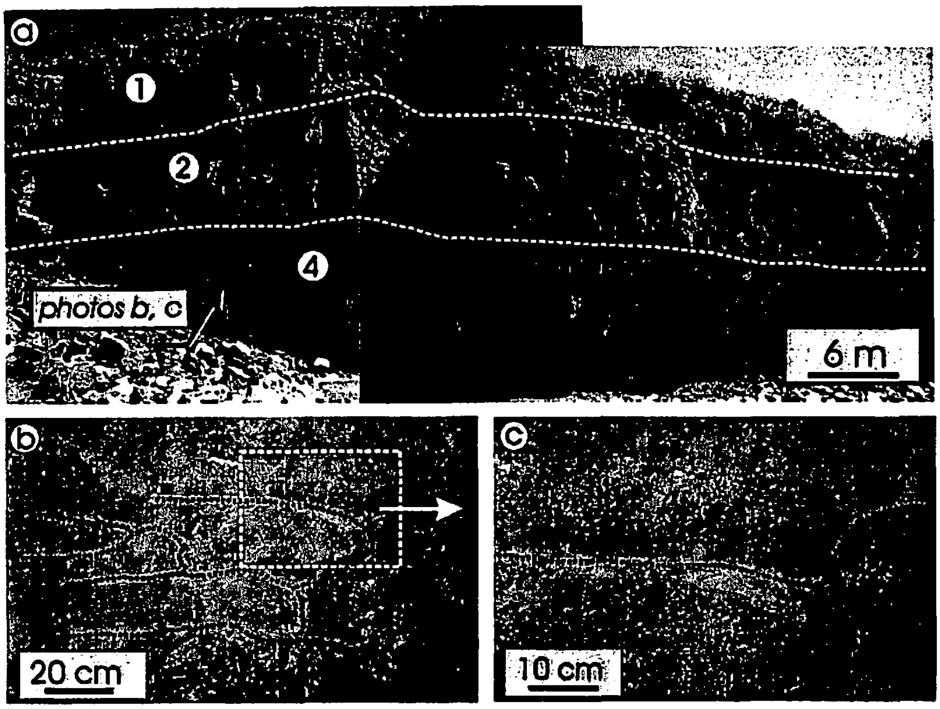
- Variation in the number of flows due to the apparent pinching out of some flows; similar features are described in sections and profiles of the CRBG (Thordarson and Self, 1998);
- Good examples of flow lobes are preserved locally (Fig. 43 and inset in Fig. 44b, c). This feature is important since it supports an inflation model for the flow lobes of the MFU and attests to the fact that most contacts between lobe fronts have been texturally annealed post emplacement (Hon et al., 1994);
- Variable thickness of flows, which may relate to ridge inflation at flow margins and tumuli features. The fact that these are inflated pahoehoe sheet flows with basalt pipe vesicles indicate a low regional slope (i.e., $<2^{\circ}$) at the time of deposition and argues against large regional-scale variations in topography;
- Within any one flow there commonly occurs the systematic distribution of vesicles and amygdules, as described for NMB flows by Kontak (2000). Note that basal pipe vesicles can be used to infer flow movement - are the indicators along this section consistent among the flows?
- Well developed, fine-grained, red-oxidized flow tops (crusted tops of lobes or lava flows) of ≤ 1-2 m thickness and are very rich in amygdules. This feature is important since it is used to signify contacts between flow lobes;
- Zeolite veins, locally abundant, have generally consistent orientations (Is this a regional control ?). At the far east end, at Bishops Creek, such veins had native copper and were explored in the 1960's;

Figure 43. Longitudinal section of area to the northeast of Margaretsville showing sheet lobes of the MFU and overlying lava flow of the UFU (flow 1). The letters are just used as reference points for joining up the sections. Note the lack of lateral coherence of the flows in parts of the section and the variation in the thickness of some flows, in particular flow 3, which may reflect formation of tumuli or pressure ridges. Note that point D is towards the east.



- Further eastwards the flows are less complex and flows 2 and 4 in Figure 43 have very consistent thickness and continue like this for several 100 m to the end of the area mapped. This consistency is similar to what is observed on the other side of Light House Point, thus indicating that the degree of complexity seen in the flows maybe somewhat anomalous.

Figure 44. Outcrop photographs of the longitudinal section in Figure 43 (see Figure 43 for location). (a) View facing southeast showing flows 1, 2, 4 - note the lateral continuity and consistency of thickness for these flows (sheet lobes). (b, c) Close up photos of part of flow2 (actually projected contact of flows 2 and 3) showing well preserved flow lobes, which are rarely seen in sheet lobes of the MFU.



Traverse 2:

This traverse starts east of the lighthouse (Fig. 42), where one can stand and observe the development of fractures in the UFU basalt - note the variation in the intensity and density of the fractures. The well-developed, radial fracture pattern (Fig. 38d), referred to informally as spindle fractures, locally characterizes the UFU, but is irregularly developed. Reference of such fractures has not been noted in the literature, but is assumed to reflect irregular cooling rates, possibly due to infiltration of ground waters as for entablature or irregular colonnade joint patterns.

Walking along the shore, just past the lighthouse you will notice the presence of small (1-3 cm), positive relief features or knobs in the basalt (Fig. 38g, h, i). These features increase in density to a maximum of 15-20/m^2. A detailed map of an area immediately below where a dirt road enters the beach area in front of a small cottage is provided to illustrate the density of the pipe features (Fig. 45). Note that the segregation pipes have subvertical orientations, thus they were emplaced after the UFU had ceased moving (i.e., stagnated). The pipes are also cross cut by cooling joints and silica veins.

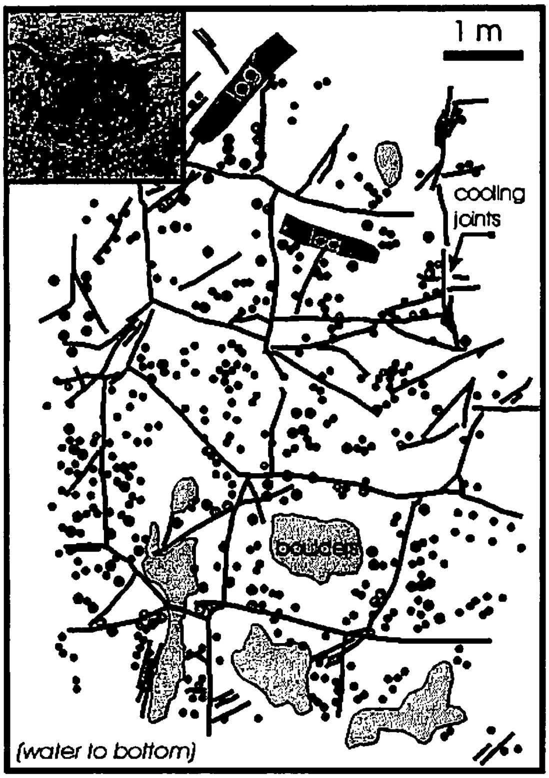


Figure 45. Map of bottom part of UFU at Morden west of the Lighthouse showing the distribution of segregation pipes. Inset figure is photo of typical pipe. Note that this is the maximum density of segregation-type pipes found in the NMB.

Continuing along the beach several features are noted:

- Exceptional exposure of the pipes is seen in the cliff face that occurs immediately to the left. Along the upper part of the cliff face is a spot where five subparallel pipes are exposed (Fig. 38e, f), one of which is distinct with the abundance of amygdules (zeolites, silica);
- Along the base of the cliff are well-exposed vesicle cylinders, unusual for the UFU.

Past the area of the well-exposed pipes, a large area in the UFU basalt of well-developed shearing is invaded by silica veins and the wall rock is intensely altered. The timing of this is clearly post deposition of the UFU, but otherwise the constraints are poor. Regardless, the intense alteration of the basalt reflects fluid focussing along this shear zone in the basalt and the shear has an orientation that is similar to many of the veins seen in the NMB indicating NW-SE extension.

Traverse 3:

Just past traverse 2 the contact between the UFU and MFU is exposed (Fig, 42); it is easily recognized by the differences in features of the two flows. Again, most notable is the nature of the MFU with the fine-grained, red-brown, crusted top and enrichment in amygdules, which contrasts with the massive, dark grey-green, medium-grained textured basalt of the UFU. The base of the UFU contains excellent pipe vesicles with abundant, smaller intervening amygdules - note the direction of flow suggested by the inclined vesicles.

Progressing along the coastline for 1-2 km one walks through a series of sheet lobes of the MFU with exceptional development of vesiculation following the pattern discussed earlier (i.e., PV, flow core, BTZ, NTZ, DZ). The zonation in these flows permits one to easily recognize the base of the upper crust (see Fig. 12 for reference) and apply the following empirical equation of Hon et al. (1994) to estimate the duration of lava growth or inflation:

$t = 164.8\ H^2$

with H= thickness of the upper crust and t is time in hours. What is the duration of the lava flows and how do they compare to what you may have expected?

The nature of the vesiculation in these flows is intriguing, as it begs discussion and debate about several issues:

(1) What is the age of the vesicle cylinders, given that they are all vertical, thus post flow movement;

(2) The net-texture zones could only have formed after the lava had attained some rigidity, thus late features;

(3) What is controlling the size of the vesicle cylinders (width, height, density)? Think also in terms of the segregation pipes that were seen at Lighthouse Point.

Stop 4. Port George

Directions (see Fig. 36)

This stop is accessible from Margaretsville by continuing out of town along the paved road and going southwest. Note that there is a junction at the west end of Margaretsville and you want to bear to the right and go southwest rather than right and head southeast! Continue along the paved road until a right turn onto a dirt road, which goes to Moshers Corner. Follow this road to the next stop at Port George.

Continue along the road to the coastline and entering Port George from the east there is a small bridge where the little hamlet begins. Park along the road here, but becareful of the traffic.

Highlights

The area of interest is around the little stream that flows into the Bay of Fundy, both to the east and west of here for 50-100 m. The UFU basalt occupies the prominent shoreline here, although the contact with the MFU can be seen to the northeast, but is only accessible at low tide. This is an excellent area to see again how the outline of the shoreline is controlled by geology, with promontories due to the UFU and embayed areas reflecting the presence of the MFU.

The UFU at this locality is again characterized by a medium-grained texture, pyroxene and plagioclase microlites, and importantly an abundance of mesostasis. However, of significance here is the presence of large (i.e., 50-60 cm wide), circular features that noted from their prominent positive or negative relief (Figs. 38j, k, l). These structures represent the third locality of such structures, the other two being Morden and Margaretsville. However, these pipes contrast in several ways, namely:

- The pipes are much larger than at the other localities;
- Pipes are commonly cored by fine-grained silica (i.e., agate; Figs. 38k, l) of cloudy white, green or red color, thus similar to Morden by different to Margaretsville;
- Pipes are dominated by a more intermediate composition versus felsic at other localities.

There are some examples of the late silica(chert) veins and oriented 0-30° and 50-60° with subvertical dips. The veins have *en echelon* orientations, banded texture, and variable width.

Continuing along the coastline here one stays in the UFU, as reflected by the uniform, generally linear shoreline and low-lying topography of the area. One can access the beach and excellent exposure of the UFU at Port Lorne, some 10 km west of here, to note the homogeneity of this unit.

Stop 5. St. Croix Cove and Chute Cove

This area is out of the way, but for those that want to see more of the MFU and the continuity of the UFU it is provided as an additional stop.

Directions (see inset Fig. 36)

Continue westwards on paved roads through East Arlington and Arlington West to the T-junction where you turn right and go northwards to Hampton. One can continue directly to the coast along this road or, alternatively, take the road to Hampton Beach - the choice depends on which cove one chooses to visit.

Highlights

This area is where the MFU next occurs after Port George and is the last opportunity to see coastal exposure of this unit prior to the Digby Gut area (next area in the guide) where it is seen at Green Point. The MFU is exposed in both St. Croix Cove and the next cove along the coast, Chute Cove, with the former providing much more spectacular vertical outcrop and the latter easier and quicker access. **The St. Croix Cove can only be accessed at low tide, so plan accordingly!** These outcrops have the same features as seen elsewhere that typify sheet lobes of the MFU.

Stop 6. Parker Mountain Quarry

Directions (see Fig. 46)

From the last stop it is suggested to go south, get on Highway 1 and head west following the majestic Annapolis River towards Annapolis Royal. Prior to arriving at this historical town, take the road north to Parker Cove, which is well marked. At the base of the North Mountain is the entrance on the right side of the road to Parker Mountain Quarry. ***This is an active quarry and in order to visit one must have proper safety attire, namely hardhat, safety glasses and safety boots - thus plan ahead accordingly.*** If interested in visiting, visit the main office and ask permission.

Highlights

Allow time to visit the beautiful town of Annapolis Royal with its many well-maintained Victorian mansions, the lovely Historic Rose Garden (several hundred varieties of roses to see), Fort Anne and the many tourist stores with displays of many local artisans. There is excellent dining to be enjoyed also. Accommodations vary from upscale inns and bed and breakfast (B&B) housing, to local motels and camping facilities. Prior to entering the town there is a causeway that traverses the Annapolis River where a tidal power generation station is in operation - visits are permitted for those interested.

The LFU provides excellent aggregate, hence, the quarry at this site; there is another quarry in this unit within view to the west, but it is not longer in use. There is exceptional exposure in the quarry and one can see the homogeneous nature of the massive, holocrystalline basalt of the LFU through about 100+ vertical m here. There is, however, a change in the nature of the columnar jointing with both the width and orientation of the columns changing up section and along strike. In addition, there is the rare occurrence of sedimentary dykes penetrating down into the basalt. After examining the site, spend a moment discussing the nature of the LFU - is this a large, ponded flow or a massive inflated flow with no preservation of lobe features?

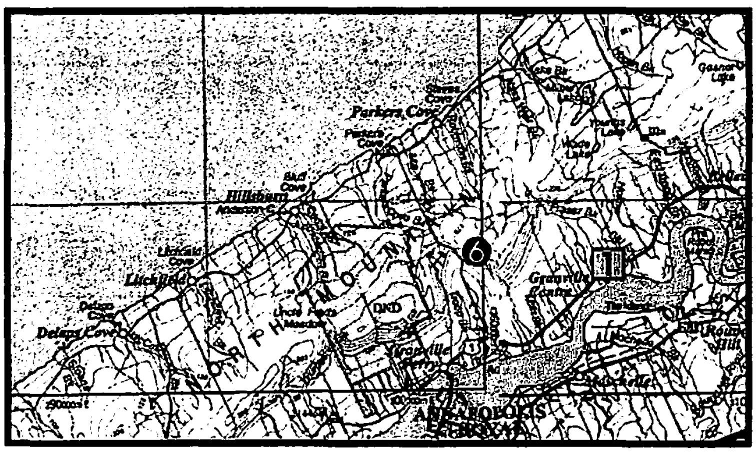


Figure 46. Topographic and road map of the area around Annapolis Royal and location of field stop 6 at Parker Mountain quarry.

DIGBY AREA

This area provides an excellent opportunity to see all three of the units in close proximity and, in addition, the presence of exceptional examples of layered mafic pegmatite in the upper and lower parts of the LFU exposed at two abandoned quarries (Mount Pleasant and Beamans Mountain, resptively). Examination of Figure 47, illustrating the topographic and DEM maps for the area, reveals the extent of the three flow units of the NMB in the Digby area. Of particular relevance here is the offset of the LFU, easily seen to the east and west of Digby Gut. Although there is no explanation at present for the origin of these features, we do note the following:

1. The base of the LFU is offset by faults, but it is not immediately clear that the entire NMB is offset. That is to say, that the MFU and UFU are not obviously displaced by the same structural features, but this may be a function of sufficiently detailed mapping of the area;

2. The general orientation of faults is subparallel to the strike of many of the silica veins and zones of intense fracturing (e.g., Margaretsville area) seen along the entire outcrop length of the NMB.

Stop 1. Mount Pleasant Quarry

Directions

From Annapolis Royal follow Highway 101, which is south of the town, and head west to Digby. Approaching Digby leave the highway at Exit 26 and follow Highway 303 northwards into town (Fig. 47a). Follow the signs for the St. John ferry and Digby Pines Hotel at the north end of town - turning left at the first major intersection (Victoria Street) with Sobeys on the left and Tim Hortons on the right. Alternatively, you can drive through town and along the waterfront and exit at the north end.

At the intersection at the north end of town across from the bay head towards Mount Pleasant-Culloden, also the road to the Digby Pines golf course, and continue along this road for 6 km until reaching the top of the mountain. There is an old quarry, although intermittently in use, at the top of the hill on the west side of the road. There is ample room to park in the quarry site.

Highlights

With reference to the DEM in Figure 47b one can see that the quarry is located near the top of the LFU. At this locality there occur spectacular examples of flat to undulating pegmatite sheets (Fig. 48; also see face map in Baldwin, 2004) exposed along the entire face of the quarry and part of the quarry floor. There are many textural varieties of pegmatite present.

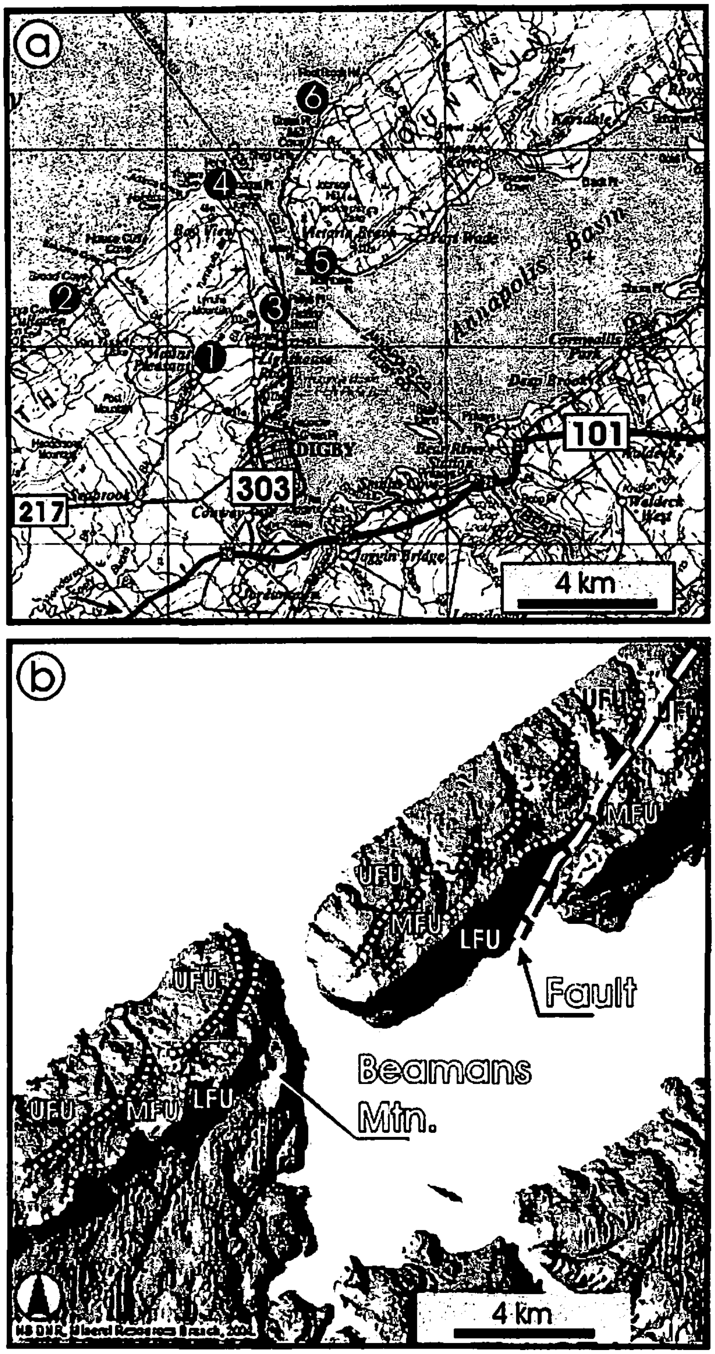


Figure 47. (a) Topographic and road map of the Digby area showing location of field stops. (b) Digital elevation model (DEM) map of the same area with traces of the contacts between flow units of the NMB. Note the presence of the fault in the eastern extent of the map.

This locality is also important from a geochronological standpoint, as this is the location of the sample which gave the U/Pb zircon age of 202 ± 1 Ma reported by Hodych and Dunning (1992). Prior to this time there had been a range of ages for the NMB related to inconsistent results obtained from conventional K-Ar dating, which were also incompatible with biostratigraphic controls. Cox et al. (2001) obtained an apatite fission track age of 191 ± 2 Ma on the same material as dated by Hodych and Dunning (1992).

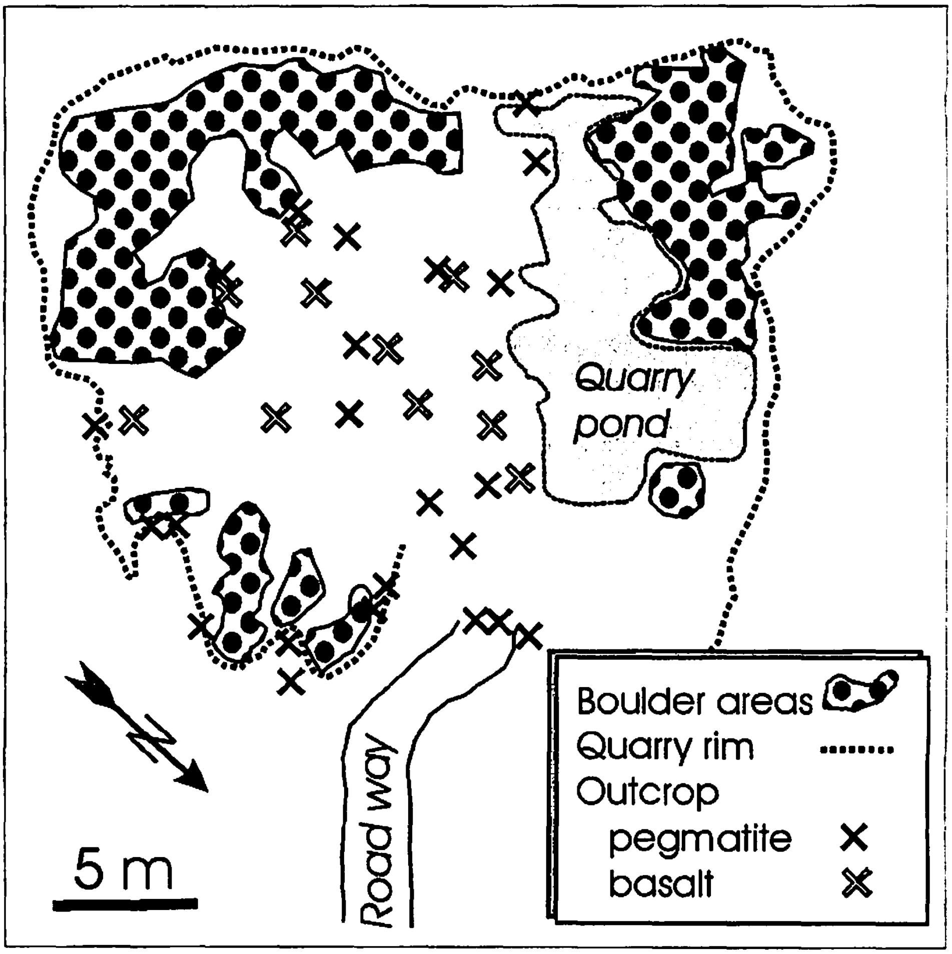
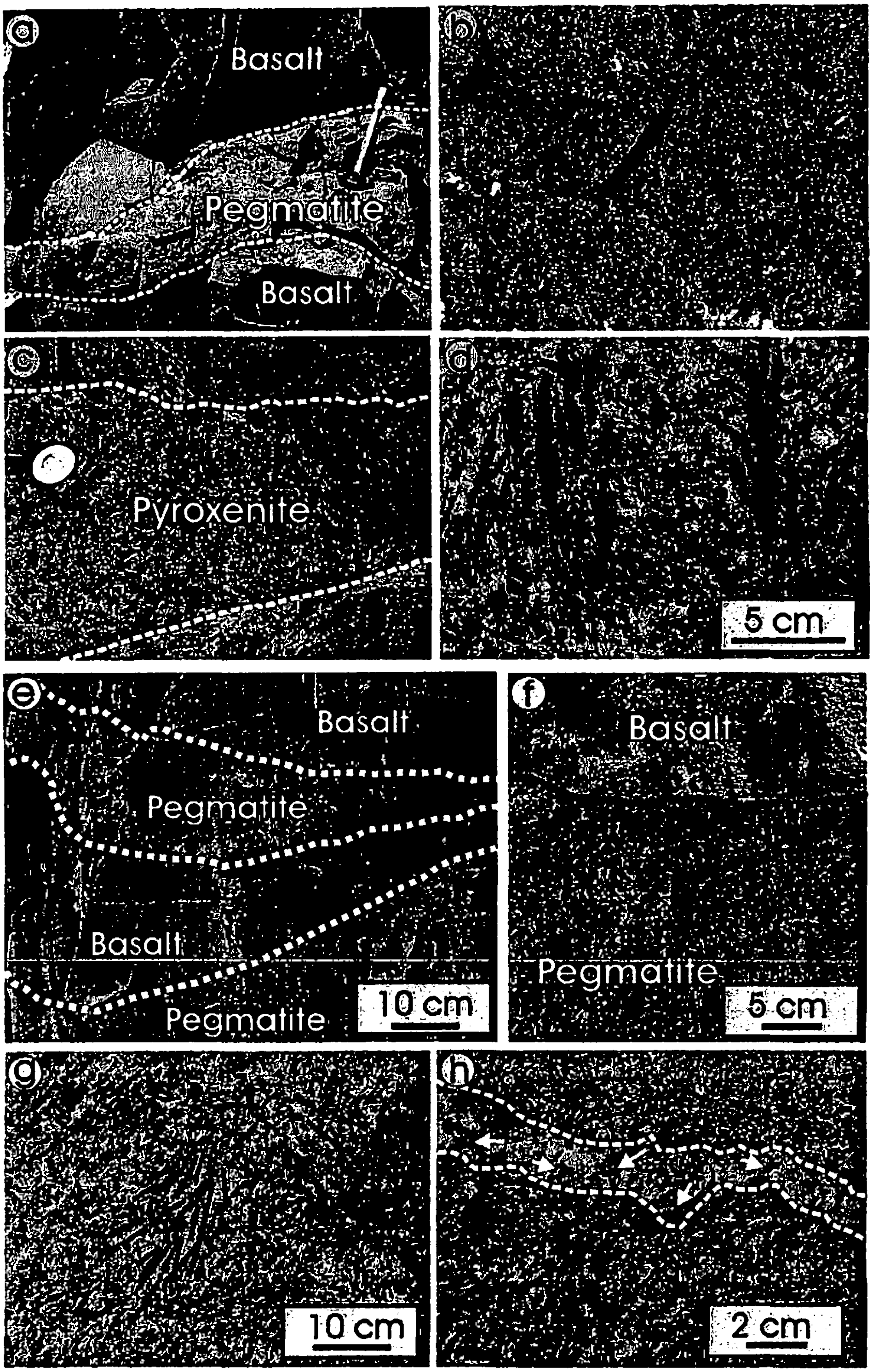


Figure 48. Map of the Mount Pleasant quarry area (after Baldwin, 2004). The pegmatite extends along the wall of the quarry, mainly on the south to north sides. Note that the pegmatite also extends along the quarry floor. The pond is a seasonal feature and size and depth may vary depending on the amount of precipitation and time of year.

Important features to note at this locality are:

- Pegmatite has a chilled margin of 1-2 cm against the host rock basalt, indicating cooling of the latter prior to pegmatite injection;
- Large variation in thickness of pegmatite sheets (Figs. 49a, c) from a few cm to ≥2 m for the bottom layer not fully exposed in the quarry;
- Several compositional and textural varieties of pegmatite (Figs. 49a, b, c, d). Variation in the nature of the pegmatite relates to the changing pyroxene:plagioclase ratio, the average grain size, and general texture;
- Medium-grained, beige colored material forms a mesostasis (Fig. 49b) in much of the pegmatite. This mesostasis is of felsic composition and is a variably crystallized granophyre enriched in residual components, including phosphorus. Devitrified glass can be seen in thin section with skeletal apatite crystals;
- Pegmatitic sheets pinch and swell with wedge-shaped terminations, similar to shear veins in, for example, mesothermal gold deposit settings;
- Excellent examples of comb-textured, Fe-rich (to 38 wt. % FeO) clinopyroxene megacrysts (≤10-15 cm) are present (Fig 49d). This mineral can locally dominate the pegmatite (>90% modally), forming a pyroxenite (Fig. 49c).

Figure 49. Outcrop photographs of mafic pegmatites at Mount Pleasant (a, b, c, d) and Beamans Mountain (e, f, g, h) quarries. (a) Undulation of mafic pegmatite with sharp contact with host basalt. Note geology hammer for scale (ca. 40 cm). (b) Coarse-grained leucogabbro with large amount of felsic mesostasis in the centre of the photo. (c) Layer of equigranular-textured pyroxenite hosted by basalt. Note that this pyroxenite contrasts markedly with the comb-textured, Fe-rich clinopyroxene in leucogabbro matrix of photo d. (e) Layers of mafic pegmatite in contact with host basalt. Note the thinning of the upper pegmatite. (f) Contact between host basalt and coarse-grained leucogabbro of the pegmatite. (g) Flamboyant-textured, coarse-grained, Fe-rich clinopyroxene in leucogabbroic part of the mafic pegmatite. The coarse pyroxenes are generally oriented perpendicular to the contact. (h) Late-stage felsic dyke material (glassy) following the contact between the pegmatite and host rock basalt. Note the presence of gas-escape structures, as indicated by the white arrows.


a
Basalt
Pegmatite
Basalt
b
c
Pyroxenite
d
5 cm
e
Basalt
Pegmatite
Basalt
Pegmatite
10 cm
f
Basalt
Pegmatite
5 cm
g
10 cm
h
2 cm

Stop 2. Culloden

Directions (see Fig. 47a)

Continue for 5 km along the paved road past Mount Pleasant quarry northward to the water where there is access via a dirt road (Culloden Wharf signage) to outcrops along the coast.

Highlights

Continuing northwards from Mount Pleasant quarry one goes around a large bend in the road and this area cuts through the MFU, which underlies the flat area on the map where a lake (i.e., local reservoir) is located. To the east of here is a prominent low-lying area ,which is also underlain by flows of the MFU (see DEM also in Fig. 47b). When the road straightens out there is a long continuous decline towards the water and along side the road are isolated outcrops of medium-grained, massive UFU basalt. At the bottom of the road there is access to the water, such as Culloden wharf, where excellent exposure of the UFU is present. There is well-developed columnar jointing to be seen and many *en echelon* vein arrays filled by chert, in some veins of banded- and colloform texture. The outcrop is generally flat along the coast here, but further to the west more challenging topography exposes thicker sections of the UFU.

Additional comments

Examination of the DEM image in Figure 47b illustrates well the geology just described. The quarry is located at the top of the LFU, the MFU is seen as the flat area and the UFU is marked by the prominent change in slope (i.e., dark ridge area on image). The road to the coast follows a river valley cut into the UFU and is prominent on the image.

Stop 3. Beamans Mountain Quarry

Directions (see Fig. 47a)

Return to the intersection at the north end of Digby and go north along the Lighthouse Road for 3.5 km and turn right onto a dirt road shortly after passing a prominent topographic high to the east (i.e., Beamans Mountain). This dirt road leads into an abandoned quarry that was excavated in the 1970's for construction of the wharf for the St. John ferry. The land is owned by a local resident who inhabits the small house on the right side of the road on the way in. He is very friendly, often drives up on his ATV to engage in conversation, and does not mind geologists wandering about the site!

Highlights

The area is located immediately north of a prominent topographic high, Beamans Mountain, which is underlain by LFU basalt. It is important to note that this is in the lower part of the LFUAbundant outcrops of equivalent rocks are also seen on the east side of this mountain along Ferry Road that parallels the water (Fig. 47a). Just past Beamans Mountain the topography flattens due to the presence of the MFU, as also seen in the case of the Mount Pleasant area where pegmatites occur. Thus, these observations indicate that we are near the top of the LFU. Also of note is the offset of the Beamans Mountain area with respect to the lower contact of the LFU, as noted above, but this is not considered relevant in terms of pegmatite formation.

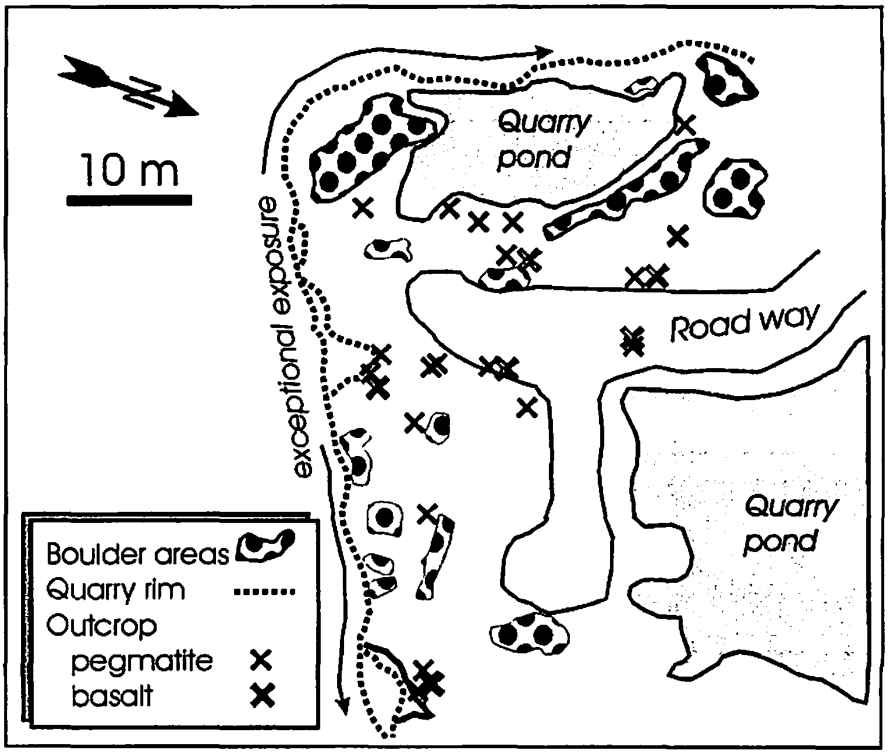


Figure 50. Map of Beamans Mountain quarry area (after Baldwin, 2004). Note that the pegmatite sheets are exposed along the southern and western walls of the quarry and also on the quarry floor.

The quarry (Fig. 50) provides exceptional exposure of layered pegmatites of variable width and extent and these are easily traced out along the old quarry face (Fig. 49e; see detailed map of this face in Baldwin, 2004). Careful examination will reveal many complexities and it is recommended to traverse from east to west along the face. Important features to note include:

- Host rock is a medium-grained basalt of the UFU and there is a chilling of the pegmatite against the wallrock. There are not structural breaks at the contacts;
- Variation in thickness of pegmatite sheets vary from a few cm to 2-3 m thickness; the sheets are 10's m long and are flat to undulating;
- Large range in the nature of the pegmatite based on the color, grain size, and mineral proportions. This variation is easily observed by doing vertical traverses through sections of the pegmatite;
- Along the south wall of the quarry wall the pegmatite is dominantly a beige color due to enrichment in plagioclase and felsic matrix (i.e., granophyre; Fig. 49f), and darker in the western area as pyroxene dominates. In the lower part of the western wall, a thick layer of pyroxenite occurs (≥2 m);
- Flamboyant, Fe-rich clinopyroxene is seen in the pegmatite (Fig. 49g). The size of the crystals and abundance vary considerably, but they are generally oriented perpendicular to the pegmatite-wallrock contact;
- Fine-grained, aphanitic, red-brown material with vesicles (i.e., gas escape features) occurs as thin (≤1-2 cm) dykes cross cutting the pegmatite at low angles or following pegmatite-wallrock contacts. Similar material is seen in the mesostasis of the pegmatite and also in thin section. This material is interpreted as a quenched felsic liquid and is variably altered as a result of post-magmatic modification.

Nature of the Pegmatite Layers at Mount Pleasant and Beamans Mountain

Now that the pegmatite layers have been observed at three exceptional localities, the two in the Digby area and also at McKay Head, it is time to reflect on the origin of these layers, keeping in mind the following features of the pegmatites. We leave the participants to discuss the nature and origin of the pegmatites based on the following observations:

- Occur in both the upper and lower parts of the LFU at several localities in the NMB (e.g., Parrsboro, Digby, East Ferry, and other areas along the North Mountain);
- Occur as multiple layers, thus the process is repeated many times over;
- Contacts are chilled against the basalt;
- Sheets are flat or undulating, with wedge-shaped terminations;

- Pyroxenes are extremely Fe-rich compared to the host rock basalt;
- Mesostasis is a late-stage felsic melt, now granophyre, enriched in, among other elements, Na, K and P;
- Textures (i.e., comb) indicate a single dilational event occurred rather than sequential cracking and sealing, as in ribbon veins.

Stop 4. Point Prim

Directions (see Fig. 47a)

Continue along Lighthouse Road from Beamans Mountain quarry to the termination of the road where there is an old lighthouse and ample parking. ***Be cautious at this locality, as there is a cliff face with a long fall down to either very cold water or hard rocks, depending on the tides!***

Highlights

This area exposes the contact between the MFU and UFU, which can be traced on the DEM image in Figure 47b. The contact is exposed just to the east of the parking area (Fig. 51a, e), which is accessible at low tide by walking along the field east of the road and then down to the beach. The MFU shows the features, as seen elsewhere, that typify this unit, namely: (1) zonation of amygdules in the middle and upper parts of the sheet lobes; (2) a red-brown, oxidized, fine-grained upper crust; (3) basal pipe vesicles. There are two or three flows of the MFU here depending on ones interpretation of what constitutes a flow. The question arises because flow 3, as shown in Figure51a and e, may relate to surface breakouts from the underlying flow 2, which is an interesting point for discussion. Also worthy of note here is that pipe vesicles at the base of flow 2 of the MFU are rotated, a consequence of a change in the sense of shear (i.e. flow movement) during rotation. This is a unique occurrence of this feature.

The vesicle-rich upper crust zone of flow 1 can be followed down into the lave core along the coast towards the south. Note the progressive decrease in the abundance of vesicles and amygdules. Also note, in particular, the absence of the NTZ and BTZ in this flow, the reason for this being unknown. The lave core for flow 1 at this locality is unusually thick (i.e., 10-15 m) and very massive, although it contains rare amygdules and is altered. The lave core can be followed out along the coast to the southeast where it is seen to have well developed jointing, locally columnar type.

The UFU at this locality shows several features typical of this unit: (1) spindle-type jointing, as described earlier (Fig. 51b); (2) well-developed columnar jointing (colonnade type), which here has distinct oxidation rings parallel to the structures and some silica veins along the joints (Fig. 51c); (3) a medium-grained texture, plagioclase and pyroxene microlites, and abundant mesostasis (Fig. 51d).

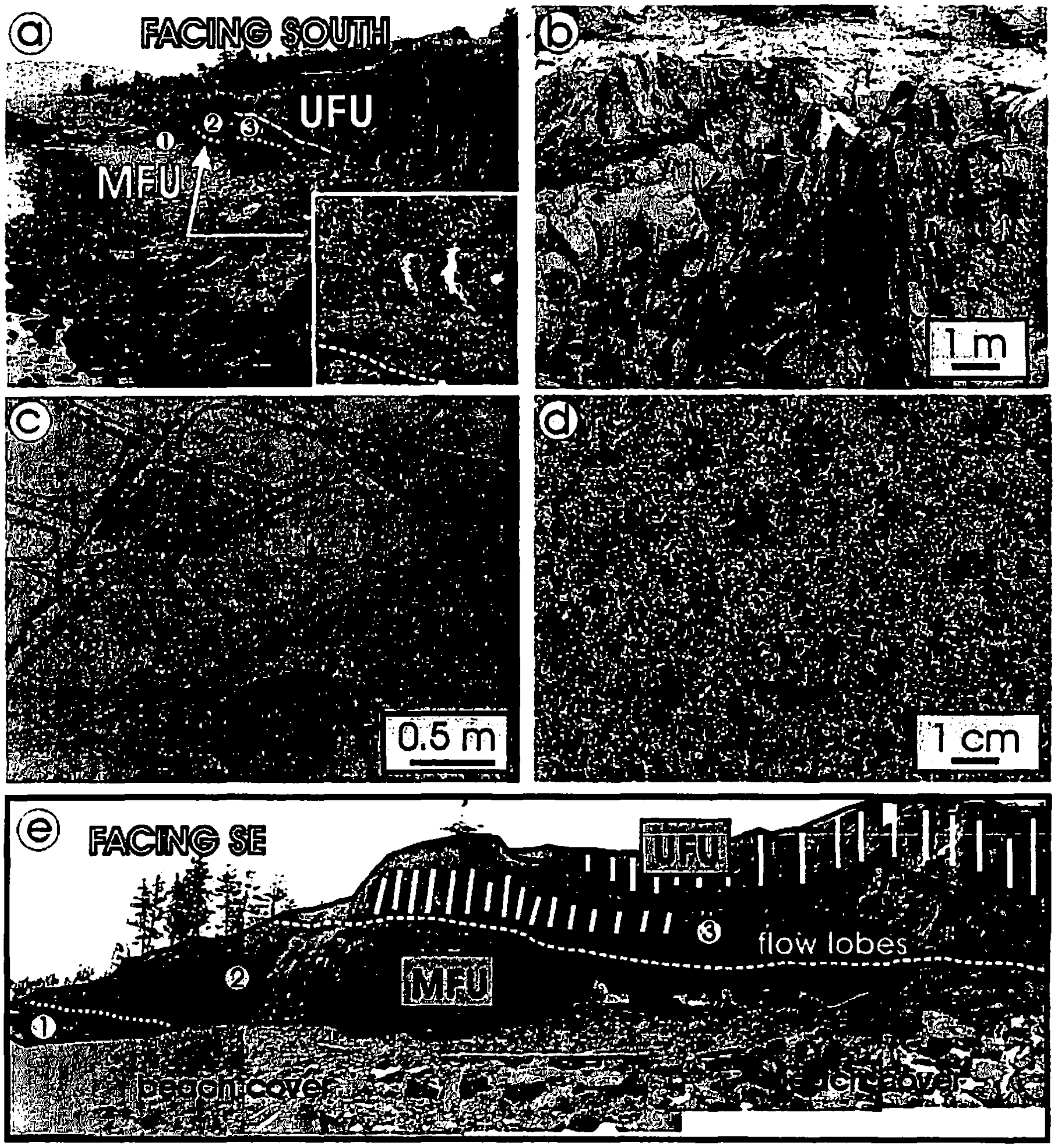


Figure 51. Photographs of outcrops at Point Prim. (a) Contact between the MFU and UFU, as seen at low tide from the point. Note the three flows of the MFU are indicated. Inset figure shows pipe vesicles at the base of flow 2; note how the vesicles are rotated

and indicate two shear directions, hence two flow directions for the lava! (b) Spindle-type fracture pattern in massive UFU basalt just north of the parking area at this stop. (c) Oxidation rings in columnar-jointed UFU basalt at same spot as previous picture. (d) Close up of hypocrystalline UFU basalt showing the presence of microlites of plagioclase and abundant mesostasis. (e) Section (facing SE) on the beach at low tide showing the three flows of the MFU and contact with overlying UFU, which continues to the point to the north. White lines indicate orientation of jointing in massive basalt and dashed black lines in flow 3 of the MFU are flow lobes.

Stops 5, 6. Victoria Bridge and Green Point

These are geologically interesting sites and although out of the way are provided for those who may have an interest in tracking down these localities. In addition, the road leading to this stop passes *Le Habitation*, or Port Royal. This site is a recreation of the first settlement in North America north of Florida, built in 1605 by the French as a fur trading post with the native Mi'kmaq. It survived until 1613 when it was attacked and destroyed by English from Virginia.

Directions (see Fig. 47a)

This area is accessed from Annapolis Royal, but is part of the Digby map area, hence the reason for the apparent confusion! From Annapolis Royal (Fig. 46) head east a few km on Highway 1 to Granville Ferry and then turn west along the north shore of the Annapolis basin. Follow the signs to Port Royal, then Victoria Beach and finally follow the road to its termination at Green Point. This is quite a detour and is only recommended for those who have time on their hands for of the NMB.

Highlights

The road follows along the Triassic Blomidon Formation sediments that underlie the NMB. Just before Victoria Beach there is outcrop of highly altered LFU basalt and sediment in an abandoned pit on the northeast side of the road. This alteration is similar to that seen underlying the basalt at Five Islands south of Parrsboro, but the origin of it is not known - hot spring activity perhaps!

Continuing past Victoria Beach the contact between the LFU and MFU is passed, as can be seen on the DEM image of Figure 47b. There are some outcrops of the MFU on the right side of the road as it turns away from the water on the north side of Victoria Beach.

At Greenpoint the coastline is easily accessed and there is abundant outcrop of typical UFU basalt is exposed, very similar to what was seen at Point Prim across Digby Gut - look west and you can see this location. In addition, there are numerous silica veins cutting the UFU here. Although the DEM image of this area (Fig. 47b) suggests that there should only be UFU basalt exposed here, the top sheet lobe of the MFU outcrops at the head of the cove just past Green Point promontory. The MFU shows excellent development of the upper crust zone, part of an inflated pahoehoe lava flow with all the features that typify this unit, as seen elsewhere in the NMB.

DIGBY NECK-LONG ISLAND AREA

Continuing past Digby down Digby Neck and onwards to Long Island, one is presented with many exceptional areas to visit, along with the possibility of some noted tourist attractions. There are whale-watching excursions that head out from this area (e.g., Freeport, East Ferry-Tiverton) and at the far end of this trek is Brier Island, a well-known bird sanctuary. Although these sites are not part of the 2005 field excursion, they are included in this field guide for the benefit of those that may wish to visit these localities on their own or for future users of the field guide.

Directions

With reference to the main provincial highway map, which we recommend as a supplement to the maps in the field guide, continue past Digby on Highway 101 for ca. 4 km and take the right turn that leads to Sandy Cove-Long Island-Brier Island. Given that there is only a single turnoff, be careful not to pass it! Continue down this road for 4 km until you come to a T-junction, at which point turn left and head westwards down Digby Neck on Highway 217. Alternatively, for those who have visited the field stops in the Digby area, return to the intersection along either Lighthouse Road or the Ferry Road and proceed south from here up the hill past the camping grounds to the left (eastwards). At the top of the hill there is an intersection and a sign indicating the way (right turn, westwards) to Sandy Cove-Long Island via Seabrook on Highway 217 (Fig. 47a). Follow this road to the next series of field stops.

Stops 1, 2. Sandy Cove

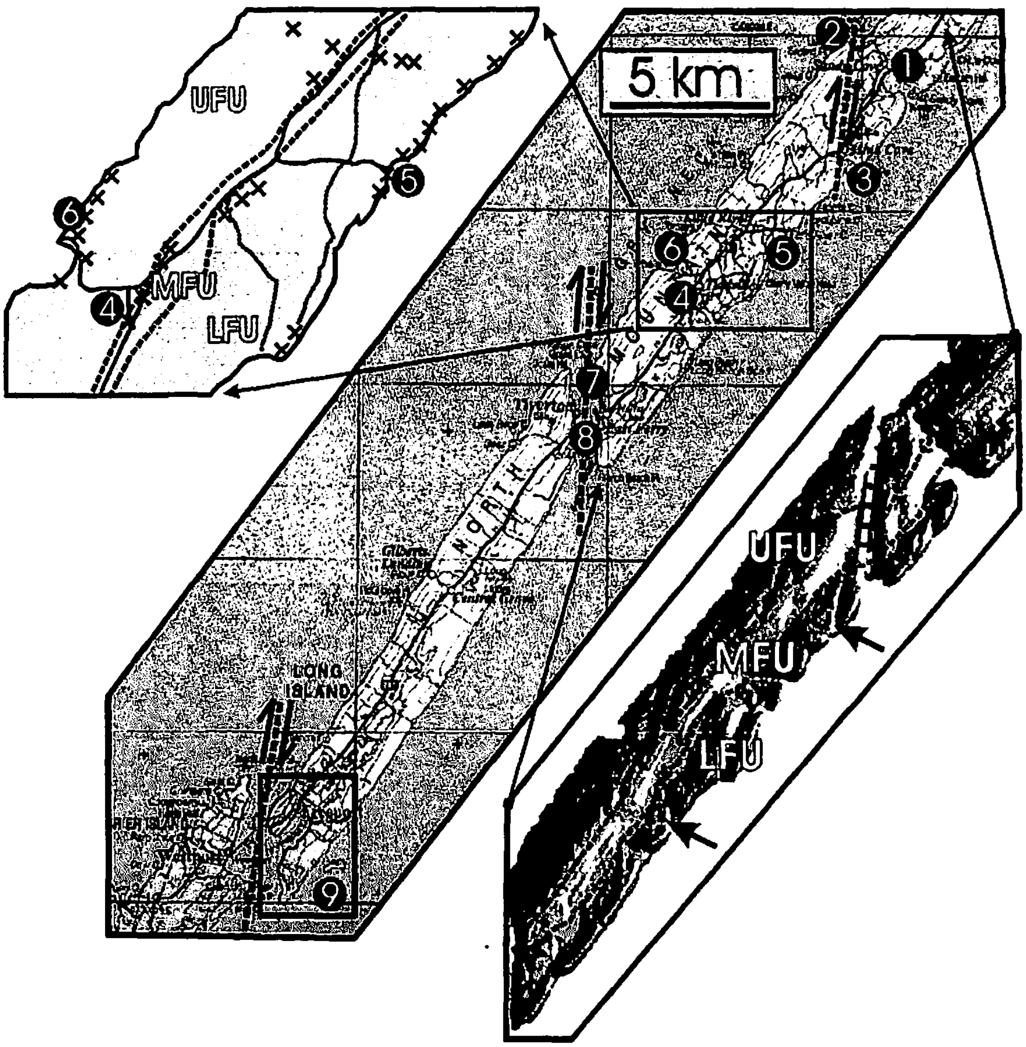
Directions (see Fig. 52)

Continue along the length of Digby Neck on Highway 217 until you come to this quaint little fishing village. Directions to the two stops are given below.

Highlights

The area nestled about the cove the forms the central point to the area, which formed as a consequence of breaching the contact between the LFU and MFU. Topographic headlands on either side of the cove entrance, analogous to Digby Gut, are underlain by massive, medium- to fine-grained, holocrystalline UFU basalt with colonnade and entablature jointing, whereas the cove itself is underlain by the MFU. The DEM image in Figure 52 illustrates well the geology of the area. An exceptional outcrop of the columnar-jointed (entablature type), fine-grained LFU basalt is exposed just before the wharf on the northeast side of the cove at **Stop1**. The columns.

Figure 52. Topography, road map and DEM image of Digby Neck-Long Island area with field stops. Note the presence of the northerly-trending dextral faults that offset the NMB. The arrows point to circular features that are sometimes seen in the bottom of the LFU, as discussed in the text.



are inclined and narrower than what is seen along the coast to the north, thus proximity to the surface of the flow may be relevant to their formation.

The UFU contrasts markedly with the LFU basalt. Access to **Stop 2** is via the paved road going northwards out of the village to the coast, where there is an active fishing wharf. Medium- to coarse-grained, hypocrystalline basalt with abundant mesostasis is exposed along the shoreline just northeast of the wharf area. Features to note at this locality:

- Well-developed cooling joints, some columnar, filled with thin silica veins and also alteration haloes about them;
- Laminated or banded, symmetrical silica veins ≤15-20 cm width with a fine-grained or aphanitic material at the margins and cores of white and red-brown silica or chalcedony; the veins are strike 180-190° and continue along the outcrop for several 10's m.

Stop 3. Mink Cove

Directions (see Fig. 52)

Continue westwards along Highway 217 for just over 2 km and take a turnoff on the left to an old fish plant at the end of a short dirt road. There is ample parking available.

Highlights

This is another opportunity to see the massive, columnar-jointed (colonnade type) basalt of the LFU that is well exposed along the coast. The columns here vary in orientation from subvertical to inclined at 60-70° and reflect an irregular cooling history for the rocks of this area. Just before the turnoff there is outcrop of the MFU by the roadside. Across the main road from this locality one can see a prominent low-lying, swampy area that is underlain by MFU basalt that has a long, thin tongue pattern on the map.

Examination of the DEM image for the area (Fig. 52) reveals two features in this area:

- A northeast-trending fault with dextral displacement. This fault has resulted in a more extensive exposure of the MFU and, along with the fault, has resulted in a formation of an expansive low-lying area due to preferential erosion;
- Presence just west of the cove of a distinct circular structure, as noted by the arrow on the DEM image. This is one of several such features in the LFU revealed by DEM images and their origin remains unknown, although a spiracle is one possibility (Webster et al., submitted).

Stops 4, 5, 6. Little River area

Directions (see Fig. 52)

Continue westwards along Highway 217 for 4 km and refer to the inset in Figure 52 for the locations of the next series of outcrops.

For Stop 5, follow the paved or dirt road all the ways into the village at Little River Cove and proceed to the wharf area. For Stop 6, follow the paved road up the steep hill (over LFU rocks) to Whale Cove; this road turns into a good gravel road that leads to the wharf area on the northeast side of the cove at the coast. Stop 4 is just off the main road (Highway 217).

Highlights

This area provides another rare opportunity to see a complete section across the NMB from the LFU, through the MFU, to the UFU. Starting with the LFU at Little River Cove (**Stop 5**) on the southeast coast, there is abundant outcrop massive, holocrystalline basalt exposed just southwest of the wharf. There are exceptional examples of subvertical colonnade jointing of the LFU exposed here and looking across the cove from the wharf to the northeast shoreline one can also see similarly developed jointing in this unit.

Proceeding back to the main road and following the map, go to the outcrop of MFU that is exposed in a hill slope (**Stop 4**). Although not a great outcrop, there is sufficient material here to apply the knowledge learned from other localities to infer what the origin of the volcanic rock is. Important features that characterize this outcrop are: (1) vesiculated, fine-grained basalt; (2) red-brown oxidized part of an upper crust zone to a sheet lobe; (3) fresh, massive non-vesiculated rock. These rocks represent the uppermost sheet lobe of the MFU and the base of the UFU. The presence of the prominent topographic high and outcrop of entablature-jointed, fine-grained, holocrystalline, UFU basalt just northeast of here also supports this interpretation.

The extensive outcrop at Whale Cove (**Stop 6**) on the northwest coast exposes typical hypocrystalline basalt of the UFU with abundant dark mesostasis, pyroxene and plagioclase microlites, and well-developed jointing. This is an opportune time to contrast the features of the UFU with the LFU just seen. Note the smaller columns (i.e., narrower) in the UFU and presence of the mesostasis. Also present here, as seen in many other cases, are the silica veinlets occupying the columnar joints and alteration rinds generating the prominent ridges along the joints. The exceptionally massive and fresh nature of the UFU here and its location on high-tide water level makes this an excellent location for aggregate production and the White Cove area just to the north of here is being examined for such purpose (as of spring 2005).

Stop 7. East Ferry

Directions (see Fig. 52)

Continue westwards along Highway 217 to the ferry loading facility at East Ferry that takes cars and passengers to Long Island, across Petit Passage. There is a nice café conveniently located across from the wharf that is open from May to October and serves hot food and refreshments.

Highlights

There are several interesting sites to observe here, as there is almost continuous exposure along the coast from south to north. This is the area that Lollis (1959) mapped nearly 50 years ago and made some significant observations, most importantly the presence of the abundant "diorite" layers in the upper part the LFU, his Lower Shore Member of the NMB. Note the prominent dextral offset of the NMB units across Petite Passage.

The following sites are suggested for viewing at East Ferry:

- Immediately across from the ferry is a rock face exposing the lower part of the UFU with exceptional development of multi-tiered, columnar jointing of colonnade and entablature style with superimposed, sub-horizontal platy jointing. The columnar jointing itself is fascinating, as there is a large range in the orientation of the columns from near vertical to shallowly inclined (Fig. 53a and also 14b);
- Continuing to the south one comes to the contact with the underlying MFU, which is marked by the red-brown, oxidized, upper crust zone of the uppermost sheet lobe of the MFU. Just below the contact occur narrow feeders to the flows (dyke rocks ?), a rarity in the NMB, however, these may just be extensions of breakouts from the lava core below;
- Presence of exceptional flow lobes with basalt with intense vesiculation surrounding them (Fig. 53b). In this area there is also intense silica alteration along the crusts of the lobes (Fig. 53c), which is very rare in the NMB;
- Further to the south outcrops the LFU, which is continually exposed at low tide. Towards the upper part of the flow occur layers of pegmatite that were referred to above. Although easily discerned by the trained eye, this is not the best place to see these features, as the rock is covered by algae material due to its continued washing by water due to the daily tides. Much better exposure is provided south of Tiverton (Fig. 53d), the next stop;

- The UFU is continually exposed along the coast north of the ferry wharf. There is well-developed, subvertical columnar jointing (colonnade type) without the chaotic entablature patterns as seen lower in the section.

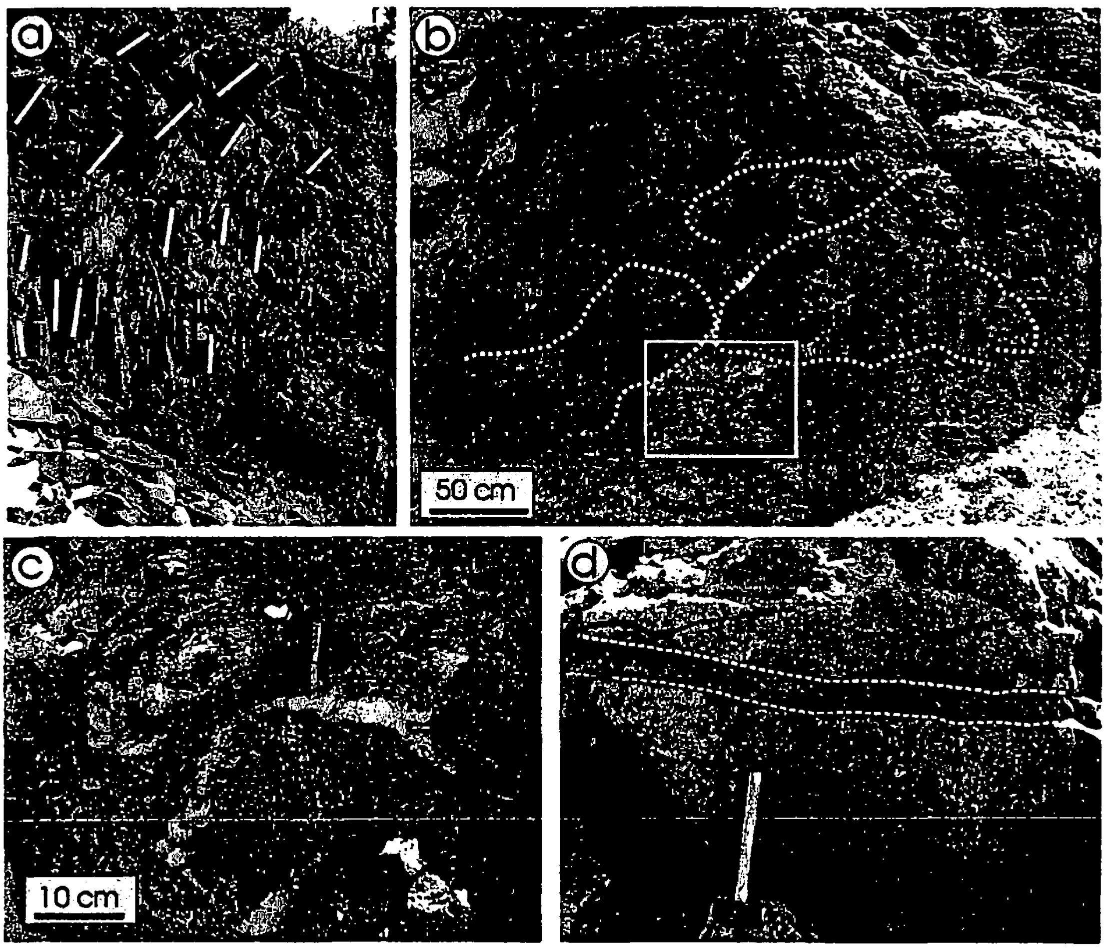


Figure 53. Photographs of NMB outcrops at East Ferry (a, b, c) and Tiverton (d). (a) Base of the UFU basalt showing extreme curvature of entablature jointing, as shown by the white bars. Note that this jointing goes into subvertical, colonnade jointing in massive basalt of the UFU below the photo. (b) Exceptional development of flow lobes(outlined by dashed white lines) in upper part of a sheet lobe in MFU lava. Area in the box is where there is intense silicification along the lobe crusts and close up is shown in the next photo. (c) Ssilicification (whie areas) of basalt lava along the crusts of the lobes. (d) Subhorizontal, pegmatite layer in massive basalt of the LFU is outlined by the dashed white line.

Stop 8. Tiverton

Directions (see Fig. 52)

This is the first stop on Long Island and is accessed by taking the ferry from East Ferry. The ferry runs year round, leaves on the half hour and there is a nominal charge of a few dollars to cross - no charge for the return voyage! Note the strength of the current as one crosses Petite Passage and drop in temperature as the ferry traverses the straight.

Highlights

This is again an excellent area to go through the sequence of the NMB from LFU, through MFU to UFU. The nature of the coastline and local topography reflects the distribution of the flow units. Beginning with the LFU, there is excellent exposure on the point of land to the south of the harbour here. At the point of land on the south side of the harbour is excellent exposure of pegmatite layers in the upper part of the UFU (Fig. 53d). North of the wharf area there are outcrops on the shoreline and the contact of the MFU and UFU, although not exposed, can be approximated. The columnar jointing in the UFU varies between subvertical to near horizontal and tiers are developed. A recent quarry operation on the hill overlooking the wharf area exposes the UFU in the pit area and can be accessed by walking up the gravel road behind the wharf.

For those wishing to take a nice hike, there is a paved road that leads to the old lighthouse at the north end of the coastline here that provides exposure of the UFU and some dramatic scenery. Follow the road going north from the wharf area and park at the gate that leads to the lighthouse area. Alternatively, for those short on time or not wanting to hike there is a recent quarry above the town, which has exposed a large amount of massive UFU basalt.

Tiverton is well known locally for its "leaning rock" which decorates many post cards in the tourist shops. This rock represents an isolated "column" of LFU basalt and is located west of the town. In order to access this site, park in the area provided a few km outside of town following the road to Freeport and then follow the hiking trail to the coast (a 20-25 minute leisurely hike).

Stop 9. Freeport

Directions (see Figs. 52, 54)

Continue along the paved road, Highway 217, from Tiverton to the village of Freeport and refer to Figure 54a for directions to sites of interest. The wharf at the west end of Long Island is where the ferry to Brier Island departs. Across Grand Passage is the village of Westport, home of the famous Captain Joshua Slocum (1844-1909), first to sail around the world alone (1895-1898) in the 37 foot sloop the *Spray*.

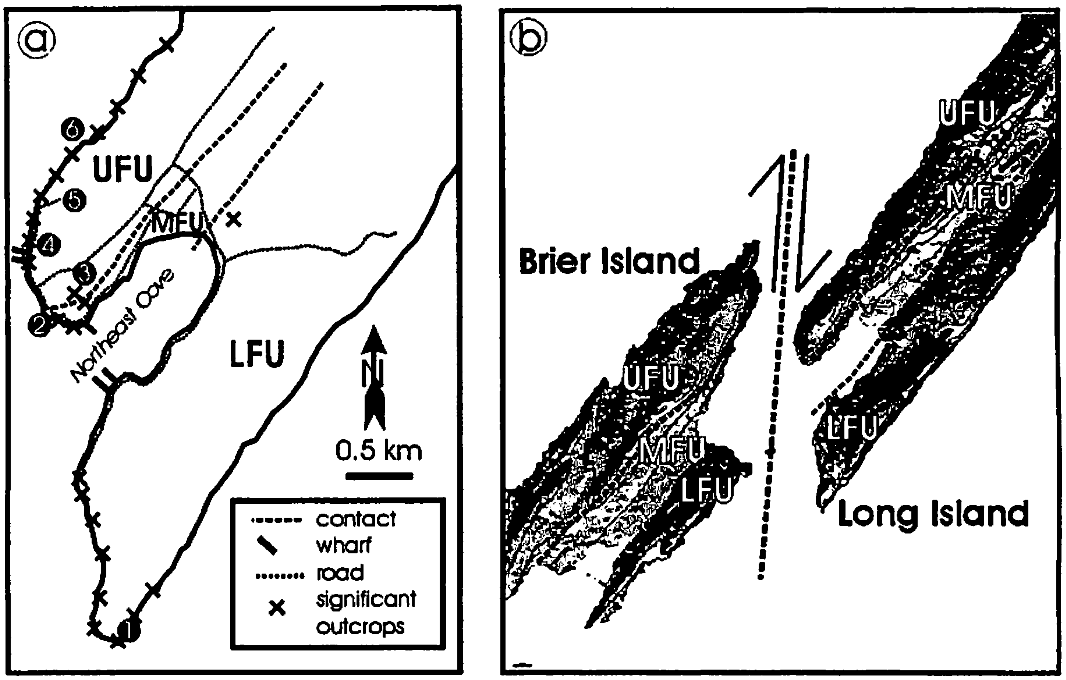


Figure 54. (a) Map of Freeport area at the west end of Long Island showing the extent of the three flow units of the NMB and recommended field stops. (b) DEM image of the western end of Long Island and most of Brier Island with superimposed geology. Note the presence of the north-trending fault with clear dextral offset.

Highlights

This area again provides a complete exposed section through all three-flow units of the NMB, but the contacts between the units are not exposed on surface. However, drilling done in the 1960s, part of a regional copper exploration program by analogy with the world famous Keweenawin copper province of the mid-continent region of North America, provided drill core that does locate the contacts. This drill core indicates that the MFU only has a true aggregate thickness of 41 m and consists of four, thin (3 to 9 m) lava flows, which are thinner and fewer in number compared to what is observed in the Annapolis Valley region and even Freeport area (Stop 8) to the east (91 m; Lollis, 1959). In addition, use of the DEM image in Figure 54b shows the extent of the major units of the NMB. This image also shows the geology of Brier Island to the west, across Grand Passage, and the dextral offset along the north-trending fault.

The sites of interest are indicated in Figure 54a and discussed below.

Site 1. Access to this area is along a paved and then dirt road on the south side of Northeast Cove. The last part requires walking, unless a four-wheel drive vehicle is being used. Hiking to the point provides spectacular coastal exposure and scenery of the LFU with well-developed columnar jointing, entablature type, in massive, holocrystalline basalt (Fig. 55a). The exposure and geology of this site is reminiscent of photos of the Giant's Causeway of Ireland or Fingal's Cave, Scotland that can be viewed on internet sites.

Site 2. Along the coastline at Ronnie's Point on the north shore of Northeast Cove, accessed from the wharf area, are exposed several sheet lobes of the MFU with typical features that characterize these flows elsewhere (Fig. 55b), including vesicle zonation, upper crust, and flow lobes. This is a good area to debate whether there are 2 or 3 lava flows represented, as it depends on ones definition of what constitutes a distinct lava flow!

Site 3. Located on the slope just above the paved road is the lowest exposure of the UFU, a massive, non-vesiculated, fresh, hypocrystalline basalt with distinct mesostasis. The basalt contrasts markedly with an outcrop of intensely vesiculated, very fine-grained basalt (MFU), which is seen just off the road at the back of driveway (summer 2004, but may no longer be exposed) lower down the slope and just north of the paved road.

Site 4. Located at the wharf and ferry area, there is well-developed columnar jointing (Fig. 55c) in fresh, massive, pyroxene-phyric and mesostasis-rich UFU basalt, which is close to the lower part of this flow unit stratigraphically.

Site 5. A quarry in the UFU provides excellent exposure of this unit in the walls of the abandoned working face. This area is of interest for two reasons: (1) there are two distinct fractures patterns in the basalt, a curvilinear one in the lower part of the exposure and a subvertical one in the upper part (Figs. 55d, e). Note that the curvilinear joint pattern has been seen elsewhere in the bottom of the UFU; and (2) in the north end of the quarry is a swarm of silica veins (020° strike, 90° dip) spaced 2-3 m apart and of 1-6 cm width (Fig. 55f). These veins are symmetrically banded with color margins and cloudy white central areas.

Site 6. This area is on the coast and provides continuous exposure of the UFU for several km to the northeast. To the northwest off Brier Island, Koskitalo (1967) refers to possible outcrops of overlying red sediments (Scots Bay equivalent rocks ?) on maps of the area, but there is not detailed discussion of these rocks. May they also be red-brown oxidized lava flows?

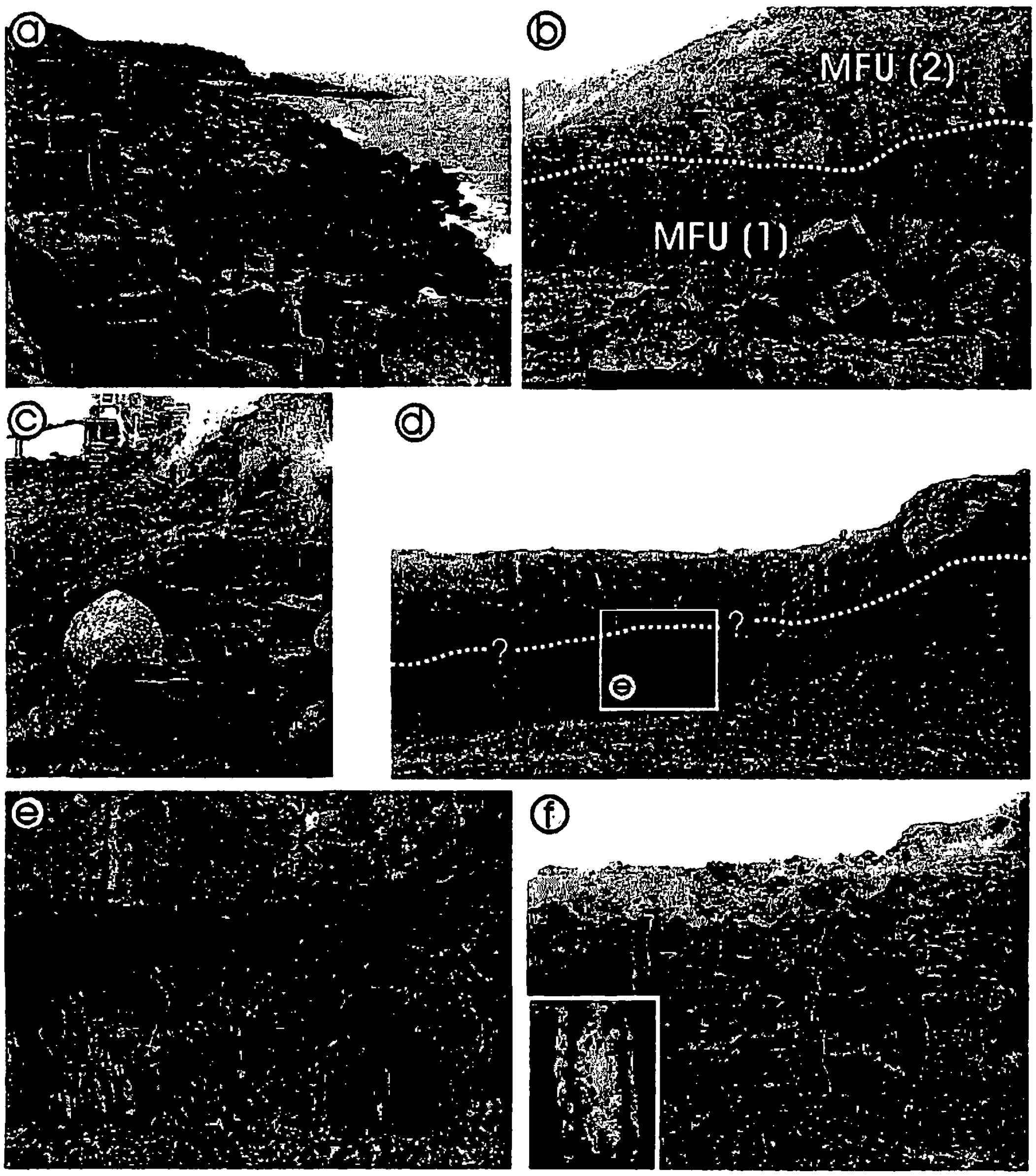


Figure 55. Photographs of outcrops in the Freeport are of Long Island. (a) Outcrop of entablature jointed LFU basalt at site 1. (b) Sheet lobes in the MFU at site 2 with contact

between two flows indicated by dashed white line. (c) Columnar jointing (entablature) in the basal part of the UFU near the ferry-wharf area at site 4. (d) Quarry area in the UFU at site 5. The different jointing pattern is used to separate out two tiers, as shown by the dashed white line. Area in box is enlarged in the next photo. (e) Curvilinear jointing pattern in the bottom of the photo in UFU basalt that contrasts with subvertical- jointing in the upper part of the photo. (f) Subparallel silica veins in the UFU basalt at site 5 in the quarry. Note that the veins are at regularly spaced intervals. Inset picture shows the banded nature of one of the chaledonic veins.

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GLOSSARY OF TERMS

The following terminology is used within the text, short summaries are provided for quick reference (in part modified after Thordarson and Self (1998) with some additional terms added).

Contacts

Distinct	contact between lobes marked by chilled surface (i.e., originally glassy surface) with reddened color; original contact between pahoehoe surfaces
Annealed, fused	contact marked by cm thick, fine-grained, crusted band, originally annealed band between lobes
Discontinuous	contacts dissipate between flows when followed in outcrop

Lava

Breakout	small lobe originating as an outbreak of lava from the molten interior or a previously formed lobe; may occur on the front, tops or sides of the lobes
Compound flow	lava flow consisting of several, overlapping lobes; in contrast simple flows consist of a single lobe (sense of Walker, 1971)
Endogenous growth	insertion of new lava into the core of existing lava leading to inflation (e.g., Birkett Flow, CRFB - 19 such injections; Walker et al., 1999)
Exogenous growth	spawning of new lava by breaking through crust and generating a new flow (see breakout)
Flow lobe	single unit of lava surrounded by a chilled (recent lobes) crust (ancient lobes) varying in long dimension (to several km) and thickness (to 10's m); consists of series of stacked sheet lobes
Inflation	growth of lava flow from the inside rather than externally (see endogenous growth)
(Lava) flow field	complex body of lava identified on basis of field relationships or chemistry and represents outpouring of single eruption; may consist of several lava flows
Lava flow	products of an individual eruptive event and is distinct to be mapped on a regional scale (the flow units of the NMB); flow should be trace to its vent; similar to sheet flow
Lava-rise pit	low areas between adjacent thicker parts of a flow that develop when areas within a flow do not inflate
Sheet lobe	lobe with a flat or gently undulating flow surface produced by one single outpouring of lava; the width of the lobe exceeds considerably its height
Sheet flow	flow composed dominantly of sheet lobes
Toes	small individual lobes surrounded by their crust on a metre- to decimetre scale
Tumulus	elliptical or domed structure(s) on the tops of pahoehoe flows created by internal pressure of the lava in the core which pushes the crust upward; may have associated axial or medial cracks

Vesiculation patterns

Diktytaxitic texture	microscopic (<2 mm), irregular, intercrystalline voids outlined by crystal faces of adjacent groundmass minerals
Horizontal vesicle	sheets of vesicular segregated material (several cm to m's thick) that are

sheet	continuous (10's m) on an outcrop scale; also referred to as segregation veins (Kuno, 1965) or vesicle sheets (Goff, 1996)
Pipe vesicles and vesicle cylinders	cylindrical pipes of near-vertical orientation that are hollow in the former and filled with vesicular segregated material in the latter
Segregation vesicles	irregular, spherical to elongate vesicles lined with segregation material (Smith, 1967) of several mm to 10 cm length and U- or V-shaped in section
Vesicles	molds of once gas-filled voids frozen in the lava of microscopic (< 2mm) or macroscopic (>2 mm) size; mega-vesicles may be 10's cm and are domed shaped with (glassy) non-vesicular segregation material in their floors
Vesicle zone	decimetre to metre thick horizons with >vol% of macroscopic vesicles

Jointing style

Colonnade	tier of widely spaces (≥40-200 cm) planar columnar joints, which bound columns
Columnar zone	lower to one-half to two-thirds of flow distinguished by elongate to block, generally four- to six-sided columns; generally corresponds to the colonnade zone
Crustal zone	upper one-half to one-thirds of flow, distinguished by uneven and irregular, tapering columns and 0.5-1.5 m joint spacing, with joint density of 2-3 times that of the columnar zone; equates to that zone containing the vesicle zone
Entablature	tier of closely (20-40 cm) planar to irregularly curved, columnar joints, which bound columns
Platy zone	characterized by densely spaced, horizontal joints, defining cm thick and decimetre long disk-shaped plates
Flow-top joints	short regular prismatic joints that occur in the top 1-2 m of the flow

Secondary features

Spiracles	features formed by steam from heated ground water blasting through a flow and forming a vent structure or opening

Petrographic Textures

Crystallinity	relative abundance of crystals versus glassy mesostasis in indicated by holocrystalline (crystallinity 90-100%), hypocrystalline (50-90%), hypohyaline (50-10%) and holohyaline (0-10%)
Mesostasis	that part of the rock that represents the residual melt at the time of final crystallization, as identified by either glassy texture today or ultra-fine grained mineral assemblage