GAC-MAC: FIELD GUIDE SUMMARY

Volcanism of the Late Silurian Eastport Formation of the Coastal Volcanic Belt, Passamaquoddy Bay, New Brunswick

GAC–MAC Halifax 2022 Pre-Meeting Field Trip

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SUMMARY

This field trip is an excursion through the exquisite, nearly pristine exposures of a Silurian, felsic-dominated bimodal volcanic and sedimentary sequence exposed in the Passamaquoddy Bay area of southwestern, New Brunswick (Eastport Formation). These rocks form the northwest extension of the Coastal Volcanic Belt that extends from southwestern New Brunswick to the southern coast of Maine. The sequence is significant because it is part of a large bimodal igneous province with evidence for supervolcano-scale eruptions that began to form during the close of the Salinic Orogeny (about 424 Ma), and continued into the Acadian Orogeny (421–400 Ma). The geochemical characteristic of the rocks can be explained by extension related volcanism but the specific drivers of the extension are uncertain. The Passamaquoddy Bay sequence is 4 km thick and comprises four cycles of basaltic-rhyolitic volcanism. Basaltic volcanism typically precedes rhyolitic volcanism in Cycles 1–3. Cycle 4 represents the waning stages of volcanism and is dominated by peritidal sediments and basaltic volcanics. A spectrum of eruptive and emplacement mechanisms is represented ranging from the Hawaiian and Strombolian-type volcanism of the basaltic flows and pyroclastic scoria deposits, to highly explosive sub-Plinian to Plinian rhyolitic pyroclastic eruptions forming pyroclastic density currents (PDC) and high grade rheomorphic ignimbrites. During this field trip we will examine key exposures illustrating this spectrum of eruptive and emplacement processes, and their diagnostic characteristics, along with evidence for the interaction between mafic and felsic magmas and a variety of peperitic breccias formed as a result of emplacement of flows on wet peritidal sediments. The constraints the depositional setting and voluminous bimodal volcanism places on tectonic models will also be considered.

RÉSUMÉ

Cette sortie sur le terrain est une excursion à travers les magnifiques affleurements pratiquement non altérés d'une séquence volcanique et sédimentaire bimodale silurienne à dominance felsique exposée dans la région de la baie de Passamaquoddy, au sud-ouest du Nouveau-Brunswick (Formation d'Eastport). Ces roches forment le prolongement nord-ouest de la Ceinture volcanique côtière qui s'étend du sud-ouest du Nouveau-Brunswick à la côte sud du Maine. La séquence est importante car elle fait partie d'une grande province ignée bimodale comprenant des preuves de super éruptions volcaniques qui ont commencé à se former à la fin de l'orogenèse salinique (environ 424 Ma) et se sont poursuivies pendant l'orogenèse acadienne (421–400 Ma). La caractéristique géochimique des roches peut être expliquée par le volcanisme lié à l'extension, mais les facteurs spécifiques de l'extension sont incertains. La séquence de la baie de Passamaquoddy a une épaisseur de 4 km et comprend quatre cycles de volcanisme basaltique-rhyolitique. Le volcanisme basaltique précède généralement le volcanisme rhyolitique dans les cycles 1–3. Le cycle 4 représente les stades décroissants du volcanisme et est dominé par des sédiments péritidaux et des roches volcaniques basaltiques. Une variété de mécanismes éruptifs et de mises en place est représentée, allant du volcanisme de type hawaïen et strombolien des coulées basaltiques et des dépôts de scories pyroclastiques, aux éruptions pyroclastiques rhyolitiques hautement explosives sous-pliniennes à pliniennes formant des courants de densité pyroclastiques et des ignimbrites rhéomorphes à haute teneur. Au cours de cette visite sur le terrain, nous examinerons les affleurements clés illustrant cette gamme de processus éruptifs et de mises en place, et leurs caractéristiques

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diagnostiques, ainsi que les preuves de l'interaction entre les magmas mafiques et felsiques et une variété de brèches pépéritiques formées à la suite de la mise en place de coulées sur des sédiments péritidaux humides. Les contraintes que le contexte de dépôt et le vaste volcanisme bimodal imposent aux modèles tectoniques seront également examinées.

Traduit par la Traductrice

INTRODUCTION

This field trip is a geotraverse through the exquisite, nearly pristine exposures of the Late Silurian, bimodal (basaltic-rhyolitic) volcanic and sedimentary sequence of the Eastport Formation in the Passamaquoddy Bay area of southwestern New Brunswick. These rocks form the northern extension of the Coastal Volcanic belt that extends south from southwestern, New Brunswick to the southern coast of Maine. Together with the bimodal Central Magmatic Belt of Maine (formerly the Piscataquis volcanic belt), and the Tobique Volcanic Belt in central New Brunswick and Quebec (Fig. 1), the Eastport Formation is part of a large bimodal igneous province with evidence for super volcano-scale eruptions (Seaman et al. 1999, 2019). These rocks, their geochemistry, eruptive styles and depositional settings, place constraints on the Late Paleozoic tectonic history of the northern Appalachians and provide insights into the evolution of large bimodal volcanic systems.

The age of the Eastport Formation is based on two dates, 421 ± 3 Ma and an informal age of 423±1 Ma (Mohammadi et al. 2019 and Van Wagoner and Dadd 2003, respectively), which corresponds to the age range of the Coastal Maine bimodal complexes of 424–420 Ma (Seaman et al. 1995, 2019; McLaughlin et al. 2003; Churchill-Dickson 2004; Turner and Burrow 2018). In contrast, two age groups of bimodal volcanism are recognized in the northern and central part of the Tobique Volcanic Belt; 422–419 Ma and 417–407 Ma (Wilson et al. 2017; Sánchez-Mora et al. 2021). The ages of magmatism in the Central Volcanic Belt of Maine, are 407-406 Ma (Rankin and Tucker 1995; Bradley et al. 2000) corresponding only with the younger of the two age groups of the Tobique. The combination of age dates, though limited, indicates that bimodal volcanism across the three belts was active for about 17 million years from 424 to 407 Ma with a possible hiatus of 2.2 Ma during that period (e.g. Wilson et al. 2017; Seaman et al. 2019). Volcanism apparently began at the same time in the Coastal and Tobique belts, but persisted longer, into the Devonian in the Tobique and Central Volcanic belts.

This time period encompasses the end of the Silurian Salinic Orogeny (440–423 Ma) and the Late Silurian–Early Devonian Acadian Orogeny (421–400 Ma) (e.g. van Staal and Barr 2012). All three of the bimodal volcanic belts were interpreted to have formed on the Ganderia terrane, which accreted to the eastern margin of Laurentia during the Salinic orogeny (e.g. van Staal 2009; Wilson et al. 2017). The geochemical characteristics of the rocks (e.g. bimodal, within plate geochemical affinities) can be explained by extension-related volcanism within an intra-arc rift and backarc on the margin of Ganderia/Laurentia situated above the northwest directed oceanic subducting plate of Avalonia as it approached Ganderia to close the Acadian Seaway (e.g.

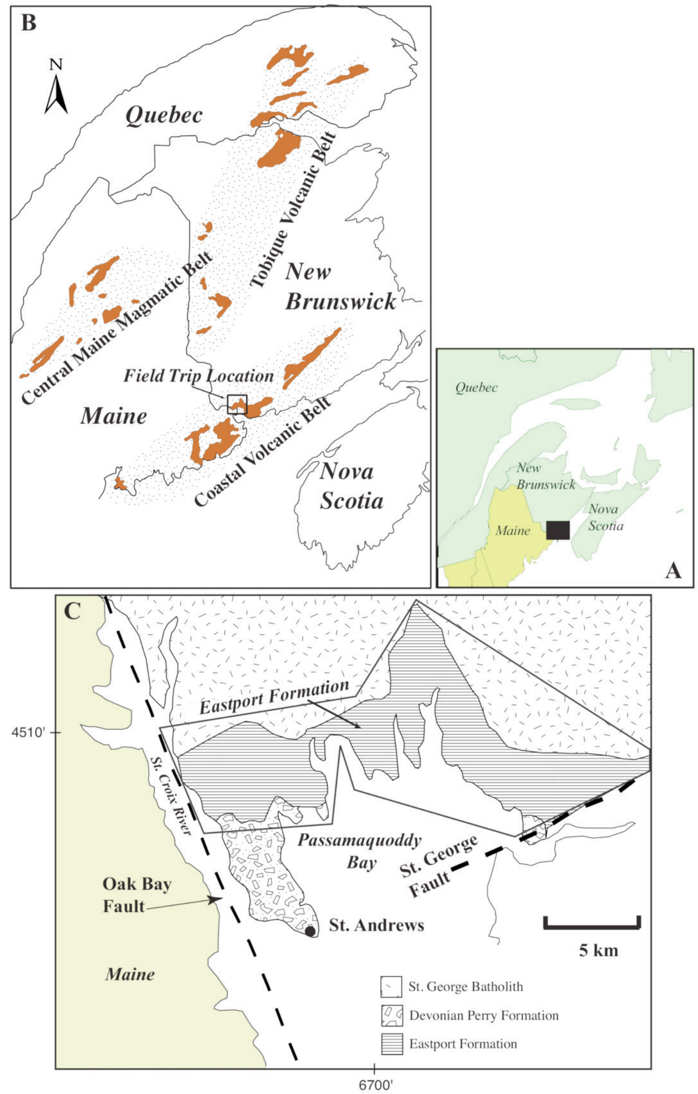

Figure 1. a) Black box shows the geographic setting of the field trip. b) Location of the Coastal, Central, and Tobique volcanic belts (after Dostal et al. 1989 and Seaman el al. 2019). The patterned areas show the locations of the belts and dark areas show exposures of volcanic rock. c) The location of the Eastport Formation in New Brunswick, (the Passamaquoddy Bay Volcanic Sequence) (after Fyffe and Fricker 1987). The striped area is detailed in Figure 2.

Fyffe et al. 1999; Van Wagoner et al. 2002; van Staal et al. 2009, 2014; van Staal and Barr 2012). However, the specific drivers of the extension remain uncertain (e.g. Piñán Llamas and Hepburn 2013; Seaman et al. 2019).

The Passamaquoddy Bay sequence of the Eastport Formation, the subject of this field trip, has a minimum thickness of about 4 km, and preserves at least four cycles of basaltic and rhyolitic volcanic rocks, and sedimentary rocks (Figs. 2 and 3) (McNeil 1989; Baldwin 1991; Van Wagoner et al. 1994). The most recent, comprehensive report of the volcanism of the Passamaquoddy Bay Sequence of the Eastport Formation is by Van Wagoner et al. (1994). They identified 63 units mappable at the 1:10,000 scale and interpreted the model of eruption and deposition for each unit. This field guide is based largely on that work and theses of Baldwin (1991) and McNeil (1989). Subse-

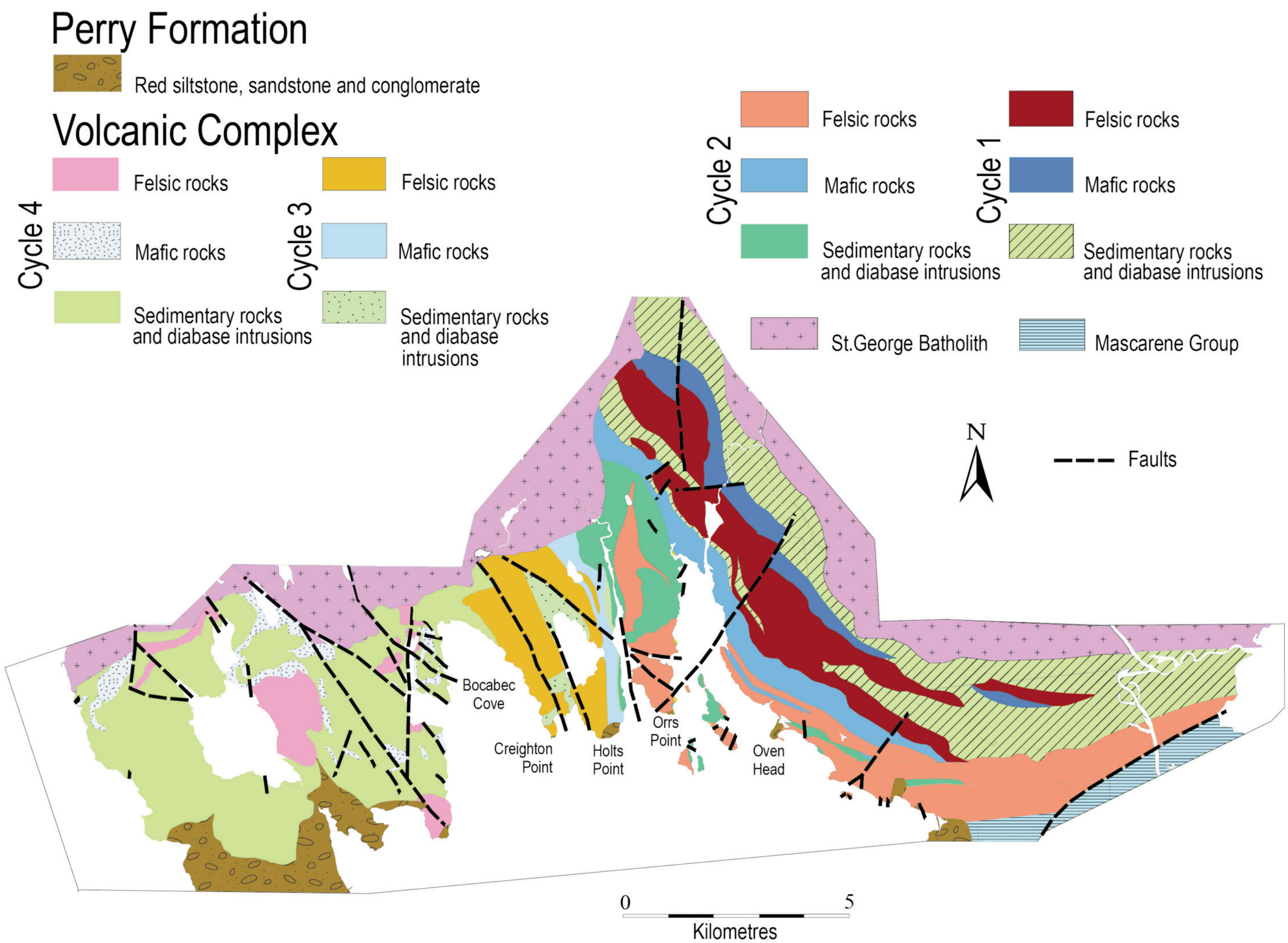

Figure 2. Generalized map of the Passamaquoddy Bay Volcanic Sequence (Eastport Formation in New Brunswick), showing the volcanic cycles; Cycle 1 is the oldest, and Cycle 4 is the youngest (modified after Van Wagoner et al. 2001, 2002).

quently, major construction produced an abundance of new outcrops, mapped by Les Fyffe which improved the accuracy of previous work.

This sequence was correlated with the Eastport Formation in Maine based on the similarity of volcanic and sedimentary rocks, and faunal assemblages (Pickerill and Pajari 1976), but the precise correlation has not been established, and there are lithologic distinctions (between the formation in Maine and New Brunswick (Lodge 2004; Van Wagoner et al. 2005; Lodge et al. 2005). The lower part of the Eastport Formation was intruded by the Saint George Batholith (Fig. 1) obscuring older portions of the Eastport such that the initiation of bimodal volcanism is unknown. The middle and parts of the sequence are overlain unconformably by the alluvial clastic rocks of the Late Devonian Perry Formation. Flow directions and the lack of clear vent facies for most of the felsic pyroclastic units suggests that the preserved sequence is somewhat distal to the source, and therefore does not represent a maximum thickness nor a complete sequence as the locus of emplacement of volcanic rocks would be expected to change.

The basaltic rocks were interpreted to be mantle melts modified by crustal contamination and mantle metasomatism from a previous subduction event. There is a trend toward more primitive mafic compositions upward in the section. The rhyolitic rocks were interpreted to be crustal melts, modified by crystal fractionation (Van Wagoner et al. 2002).

Basaltic volcanism typically precedes episodes of rhyolitic volcanism in the cycles 1–3 (Fig. 3). The presence of juvenile basaltic ejecta in some of the felsic pyroclastic units is an indication of coeval and co-spatial basaltic and rhyolitic volcanism (Fig. 4a). Enclaves of mafic rocks in felsic flows and intrusive sequences have been observed elsewhere in large igneous provinces associated with some of the world's largest eruptions (e.g. Cimarelli et al. 2008; Bryan et al. 2010). This relationship is consistent with the injection of mafic magma triggering felsic eruptions (Van Wagoner et al. 2002). Rhyolitic units are the most voluminous in the first three cycles. The final cycle represents the waning stages of volcanism with basaltic volcanic rocks being more abundant than rhyolitic, and sedimentary rocks predominating (Van Wagoner et al. 1994).

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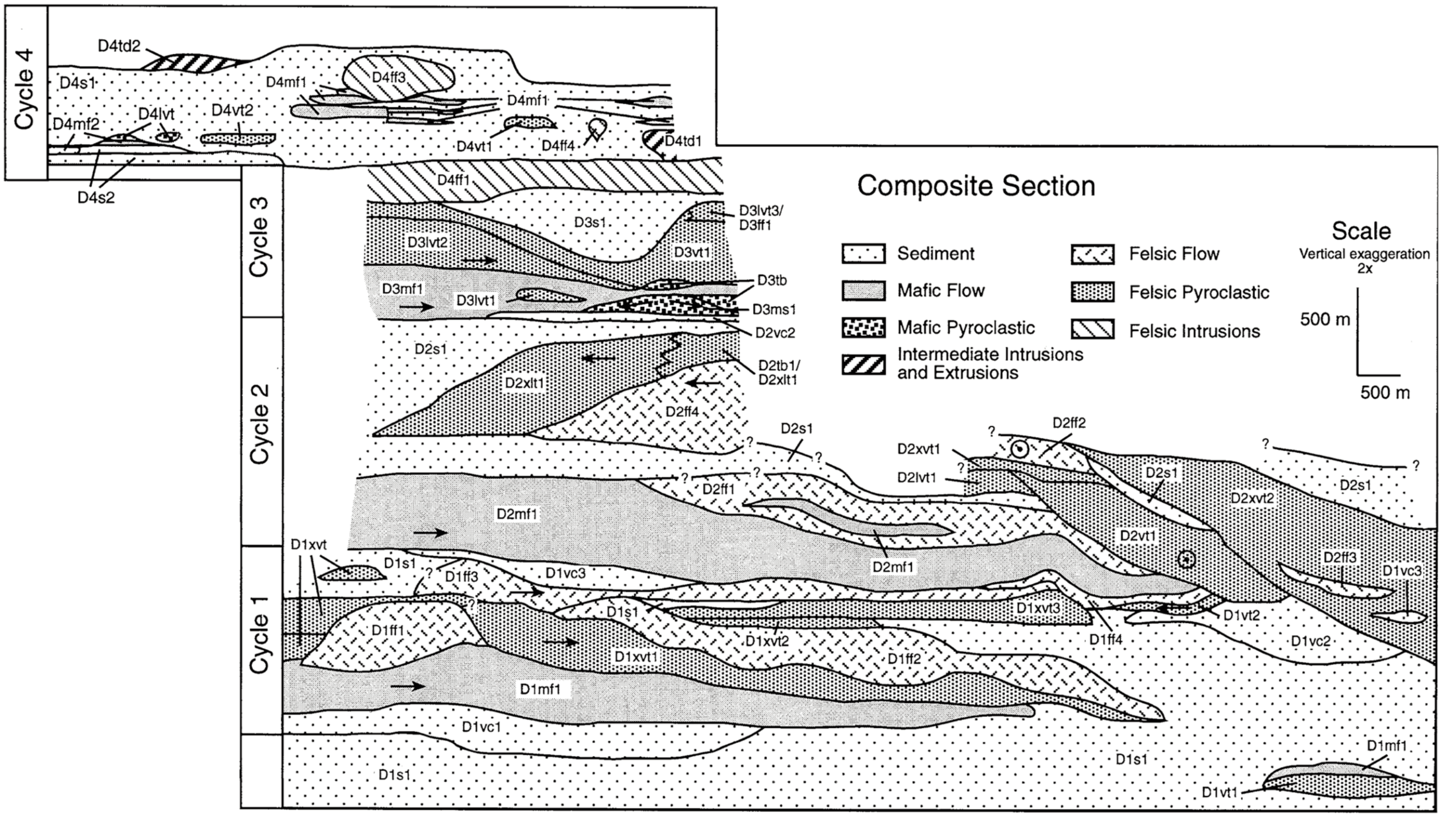

Figure 3. Composite section of the Passamaquoddy Bay Sequence of the Eastport Formation in New Brunswick. The four cycles of mafic-felsic volcanism are indicated on the left. Arrows indicate the major component of flow direction in the plane of the section. Circled dots indicate flow direction perpendicular to the page. Lithological codes: D=Silurian, s=sedimentary rock, c=conglomerate, vc = volcaniclastirock, mf = mafic flow, ms = mafic scoria deposit, tb = tuff breccia, f = felsic flow or dome, td = trachydacite dome, v = vitric, l = lithic, t = tuff. From Van Wagoner et al. 1994; Dadd and Van Wagoner 2002.

The sedimentary facies and fossils (Pickerill and Pajari 1976) indicate deposition in a peritidal environment comprising tidal flats and channels interbedded upward in the sequence with alluvial fan sediments (cycles 3 and 4). There are three periods of relative volcanic quiescence or non-deposition separating cycles of paired mafic-felsic volcanism (Fig. 3). The flows, both basaltic and rhyolitic, interacted with wet sediment to form a variety of peperitic breccias (Fig. 5a, b) (Dadd and Van Wagoner 2002).

A spectrum of eruptive and emplacement mechanisms is represented ranging from the Hawaiian and Strombolian-type volcanism of the basaltic flows and pyroclastic scoria deposits, to highly explosive sub-Plinian to Plinian rhyolitic pyroclastic eruptions forming pyroclastic density currents (PDC) and high grade ignimbrites. Basaltic flows are pahoehoe-type flows (Fig. 6a) that thin to the south and are interpreted to have had a source in the northern part of the map area. A basaltic scoria cone deposit (Fig. 6b) and evidence for such deposits in the clasts of volcaniclastic units in Cycle 3 represent Surtseyan-type volcanism.

The Passamaquoddy Bay volcanic sequence also includes a significant component of rhyolite lava flows which are typically banded, and primarily though not exclusively crystal poor. Hydrous mineral phases are notably absent throughout the sequence. Though most of the rhyolite flows are subaerial, there is evidence for subaqueous rhyolite flows associated with marine sediments in Cycle 2.

The felsic pyroclastic rocks are among the most varied and complex rocks in the section, and comprise weakly to strongly welded vitric, crystal and lapilli tuff and tuff breccias. Some of the densely welded tuffs have a eutaxitic foliation that is complexly folded typical of rheomorphic high-grade pyroclastic density currents (e.g. Brown and Andrews 2015) and are difficult to distinguish from rhyolitic lava flows. Despite the availability of external water in the peritidal environment, most of the explosive volcanism was driven by magmatic volatiles. An exception is a sequence of bedded accretionary lapilli tuffs (Fig. 4b) and tuffs containing other ash aggregates (e.g. Brown et al. 2010) interpreted to have been formed by phreatomagmatic eruptions.

This combination of volcanic deposits, particularly the apparently large volume rhyolite lava flows, intensely welded rheomorphic ignimbrites, ash deposits with abundant ash aggregates and accretionary lapilli, and the associated pahoehoe-style basaltic flows were interpreted by Van Wagoner et al. (1988, 1994) to be most akin to Snake River-type volcanism (e.g. Branney et al. 2008; Knott et al. 2016).

FIELD TRIP ITINERARY

Key exposures will be examined to show how the Pas-

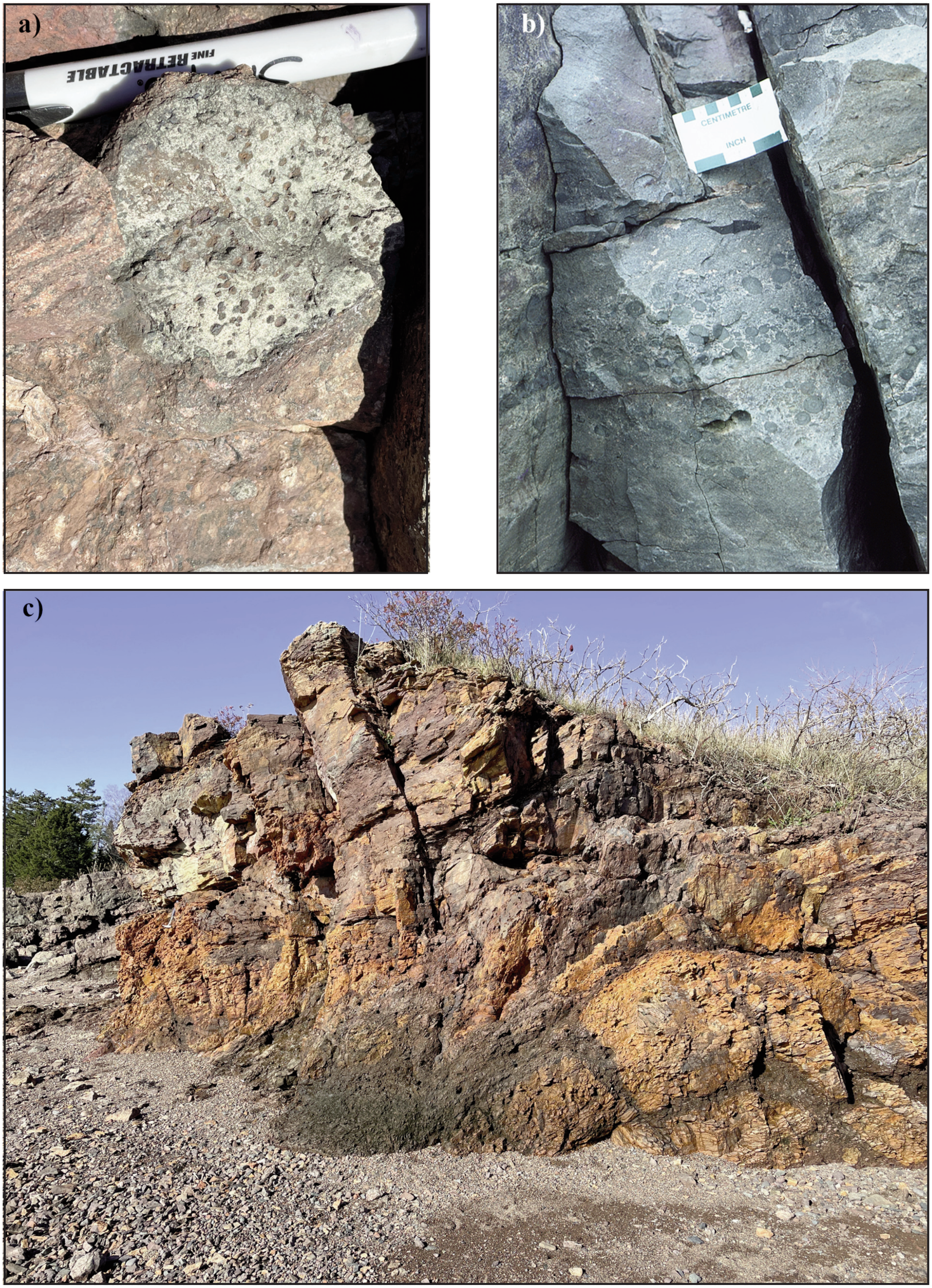

Figure 4. Cycle 2 felsic pyroclastic rocks at Oven Head on the Passamaquoddy Bay coast. a) Juvenile mafic pyroclast in a felsic welded heterolithic lapilli tuff and tuff breccia. b) Accretionary lapilli in a sequence of bedded tuff and lapilli tuffs. c) Hydrothermally altered and brecciated rheomorphic pyroclastic flow. Photo credit: N. Van Wagoner.

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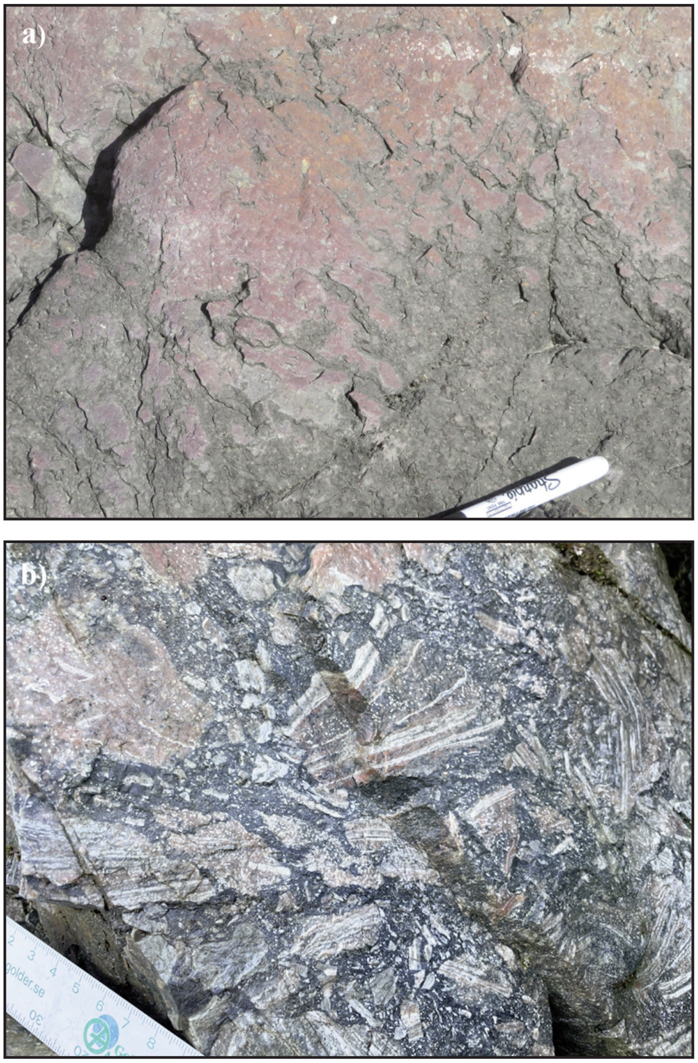

Figure 5. Two contrasting textures of peperitic breccias. a) In this basaltic peperitic breccia the lava flow has mingled with the underlying sediment to form globular shapes in the sediment. b) This photo shows the breccia at the margin of a rhyolite flow. In contrast to the basaltic peperite, the rhyolitic brecciated fragments are angular and blocky. Spherulites are visible in some of the fragments. Photo credit: N. Van Wagoner.

samaquoddy Bay volcanic sequence evolved through time and the range of eruptive and emplacement processes. Diagnostic features observed in outcrop will be viewed simultaneously with textures visible in photomicrographs, and the geochemical characteristics of the rocks. The tentative schedule follows but adjustments may be required to accommodate time and weather.

Day 1 will be spent in transit from Halifax to St. Andrews, New Brunswick. Before heading to our accommodation at the Huntsman Marine Science Centre, a stop is planned along the Passamaquoddy Bay coast where the Devonian Perry Formation is in unconformable contact with the underlying medium-bedded pyroclastic rocks of Cycle 2 of the Eastport Formation. These rocks, were formed by pulses of PDCs. They are interbedded with shallow marine sediments near the upper part of the sequence and overlain by a rhyolite lava flow.

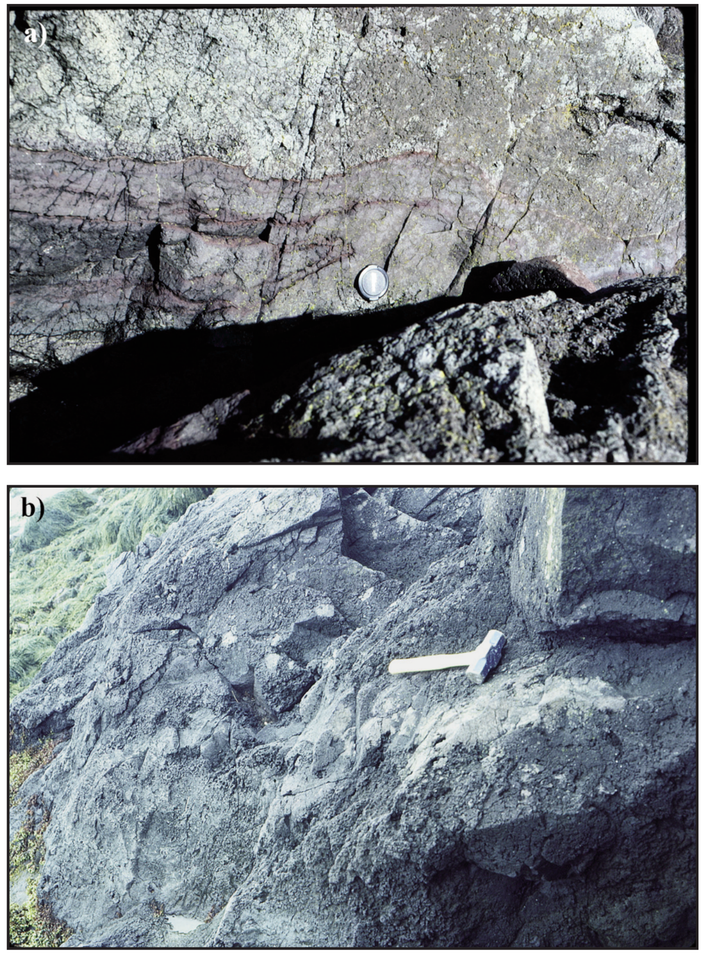

Figure 6. Cycle 3 basaltic volcanism. a) Pahoehoe toes with oxidized selvages. b) Large bomb just below the rock hammer in a scoria deposit. Photo credit: N. Van Wagoner.

Day 2 will start at an inland section along a road cut that traverses through cycles 1 and 2 including maroon marine sedimentary rocks, the peperitic breccias at the margin of a rhyolitic flow, basaltic lapilli tuffs and amygdaloidal flows, and ending at a fault contact between cycles 2 and 3. With low tide in the afternoon, the tour of Cycle 2 will continue along the coast where a spectacular deposit of bedded accretionary lapilli tuffs (Fig. 4b), interpreted to be formed by silicic phreatomagmatic volcanism, are exposed at a tombolo. These rocks are underlain by a densely welded and rheomorphic heterolithic tuff to tuff breccia that includes both felsic and mafic juvenile pyroclasts (Fig. 4a), that is hydrothermally altered in places (Fig. 4c). The day will end at a coastal exposure to the east at the margin of a massive rhyolite flow of Cycle 4, and the underlying Cycle 3 fluvial sedimentary rocks and bedded tuffaceous PDCs also with rhyolitic and basaltic juvenile pyroclasts as observed in Cycle 2.

Day 3 will start with a visit to two inland sections; a rhyolitic subaerial lava flow of Cycle 1 and the overlying mafic lava flows of Cycle 2 and their associated peperitic breccias, and the exposure of rhyolitic pillow flow and associated mafic volcaniclastic rocks, also of Cycle 2. As the tides recede the rest of the day will be spent traversing a coastal section of Cycle 3, from the lower-most contact with Cycle 2 fossiliferous shallow marine sedimentary rocks, through a sequence of volcaniclastic rocks, and continuing up section through mafic tuffs and tuff breccias interpreted to be scoria cones, overlain by mafic pahoehoe flows (Fig. 6), and then into the overlying felsic vitric tuffs and felsic flows. If time permits there will be one last stop in the thick sequences of sedimentary rocks and basaltic lava flows of Cycle 4 that represent the waning phases of volcanism. A special tour of the Huntsman Marine Aquarium is planned for the evening.

Day 4 will be spent in transit back to the GAC–MAC 2022 Halifax conference in time for the opening events in the evening.

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