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STRATIGRAPHY AND PETROCHEMICAL EVOLUTION OF VOLCANIC ROCKS FROM THE LONG HARBOUR GROUP AND RENCONTRE FORMATION, AVALON ZONE, NEWFOUNDLAND

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ABSTRACT

Bimodal volcanic and cogenetic volcano-sedimentary rocks of the Long Harbour Group and Rencontre Formation (Fortune Group), northern Fortune Bay, are among the youngest Precambrian rocks of the Avalon Zone in Newfoundland. Previous U–Pb dating of rhyolites from the base and top of the Long Harbour Group indicate an age spanning ca. *570–550 Ma. The lowermost Belle Bay Formation is conformably overlain by the Andersons Cove and Mooring Cove formations, each of which is locally unconformably overlain by the Rencontre Formation. Microspherulitic, flow-banded rhyolite from the upper Belle Bay Formation is rare-earth-element (REE) enriched, and is an A-type, alkali rhyolite. Mafic volcanic flows, bombs and breccias in the overlying Mooring Cove and Rencontre formations are subdivided into four petrochemical suites. Basalts of the stratigraphically lowest, suite 1, have plagioclase phenocrysts with honeycomb-textured cores and sieve-textured rims, reflecting complex petrogenetic histories related to repeated magmatic replenishment. They have low Mg#'s, Ni, Co and V, and high SiO_2 and Zr contents, negatively sloped multi-element patterns and prominent negative Nb anomalies. They are similar to mature magmatic arc rocks but are more heavy-REE-enriched and lack Zr and Hf troughs characteristic of calc-alkaline basalts. Suites 2 and 3 are tholeiitic basalts, have iron-enrichment trends, and flatter multi-element patterns relative to suite 1 basalts. Suite 2 rocks contain primary clinopyroxene, have the flattest multi-element patterns (lowest La/Yb and La/Sm ratios), and contain higher Mg#, Ni, Cr, V and Co and lower SiO_2, Zr and Th than suite 3 rocks. Suite 2 rocks are the most primitive and originated from a more NMORB-like, albeit enriched source. Suite 3 basalts, intermediate between those of suites 1 and 2, have higher light-REE contents, higher La/Yb ratios, more variable Th and Nb, and originated from a more EMORB-like source than suite 2. Suite 4 basalts have relatively smooth negative multi-element patterns, and high TiO_2 and P_2O_5 relative to the other three suites. They are alkali, OIB-like basalts, and originated from low-degree partial melting of a deeper source than the other basalt suites.*

Petrochemical investigation of the basalts indicates a progression from calc-alkaline, through transitional basaltic compositions ranging from NMORB-like to EMORB-like, to alkaline. This temporal change reflects progressive deepening of the magmatic source, resulting from late Ediacaran extension of an inherited lower Ediacaran volcanic arc. The decreasing lithospheric input and increasing source depths through time reflect the waning of this extensional pulse. Subsequent extension continued episodically, possibly evolving to rifting by Terreneuvian to Miaolingian times.

INTRODUCTION

The Long Harbour Group (White, 1939) comprises a thick sequence of bimodal volcanic rocks (felsic and mafic) and the overlying volcano-sedimentary units along the north shore of Fortune Bay, extending from Belle Bay in the west to the northeastern arm of Fortune Bay in the east (Figure 1). Previous work suggested that the volcanic constituents of the group are alkaline (O'Brien *et al.*, 1995, 1996) and detailed stratigraphic and sedimentological investigations of the overlying Rencontre Formation indicated its deposition occurred in an extensional to transtensional setting (Smith, 1984; Smith and Hiscott, 1984). Therefore, the Long Harbour Group is interpreted to mark the onset of significant episodes of extension in the Avalon Zone characterized by alkali magmatism (for a Miaolingian case study, *see* Mills and Álvaro, 2023). The Rencontre Formation marks the beginning of deposition of the terminal Ediacaran to Ordovician cover sequence that characterizes the microcontinent of Avalonia (O'Brien *et al.*, 1996; Landing, 1996; Murphy *et al.*, 2023). Bedrock mapping of the Rencontre East–Belle Bay area was completed at 1:50 000-scale by Williams (1971), and later included in a 1:100 000-scale compilation of the Connaigre Peninsula and adjacent

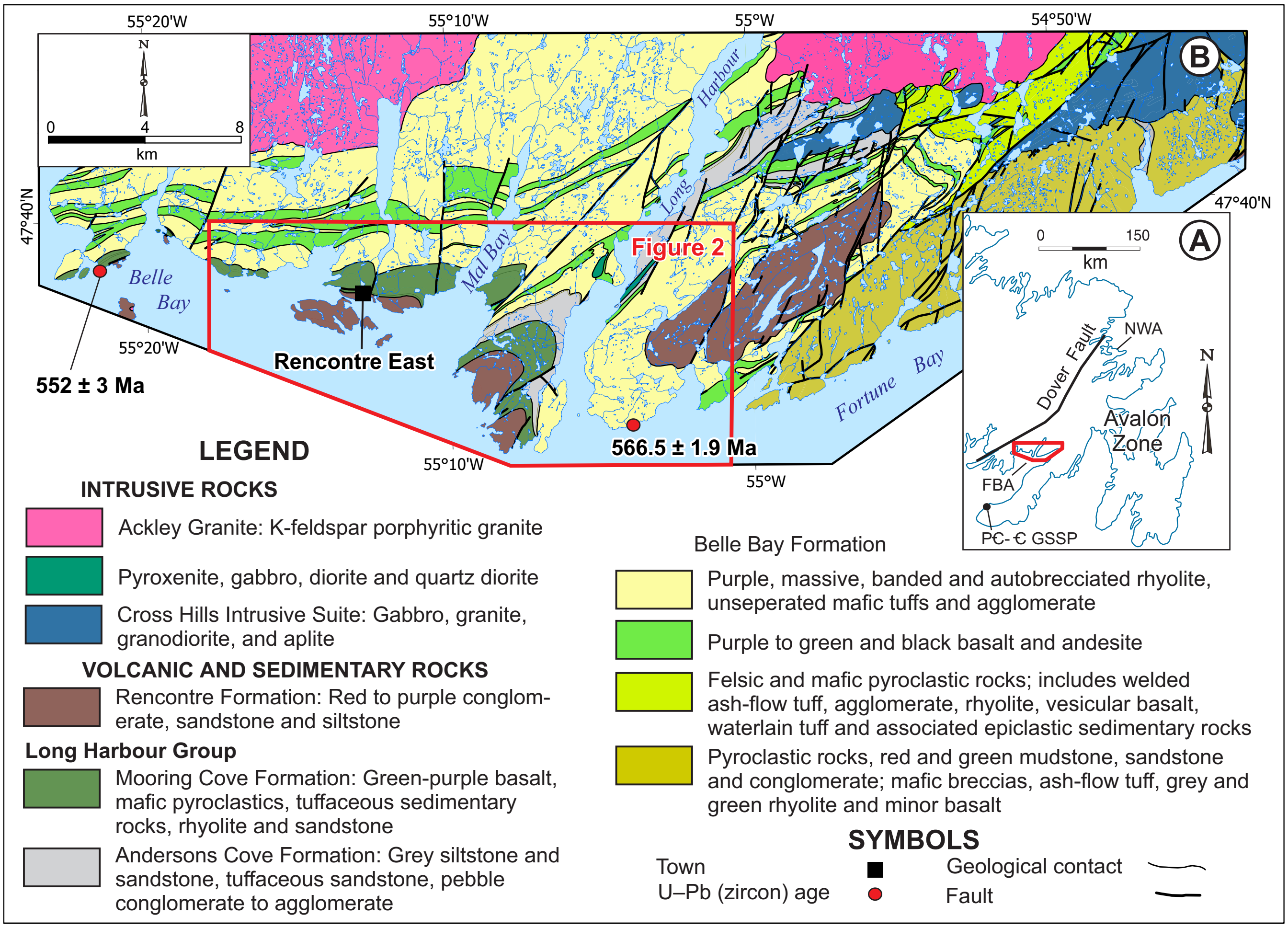

Figure 1. *A) Inset map showing portion of the Island of Newfoundland comprising the Avalon Zone, northwestern Avalon Zone area (NWA), the Fortune Bay area (FBA) and the location of the Precambrian–Cambrian Global Stratotype Section and Point (GSSP); the red polygon indicates the area shown in B; B) Generalized geology of the northern Fortune Bay area, modified from Sparkes* et al. *(2023); geology after Williams (1971), O'Brien* et al. *(1984) and O'Brien (1998); the red polygon in B shows the study area, depicted in Figure 2.*

regions (O'Brien, 1998). Previous work, including pioneering studies, regional surveys and subsequent thematic studies, is summarized by O'Brien *et al.* (1995).

Previous age constraints on the Long Harbour Group include U–Pb zircon ages of 568 ± 5 Ma and 552 ± 3 Ma for rhyolites from near the base and top of the group, respectively (O'Brien *et al.*, 1995). The location of the younger dated sample is ~10 km west of Rencontre East (O'Brien, 1998; *see* Figure 1), but that of the older dated rock is uncertain, and the data, methodology, concordia plots and descriptive details of the dated rocks were never published. A more recent age of 566.5 ± 1.9 Ma was obtained by CA-TIMS for a rhyolite from the lower Long Harbour Group (Belle Bay Formation) as part of a thesis examining the timing of associated low-sulphidation mineralization (Ferguson, 2017). Available lithogeochemical data for the Long Harbour Group are included in Miller (1994) and Sparkes and Sandeman (2015). The Miller (1994) dataset includes trace-element data for 15 elements (with Ce and Nb being the only REE elements analyzed), and the Sparkes and Sandeman (2015) dataset includes a greater array of elemental data for felsic and mafic volcanic rocks of the Long Harbour Group from northern Fortune Bay (between Long Harbour and the northeastern arm of Fortune Bay).

New lithogeochemical data are presented for 25 rock samples from the Long Harbour Group and the overlying Rencontre Formation in the vicinity of Rencontre East. These results are combined with lithogeochemical data from 10 unaltered rhyolite samples (Belle Bay Formation, Sparkes and Sandeman, 2015), which, in conjunction with details of the local stratigraphy, provide insights into the tectonomagmatic evolution across the Long Harbour Group–Rencontre Formation transition.

REGIONAL GEOLOGY

The sea cliffs and rocky foreshore areas along northern Fortune Bay, between Rencontre East village and Stone Cove (Figure 2) provide excellent, continuous exposure of the Long Harbour Group and the unconformably overlying Rencontre Formation (Fortune Group; Fletcher, 2006). The strata of the Long Harbour Group (rhyolites and basaltic lava flows) strike approximately east–west and dip consistently toward the south, except on the southern part of the peninsula between Mal Bay and Long Harbour, where bedding is folded about southwest-plunging folds. This mainly volcanic basement is unconformably overlain by volcano-sedimentary rocks of the Rencontre Formation, which form the cores of a series of faulted, gently to moderately southwest- and northeast-plunging synclines. These synclines are composed of reddish conglomerates and have bedding dips ranging from subvertical (close to the faulted flanks) to horizontal in central parts of the synclines, where strikes are variable. A steeply southeast-dipping axial–planar cleavage is locally developed and is the dominant tectonic fabric in the study area. A second subvertical, north-northeast-striking cleavage is locally evident close to some subvertical flanks (*e.g.*, on the northwestern limb of the Hoop Cove syncline; Figure 2).

The base of the Long Harbour Group is not exposed, as it is truncated by the Ackley Granite to the north (Figure 1). The group has been traditionally subdivided into four formations which, in ascending order, are the Belle Bay, Andersons Cove, Mooring Cove and Rencontre formations (Williams, 1971; O'Brien *et al.*, 1995; O'Brien, 1998). However, the basal unconformity below the Rencontre Formation led Fletcher (2006) to instead include it, together with the conformably overlying Chapel Island Formation, in the Fortune Group (*see* Figure 3), a proposal followed and supported here.

The Belle Bay Formation, up to 3000-m thick, comprises mainly felsic and mafic volcanic rocks, and minor pyroclastic and sedimentary rocks (Williams, 1971). The top of the formation is drawn at the lowest stratigraphic occurrence of grey siltstone and fine-grained sandstone that characterize the up to 1200-m thick Andersons Cove Formation. The

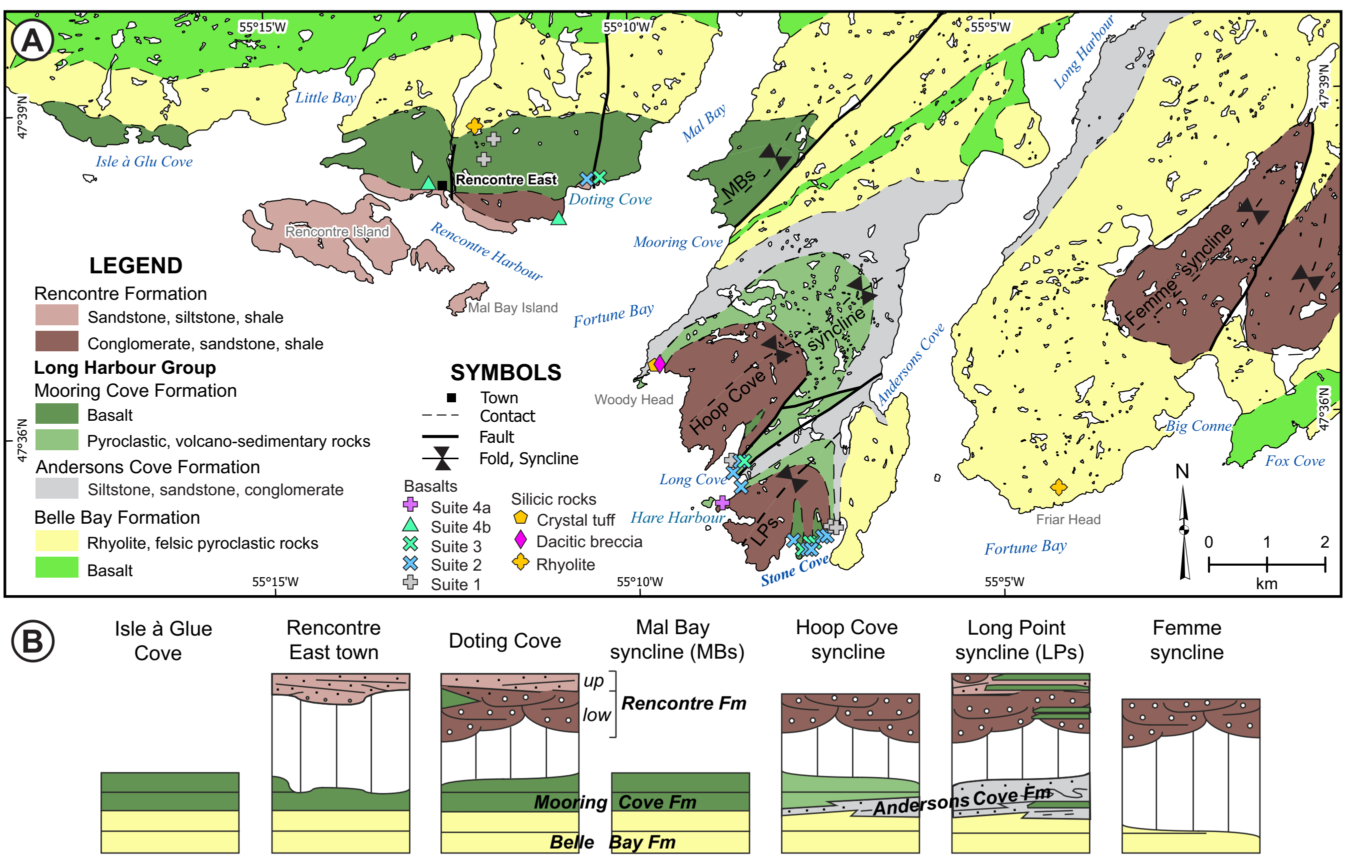

Figure 2. *Generalized geology (A) and schematic stratigraphic columns (B) of Rencontre East area showing locations of lithogeochemistry samples; geology modified after Williams (1971) and Smith and Hiscott (1984).*

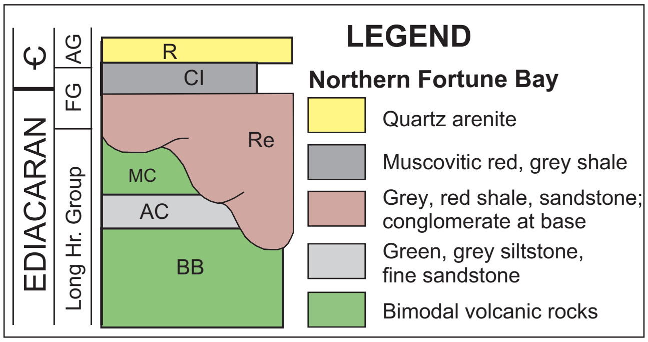

Figure 3. *Schematic stratigraphic section for upper Ediacaran to Terreneuvian rocks from the northern Fortune Bay area (modified from Williams, 1971; Smith and Hiscott, 1984; Fletcher, 2006). AC–Andersons Cove Formation, AG–Adeyton Group, BB–Belle Bay Formation, CI–Chapel Island Formation, FG–Fortune Group, MC–Mooring Cove Formation, R–Random Formation, Re–Rencontre Formation.*

conformably overlying, 500–750-m thick Mooring Cove Formation is recognizable in southern parts of the peninsula between Mal Bay and Long Harbour (Figure 2). It comprises mafic and lesser felsic volcanic flows, pyroclastic rocks including agglomerates and tuffs, and local sedimentary interbeds ranging from conglomerate to shale. Outside the stratotypes, the Andersons Cove and Mooring Cove formations are difficult to distinguish and may be thin to absent. The first occurrence of reddish-pink conglomeratic channels marks the base of the overlying Rencontre Formation. The uppermost basalt interbeds, particularly in the Stone Cove area (Figures 2 and 4) must therefore be assigned to the Rencontre Formation. Where the Andersons Cove Formation is absent, the Mooring Cove Formation directly overlies the Belle Bay Formation with presumed disconformity (*e.g.*, the Mal Bay syncline in Williams, 1971). Where both the Andersons Cove and Mooring Cove formations are absent, the Rencontre Formation directly overlies the Belle Bay Formation (*e.g.*, Femme Syncline in Williams, 1971;

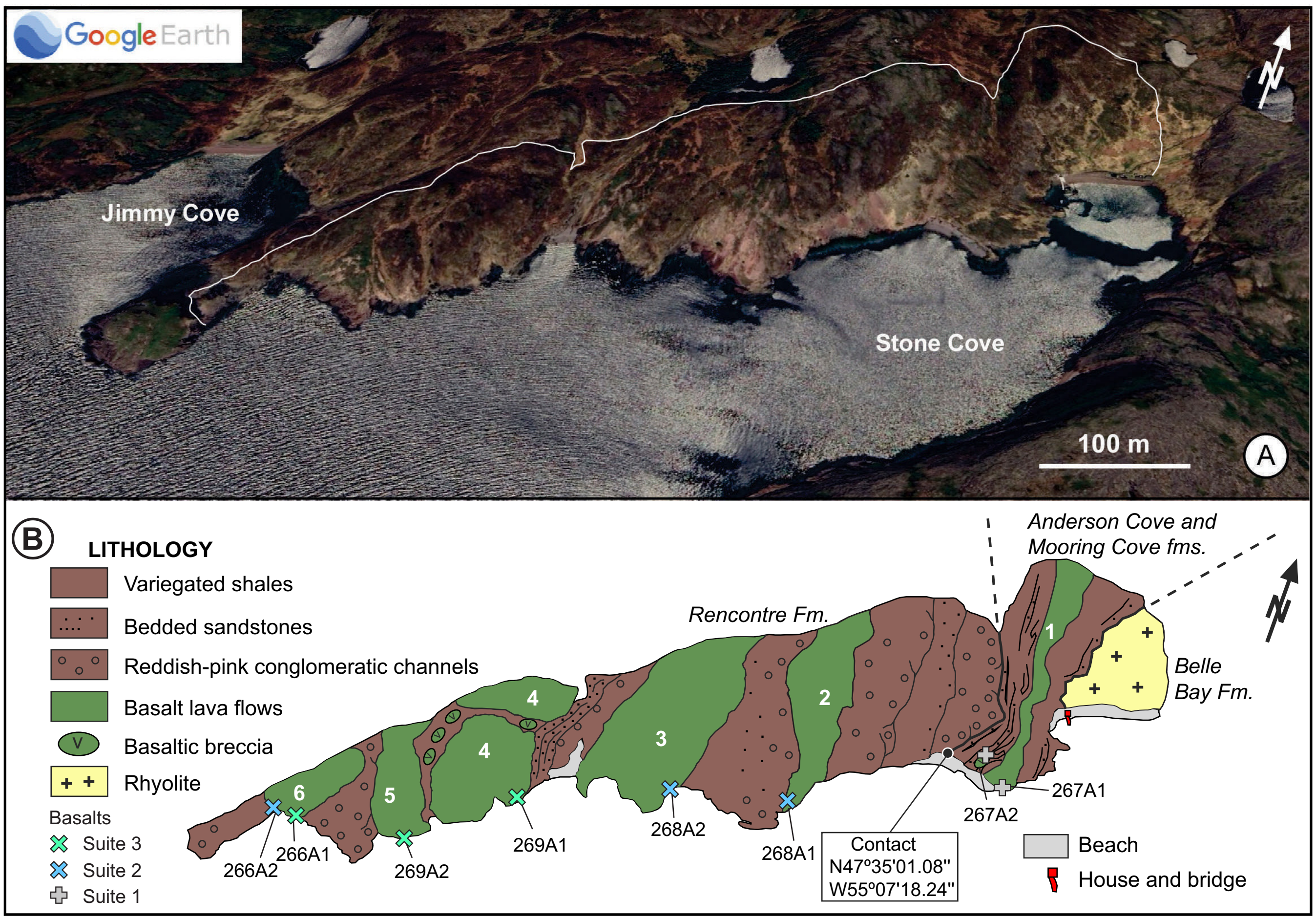

Figure 4. *Detail of Stone Cove area. A) GoogleEarth image, with white line delimiting the extent of B) sketch map of Long Harbour Group to lower Rencontre Formation along the shoreline of Stone Cove showing sample locations. Sample numbers are prefixed by 23AM and lithogeochemical results are in the Supplementary data. Contact–coordinates for contact between Long Harbour Group and Rencontre Formation. Basalt lava flows are numbered from 1 to 6.*

Figures 1 and 2). Therefore, the Rencontre Formation must unconformably overlie any of the underlying formations of the Long Harbour Group (Figure 2B) and is interpreted to represent the sealing of an inherited (tilted and eroded) palaeorelief. Its lithological similarity to the overlying Chapel Island Formation, and their collective distinction from underlying and overlying lithologies, provide the requisite lithostratigraphic criteria to support designation of both formations to a single group – the Fortune Group (Fletcher, 2006).

The Rencontre Formation, variable between 600–1500 m in thickness, consists of reddish breccias and conglomerates with sandstone and shale interbeds that become dominant up-section (Williams, 1971; Smith, 1984; Smith and Hiscott, 1984). The formation has been traditionally subdivided into several informal and unnamed members, the lower of which may be a useful marker bed due to its remarkable reddish colour. The lower Rencontre Formation is coarse-grained, conglomeratic, commonly contains felsic and mafic volcanic clasts, and includes sparse volcanic flows near its base on the peninsula between Mal Bay and Long Harbour (Williams, 1971; Figures 1 and 2). The overlying members of the Rencontre Formation are dominated by pale grey to reddish thinner bedded and more muscovitic sandstones and siltstones relative to the lower succession. On Chapel Island (not shown), about 8 km southwest of Rencontre Island, the Rencontre Formation is conformably overlain by the shales, fine-grained sandstones and subsidiary carbonate interbeds of the Chapel Island Formation (Smith and Hiscott, 1984). Farther south at Fortune Head on Burin Peninsula (*see* Figure 1 Inset), the Chapel Island Formation hosts the global Precambrian–Cambrian boundary stratotype section and point (GSSP) (Narbonne *et al.*, 1987; Myrow and Hiscott, 1993; Landing, 1992, 1994, 2004) and is conformably overlain by the Random Formation (Anderson, 1981; basal Adeyton Group as revised by Fletcher, 2006; Figure 3).

The basin fill of the upper Rencontre Formation in the Fortune Bay area has been interpreted as deposited in a transgressive fluvial to open-marine setting (Smith and Hiscott, 1984). Deposition initiated in a small, fault-bounded trough, where episodic pulses of fault activity generated block uplift and tilting, leading to deposition of coarse terrestrial clastic deposition, succeeded by fine-grained marine units that sequentially overstepped the earlier basin margins (Smith, 1984; Smith and Hiscott, 1984). The tectonic setting was likely extensional to transtensional and continued into Terreneuvian time, when sea-level rise led to a global marine transgression (Hiscott, 1982; Smith and Hiscott, 1984).

METHODS

Twenty-five rock samples, including one field duplicate, were collected from the Rencontre East area (Figure 2). Twenty-two of these are basalts collected from a range of stratigraphic positions within the upper Belle Bay, Mooring Cove and Rencontre formations. Three felsic to intermediate rocks were collected, including a flow-banded rhyolite from the upper Belle Bay Formation and crystal lithic tuff and dacitic breccia, both from the base of the Mooring Cove Formation near Woody Head (Figure 2). All samples were representative of the rock unit and free of veins and obvious alteration. Weathered surfaces were carefully removed either at the sample site using a rock hammer or later, using a rock saw. Slabs were prepared for photography and archival storage. Thin sections were prepared by local lapidary services, and approximately two kilograms of clean, homogeneous rock fragments were selected and submitted to the Geological Survey's Geochemistry Laboratory for processing. Analytical methodology is described in detail by Finch *et al.* (2018). Sample locations are shown in Figures 2 and 4. Lithogeochemical data and geographic coordinates are presented in the Supplemental data file. Key geochemical features are captured in Table 1. Lithogeochemical data from nine rhyolites and one crystal tuff of the Belle Bay Formation (Sparkes and Sandeman, 2015) were used to augment our limited data for silicic rocks.

FIELD DESCRIPTIONS AND PETROGRAPHY

RENCONTRE EAST AREA

The stratigraphically lowest unit examined is a flow-banded rhyolite located near the top of the Belle Bay Formation, north of Rencontre East (Figure 2). This pinkish-grey rock features prominent mm-scale flow banding (Plate 1A). Petrographic analysis reveals a very fine-grained quartzofeldspathic microspherulitic texture defined, in part, by concentric fine-grained opaque grains (likely secondary iron oxyhydroxide phases) between the core and rim of each microspherulite, and fine, dusty sericite between microspherulites (Plate 1B). To the south, the rhyolite is overlain by basalt assigned to the Mooring Cove Formation (Williams, 1971). These basalts range from aphanitic with small (1–2 mm) quartz–epidote amygdales (Plate 1C) to porphyritic basalt with up to 50% plagioclase phenocrysts (Plate 1D) that show patchy epidote and more pervasive saussurite alteration (Plate 1E). Near Rencontre Harbour (Figure 2), the Mooring Cove basalt is either unconformably overlain or in tectonic contact with massive to thick-bedded conglomerates of the lower Rencontre Formation (see Smith and Hiscott, 1984). The stratigraphically uppermost basalt is

Table 1. Salient lithogeochemical features of the four petrochemical basalt groups of the Long Harbour Group and Rencontre Formation, as recognized in this study

Basalt Groups	Suite 1	Suite 2	Suite 3	Suite 4a	Suite 4b
n	5	9*	5	1	2
Mg#	42.3	54.3	51.0	55.4	40.2
SiO_2	53.6	45.0	48.0	44.4	45.8
$(La/Yb)_{PM}$	4.20	2.71	3.84	5.00	9.56
$(La/Sm)_{PM}$	2.00	1.33	1.86	2.10	2.67
$(Gd/Yb)_{PM}$	1.63	1.69	1.63	1.89	2.48
$(Th/La)_{PM}$	1.87	0.56	0.75	0.73	1.01
$(La/Nb)_{PM}$	3.00	2.03	1.44	1.19	0.94
$(Th/Nb)_{PM}$	5.46	1.10	1.02	0.87	0.95
Eu/Eu* Range	0.80–0.94	0.92–1.10	0.86–0.99	1.06	0.95–0.98
Zr/Y	5.77	5.18	6.59	6.61	8.66
Nb/Y	0.23	0.20	0.43	0.62	1.36
Th	5.64	0.83	1.93	1.92	5.08
Sr	366	280	306	555	312
Zr	226	164	232	197	285
ΣREE	159	104	140	136	220
TiO_2	2.01	2.15	2.09	2.43	3.43
P_2O_5	0.37	0.40	0.38	0.52	0.63
V	207	274	230	238	229
Cr	86	167	57	287	13
Ni	43	84	48	95	23

Note: PM = primitive mantle-normalized (using values of Sun and McDonough, 1989); n = number of samples; * includes one field duplicate; Mg# = (MgO/40.312) / [(MgO/40.312) + (FeO^T/71.847)] x 100; ΣREE = sum of REEs

interbedded with red pebbly sandstone and granule conglomerate of the Rencontre Formation and was sampled approximately 500 m south of Doting Cove, or 2.5 km east-southeast of the town of Rencontre East (Figure 2). This aphanitic basalt exhibits trachytic texture and contains irregular, 1 mm chlorite amygdales (Plate 1F).

WOODY HEAD TO HARE HARBOUR

The Mooring Cove Formation at Woody Head (Figure 2) comprises mainly pyroclastic rocks, commonly brecciated, with both angular to subangular grey siliceous fragments in a brick-red matrix (Plate 2A) and angular pinkish siliceous fragments in a dark-grey matrix. These rocks are generally structureless, although to the west of these massive rocks primary layering is evident as crude, alternating upward-coarsening and upward-fining layers in moderately west-dipping lithic tuffs. This west-dipping sequence occurs in the footwall of a subvertical fault separating it from moderately east-dipping reddish conglomeratic rocks with common sand injections perpendicular to bedding. The latter rocks, in the hangingwall of the northeast-trending normal fault, are likely part of the lower Rencontre Formation. The pyroclastic breccia near the base of the footwall succession appears strongly altered in thin-section, with fragments composed of fine white mica and quartz, and the outline of relict feldspar phenocrysts barely discernible within some fragments.

At Long Cove (Figure 2), basalt flows are interbedded with red siltstone, sandstone, basaltic agglomerate, breccia and boulder conglomerate (Plate 2B) of the Mooring Cove Formation. The agglomerate comprises rounded basalt boulders, up to 60 cm in length, within red-weathering basalt breccia (Plate 2C). Some of the boulders are likely volcanic bombs, based on their fusiform shape and preserved chill margins. Mafic clasts and rare silicic welded tuff fragments are set in a glassy matrix (Plate 2D) of the mainly basaltic breccia. Farther south at Hare Harbour, reddish pebble conglomerate, minor shale and sandstone are interbedded with amygdaloidal basalt of the lower Rencontre Formation. The sequence here dips steeply to the southeast on the northern limb of the Long Point syncline (Figure 2).

STONE COVE

In the Stone Cove area (Figures 2 and 4), the Belle Bay and broadly, the Andersons Cove and Mooring Cove formations, can be recognized although the latter two are difficult to distinguish here. Lithologies above the Belle Bay Formation include reddish sandstone/shale alternations punctuated by contorted to slumped breccia lenses, pyroclastic interbeds and basaltic lava flows (Figure 4B). Basalt flows are interbedded with red shale and red, purple and grey siltstone and sandstone (Plate 3A, B). Synsedimentary folds and slumps occur locally within the red shale of the Mooring Cove Formation (Plate 3C), and basaltic bombs with chill margins are common (Sample 23AM267A2 of Figure 4; Plate 3D). The first occurrence of a reddish conglomeratic channel marks the base of the Rencontre Formation (contact indicated on Figure 4B), above which five distinct basalt flows occur. Below the second basalt flow along the Stone Cove section (Figure 4B), a distinctive unit of grey, finely laminated claystone to siltstone with intercalations and lenses of coarse-grained sandstone occurs and exhibits complex convolute bedding, slumping and other synsedimentary structures (Plate 3E). Some basalt flows above this level have apparently baked the tops of underlying sandstone beds (*e.g.*, basalt flow 3 in Figure 4; Plate 3F). Stratigraphically above this flow, the basalts are interbedded with sparse sedimentary rocks displaying an overall upward-coarsening, and conglomerate becomes more volumetrically significant toward the top of the section (Figure 4).

The lowermost flow in this Stone Cove section (flow 1 and sample 23AM267A1 in Figure 4B) contains plagioclase phenocrysts (2 mm in length) exhibiting honeycomb-textured cores surrounded by sieve-textured rims, in a groundmass comprising mainly -400 µm plagioclase laths,

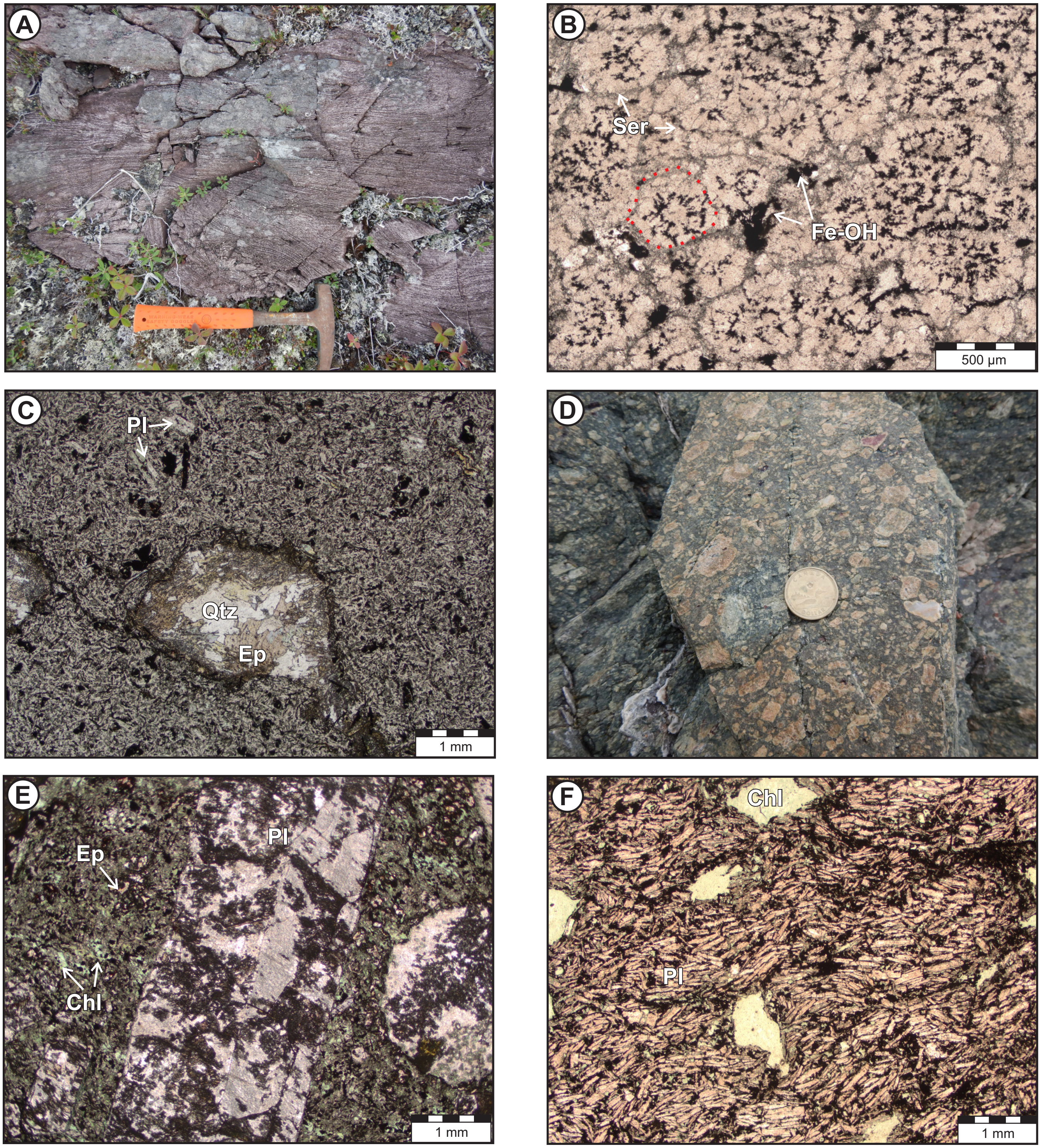

Plate 1. *Field photographs and photomicrographs from the Rencontre East area (Rencontre Harbour to Doting Cove). A) Pink, flow-banded rhyolite of the upper Belle Bay Formation; B) Belle Bay rhyolite showing quartzofeldspathic microspherulites (one example outlined by the red dotted line), with opaque (likely iron oxyhydroxide) phases in the cores, at core-rim boundaries and between microspherulites, under plane-polarized light; C) Quartz- and epidote-filled amygdale and plagioclase microlaths in basalt from 1.5 km northeast of Rencontre East, under plane-polarized light; D) Plagioclase porphyritic basalt from near Doting Cove; E) Patchily altered (sericite and epidote) plagioclase phenocryst in chloritized basalt groundmass, with quartz- and epidote-filled amygdale (right-hand side), from Doting Cove, viewed under plane-polarized light; F) Trachytic textured basalt containing irregular-shaped chlorite amygdales, viewed under plane-polarized light. Chl–chlorite, Ep–epidote, Fe-OH–iron (oxy)hydroxide phases, Pl–plagioclase, Qtz–quartz, Ser–sericite.*

interstitial chlorite with minor epidote and titanite (Plate 4A, B). Petrographic analysis of a basaltic bomb in the overlying strata (Sample 23AM267A2 on Figure 4B) shows similar mineralogy to the underlying flow, but with more pervasive chloritization. The succeeding flows in the Stone Cove area (flows 2 and 3, Figure 4B) preserve primary clinopyroxene and exhibit subophitic texture with 200–500 µm plagioclase laths partially encased in clinopyroxene (Plates 4C, D). Clinopyroxene crystals range up to 2 mm, based on optical continuity. Flows 4 and 5 (Figure 4B) are aphanitic to glassy and contain more abundant titanite than flows lower in the section. Minor subhedral, high

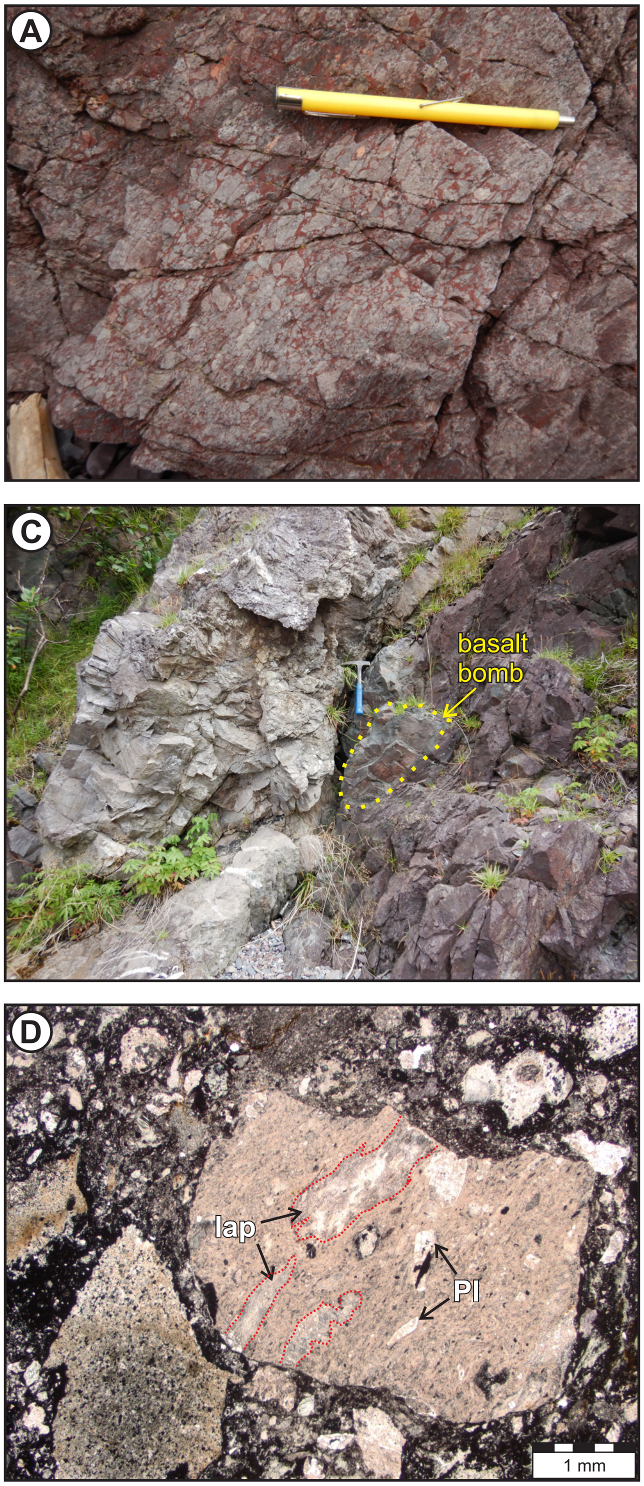

Plate 2. *Volcanic rocks from the Woody Head to Hare Harbour area. A) Basaltic breccia with brick-red matrix at Woody Head; B) Subrounded basalt boulders in monomictic boulder conglomerate overlying amygdaloidal basalt at Long Cove; amygdales have coalesced to mimic flow layering; C) Fusiform basalt bomb in red-weathering volcanic breccia at Long Cove; D) Plagioclase crystals and flattened lapilli in a subangular welded tuff fragment floating in a glassy (black) matrix. lap–lapilli, Pl–plagioclase*

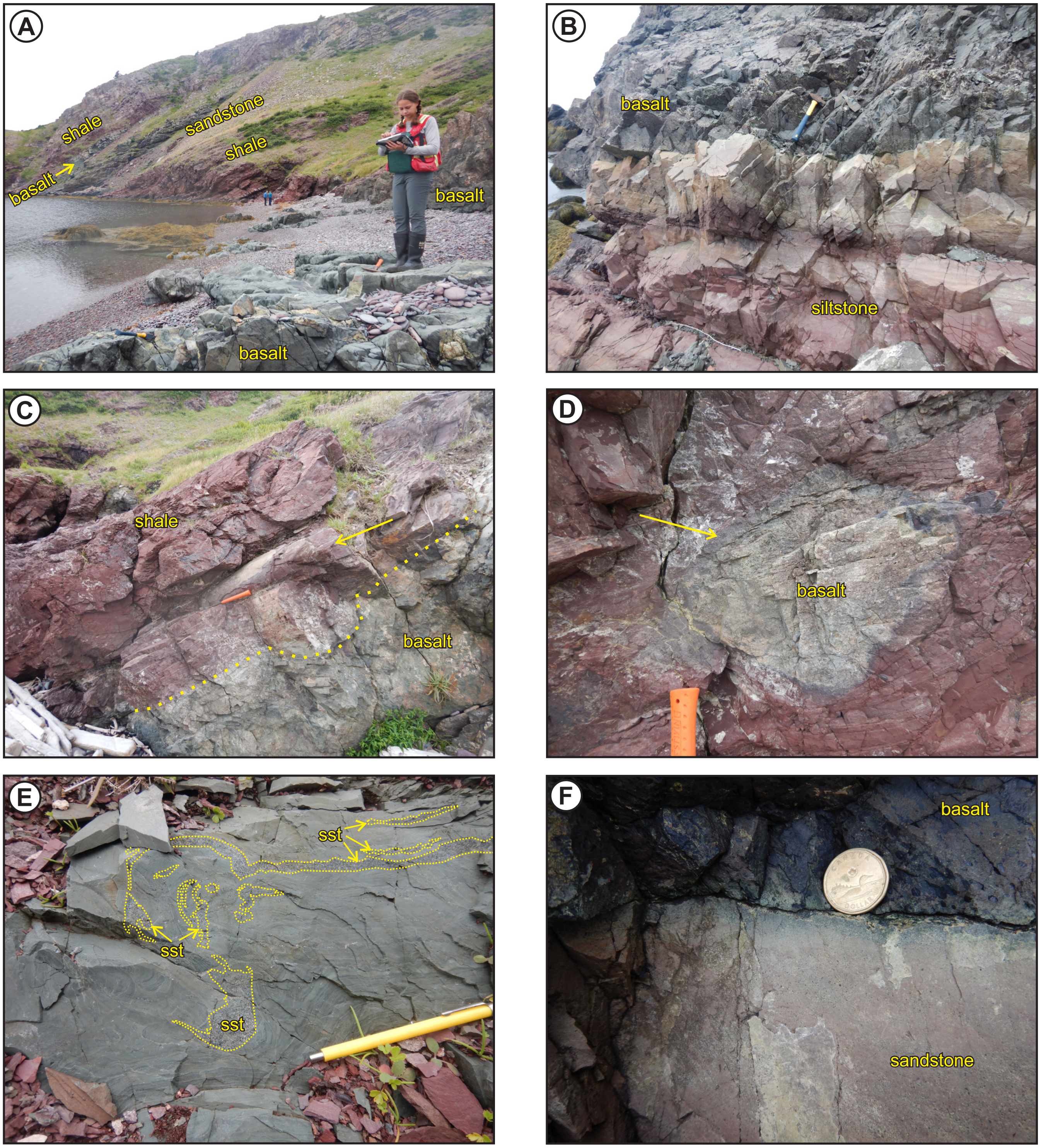

Plate 3. *Field photographs from the Stone Cove area. A, B) Interbedded basalt, shale and sandstone; views to the southwest; C) Synsedimentary fold in red shale above a basalt flow; yellow arrow points to fold and indicates direction of plunge; D) Chill margin on a basalt bomb within red shale; E) Distinctive grey unit (mid-Stone Cove-sequence) comprising very coarse-grained sandstone laminae and lenses within convolute laminated mudstone; F) Baked top of sandstone bed beneath a basalt flow.*

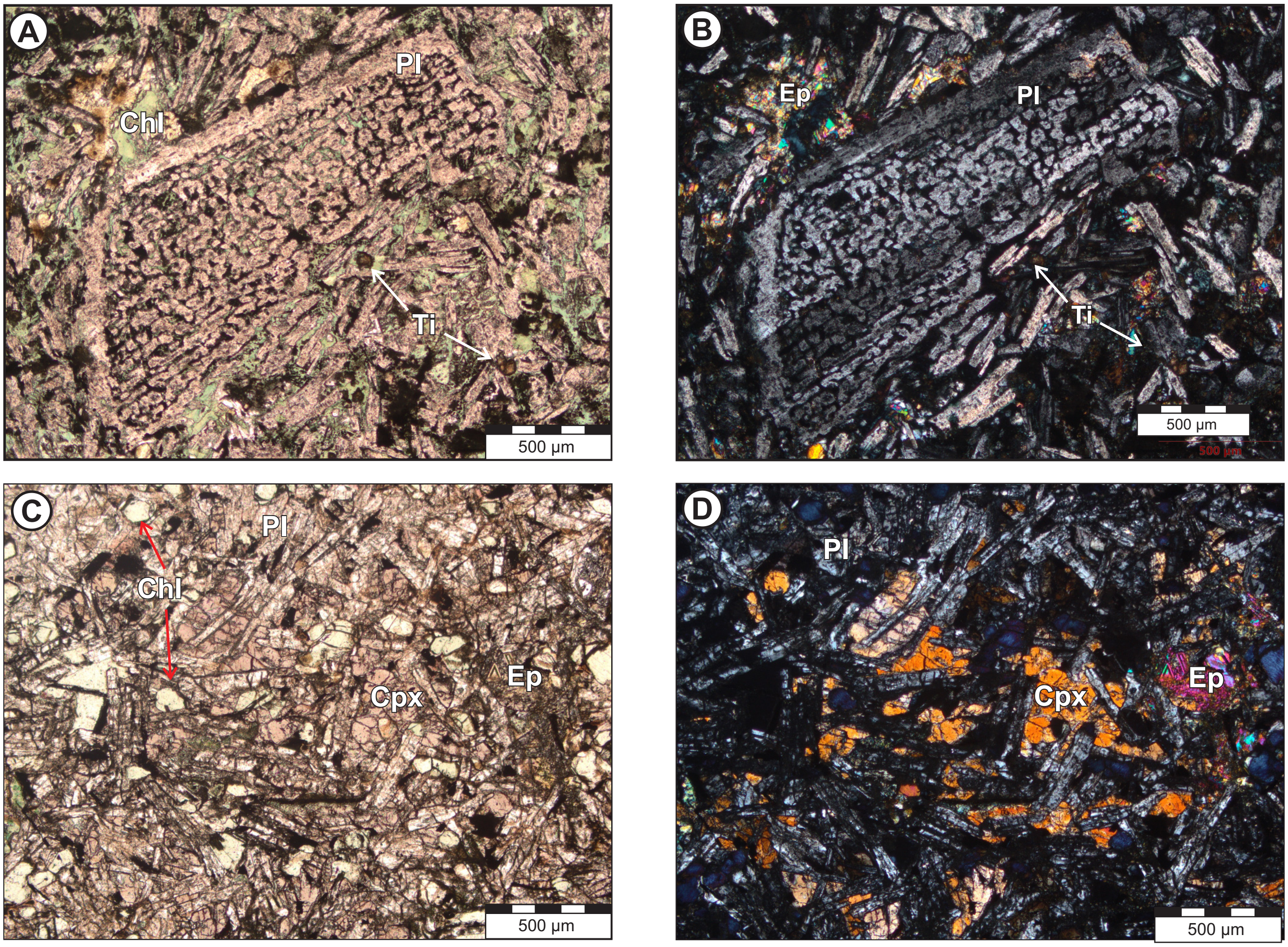

Plate 4. *Photomicrographs from the Stone Cove area. A, B) Honeycomb-textured plagioclase core with a brighter, slightly sieve-textured rim, under plane-polarized and cross-polarized light, respectively (sample 23AM267A1, from flow #1 near the base of the Stone Cove section on Figure 4); C, D) Intergrown clinopyroxene and plagioclase (subophitic texture) in basalt from the Rencontre Formation, middle of the Stone Cove section (sample 23AM268A1, from flow #2 on Figure 4), under plane-polarized and cross-polarized light, respectively. Chl–chlorite, Cpx–clinopyroxene, Ep–epidote, Pl–plagioclase, Ti–titanite.*

relief, 400–600 µm long grains, comprising chlorite cores and rims of ultra-fine-grained iron oxides (and/or hydroxides) may be pseudomorphs after olivine. The lower part of flow 6 is mineralogically and texturally similar to flows 4 and 5, whereas the upper part contains subophitic clinopyroxene and plagioclase and resembles flows 2 and 3. It is unclear if the upper part is faulted against the lower part or if one part is a sill rather than a flow, but either of these two cases would explain these differences and is therefore considered likely.

LITHOGEOCHEMISTRY

Previous work has demonstrated that even apparently unaltered volcanic rocks of the Avalon Zone in Newfoundland have been variably affected by weak to modest alteration and/or metamorphism, resulting in local modification of certain mobile major and trace elements (Hughes, 1973; Mills and Sandeman, 2015, 2021; Mills and Álvaro, 2023). Volcanic rocks of the Long Harbour Group are therefore evaluated and interpreted primarily on their trace-element compositions, as these elements remain relatively immobile during alteration and metamorphism (Pearce and Cann, 1973; Floyd and Winchester, 1975; Middleburg *et al.*, 1988).

In terms of TAS (total alkalis *vs.* silica) classification, the rocks from the Rencontre East area range from picrobasalt, through to rhyolite (Figure 5A). The bimodality of the samples is far more apparent in their trace-element rock-type classification. Only two basalts are alkaline (Figure 5B).

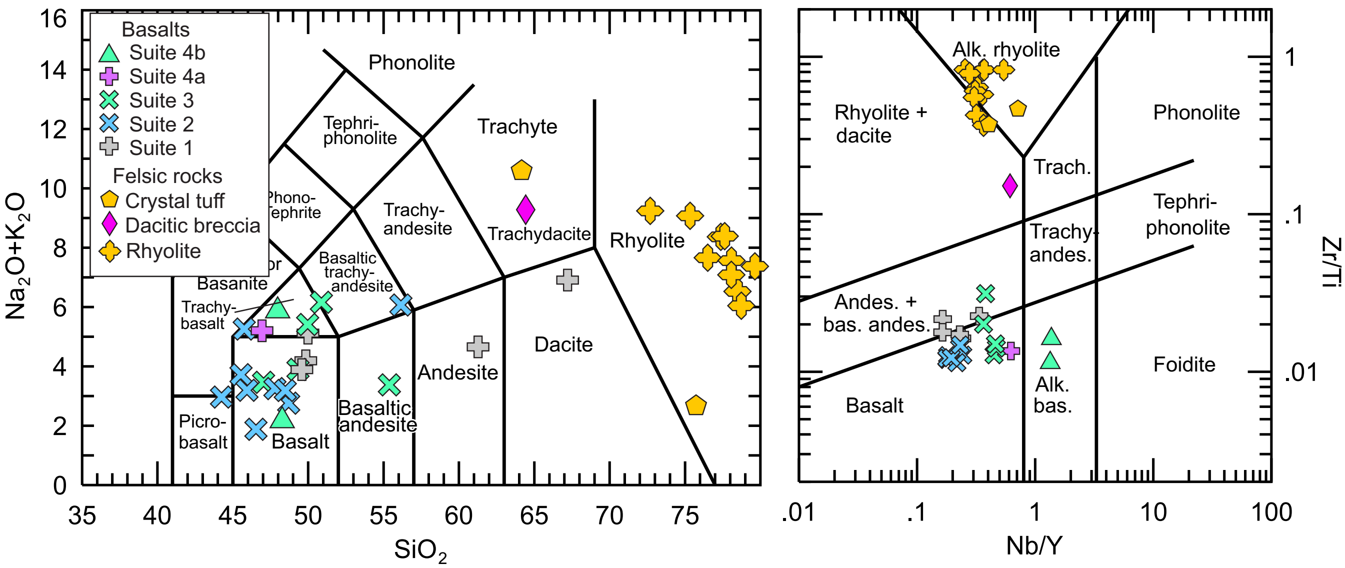

Figure 5. *Rock classification diagrams. A) Total alkalis* vs. *silica diagram (LeBas* et al.*, 1986); B) Zr/Ti* vs. *Nb/Y diagram (Pearce, 1996).*

MAFIC VOLCANIC ROCKS

Basaltic rock samples from the Long Harbour Group are divided into four petrochemical suites based primarily, and objectively, on their multi-element signatures. Suite 1 includes flows, volcanic bombs and mafic breccias from the Mooring Cove Formation, and with the exception of rhyolite from the Belle Bay Formation, are the lowest stratigraphic levels sampled in this study. They have low average MgO, Mg#, Ni, Co and V and the highest SiO_2 and Zr of the four petrochemical groups (Figure 6 and Table 1). These rocks also have negative multi-element slopes, modest P and Ti troughs, and prominent negative Nb anomalies (Figure 6), as quantified by their high $(La/Nb)_{PM}$ and $(Th/Nb)_{PM}$ ratios (Table 1).

Suite 2 includes mainly basalt flows and one basaltic bomb from the Hare Harbour and Stone Cove areas (Figure 2). In the Stone Cove area, these rocks occur above the base of the Rencontre Formation (Figure 4B). In the Long Cove area, they occur as bombs and flows among pyroclastic rocks and breccias of the Mooring Cove Formation. Suite 2 rocks have the lowest Zr, La, Th, Nb and ΣREEs of the Long Harbour Group basalts (Figures 6 and 7; Table 1). Their multi-element patterns are flatter than those of suite 1 and their low Th values lend a distinctive shape to their multi-element patterns (Figure 7). They also lack the small troughs in P and Ti exhibited by suite 1 basalts.

Suite 3 rocks comprise three of the basalt flows from the Stone Cove area (Figure 4B), one amygdaloidal flow from the Rencontre Formation at Long Cove and one plagioclase porphyritic flow from the upper Mooring Cove Formation near Doting Cove (Figure 2). This suite is chemically similar to suite 2 but contains lower Mg#, Ni, Cr, V, and Co and higher SiO_2, Zr and Th (Figures 6 and 7; Table 1). They have slightly higher light-rare-earth-element (LREE) contents than suite 2 does, as expressed by their higher $(La/Yb)_{PM}$ and $(La/Sm)_{PM}$ ratios and they have more variable Th and Nb contents relative to suite 2 (Figure 7). One sample from suite 3 exhibits small negative P and Ti anomalies similar to those displayed by suite 1 rocks (Figure 7).

Suite 4 basalts include one flow from the upper Mooring Cove Formation and one flow from the lower Rencontre Formation in the Rencontre East area (Figure 2). The first of these was from a cliff exposed among the heavily vegetated hills near the town of Rencontre East. A third suite 4 basalt is a flow from the Rencontre Formation near Hare Harbour (Figure 2). Despite the small number of samples in this suite and their similar multi-element patterns (Figure 7), it is subdivided into two sub-suites. The sole sample comprising suite 4a is the Hare Harbour sample, which has higher Mg#, Cr, Ni, V and Co and lower SiO_2, Zr and Th than the two basalts from the Rencontre area (Figures 2 and 6; Table 1). The lower $(La/Yb)_{PM}$ and $(La/Sm)_{PM}$ ratios of the Hare Harbour sample provide a quantifiable measure of its flatter multi-element pattern (Figure 7; Table 1).

PETROGRAPHIC CHARACTERISTICS OF THE LITHOGEOCHEMICAL SUITES

Some petrographic features are common to the geochemical suites and help to characterize them petrochemically. Suite 1 basalts are commonly amygdaloidal, with

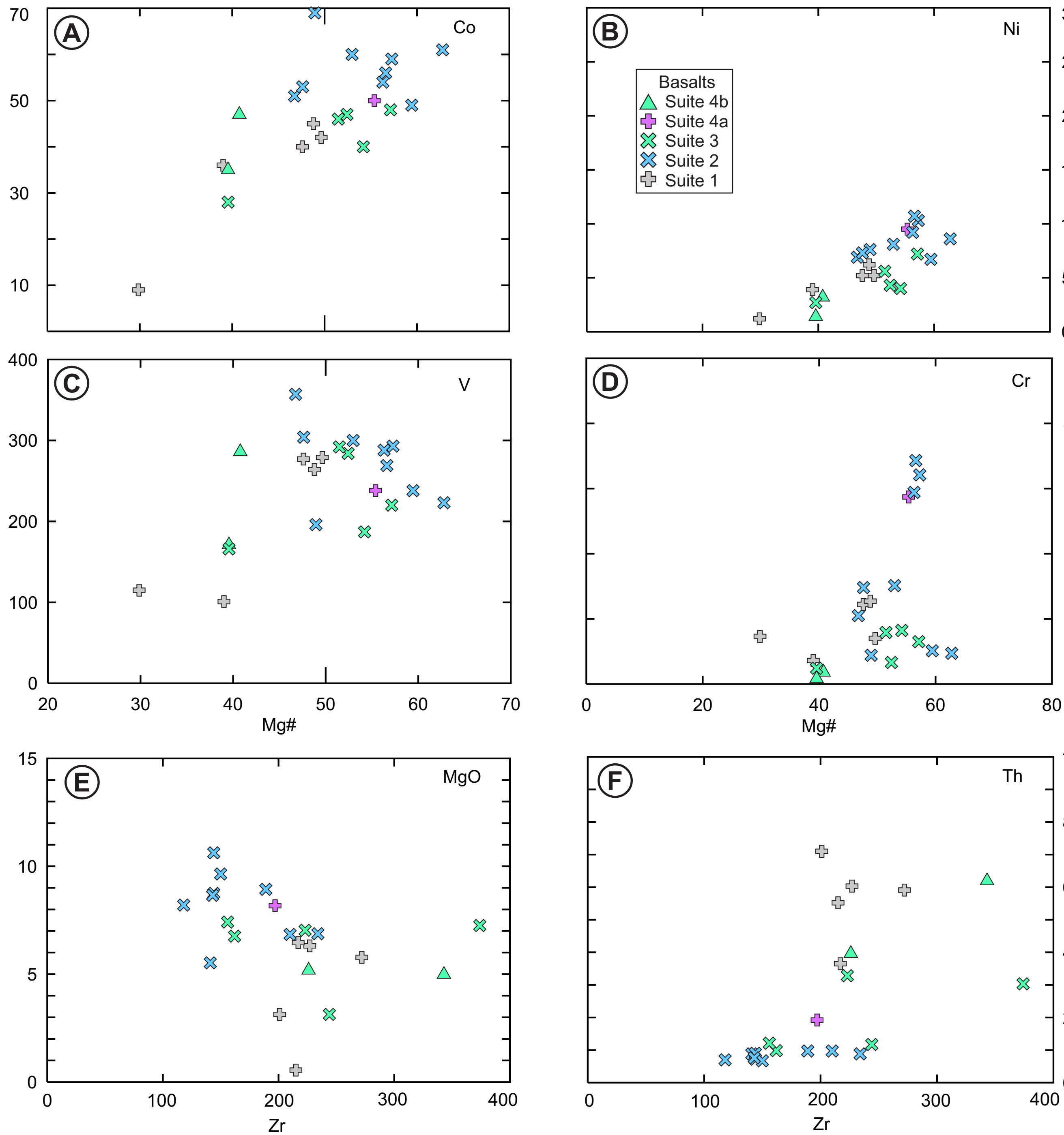

Figure 6. *Selected element-element diagrams for mafic rocks from the study area. Coloured arrows in G and I highlight Fe and Ti enrichment trends displayed by petrochemical suites 1 through 3.*

quartz and epidote infilling the amygdales. Plagioclase phenocrysts with honeycomb-textured cores, and sieve-textured rims and smaller laths, indicative of a complex petrogenetic history, were observed only within this petrochemical suite. Rare silicic welded tuff fragments were discovered in one suite 1 sample (basaltic breccia from the Long Cove area). Suite 2 basalts are characterized by subophitic clinopyroxene – plagioclase intergrowth textures. Alteration of plagioclase is weaker than in suite 1 basalts, and saussurite and chlorite are the main alteration phases. Suite 3 basalts typically have a glassy groundmass, which is variably chloritized and plagioclase phenocrysts appear patchily altered by

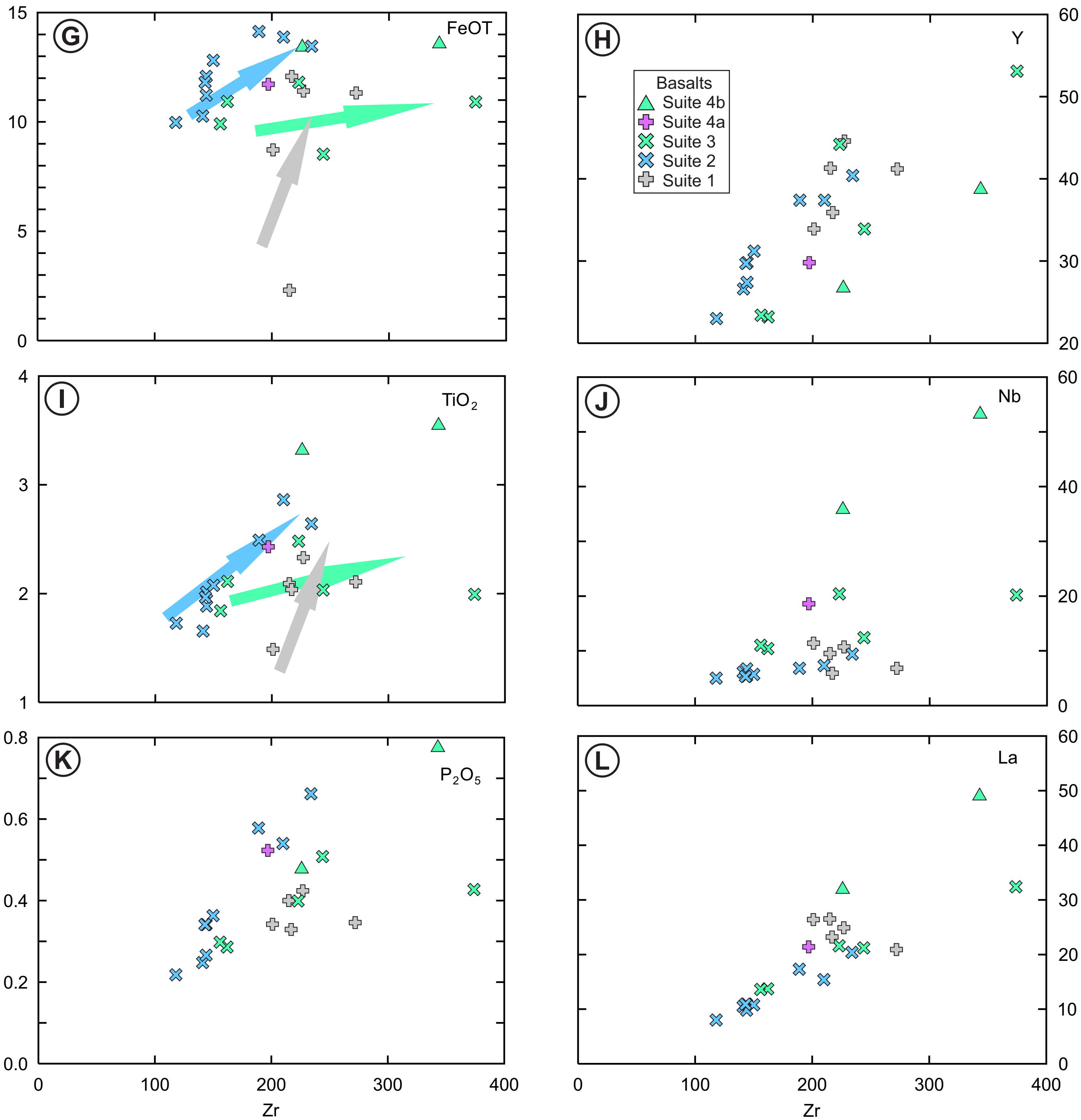

Figure 6. *Continued.*

saussurite and epidote in most of these samples. Suite 4 basalts either exhibit a well-developed trachytic flow texture or they contain untwinned, unzoned, fractured and minimally saussurite-altered plagioclase phenocrysts in a variably chloritized groundmass. Titanite and iron oxide phases are most abundant in basalts of suites 3 and 4.

SILICIC VOLCANIC AND PYROCLASTIC ROCKS

Three samples from the study area are felsic to intermediate in composition, and these are combined with nine rhyolites and a crystal tuff previously collected from the Belle Bay Formation (Sparkes and Sandeman, 2015). The pyroclastic rocks from the Woody Head area have a chemical

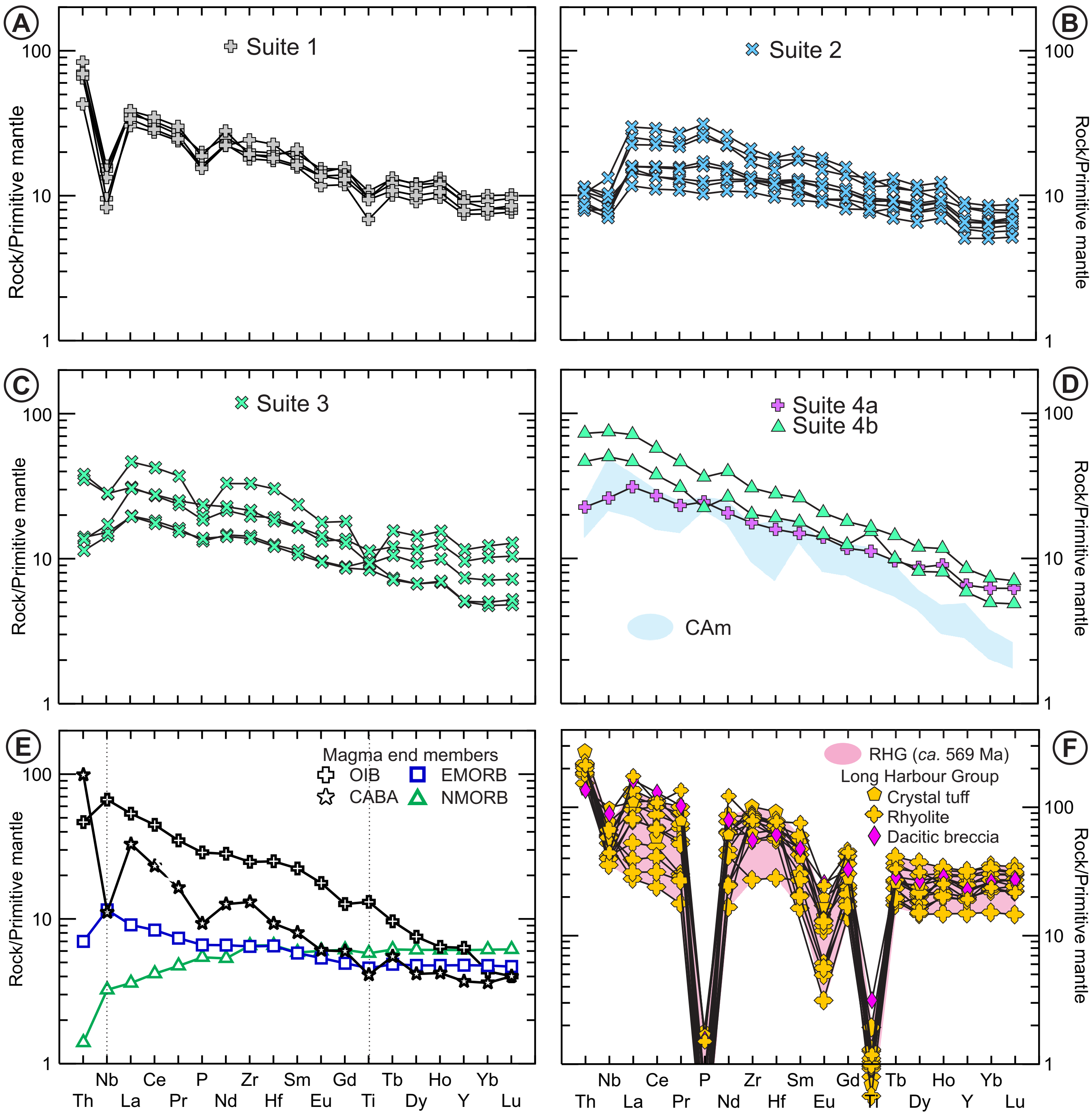

Figure 7. *Primitive mantle-normalized multi-element plots for rock samples from the Rencontre area. A–D) Petrogenetic mafic rock suites 1–4 from the study area. CAm–basalts of the Cambrian Chapel Arm member on western Avalon Peninsula (from Mills and Álvaro, 2023); E) Representative multi-element patterns for source end members. CABA–calc-alkaline basaltic andesite (CA 172; Guiseppe* et al., *2018); EMORB, NMORB, and OIB–enriched and normal mid-ocean ridge basalt, and ocean-island basalt, respectively (Sun and McDonough, 1989); F) Silicic rocks from the Rencontre area; including ten previously published analyses from the Long Harbour Group (Sparkes and Sandeman, 2015), and pink field for the* ca. *569 Ma Rocky Harbour Group from the northwestern Avalon Zone (Mills* et al., *2021).*

composition of trachydacite to rhyolite (Figure 5A) or dacite to alkali rhyolite (Figure 5B), respectively. The flow-banded rhyolites of the Belle Bay Formation contain elevated REE and other high valence cations, show enriched and relatively flat multi-element patterns with deep P and Ti troughs, prominent Eu troughs and small negative Nb anomalies (Figure 7F). They are highly siliceous (>75% SiO_2), A-type, within-plate, alkali rhyolites (Figure 9).

INTERPRETATION

Suite 1 basalts are chemically characterized by their steep negative-sloped multi-element patterns, with notable negative Nb anomalies and small P and Ti troughs. One sample from this suite is a mafic breccia that contains rare fragments of felsic material, likely affecting its bulk composition. This mixed rock has the highest $(La/Yb)_{PM}$ and $(La/Sm)_{PM}$ ratios – 5.13 and 2.43 *vs.* averages of 3.91 and 1.81, respectively, for the remaining rocks of suite 1. The lower Mooring Cove Formation at Stone Cove contains plagioclase phenocrysts, with honeycomb-textured cores and dusty, sieve-textured rims. Some smaller plagioclase grains are also variably sieve-textured. These textures indicate a complex petrogenetic history, likely involving repeated magmatic pulses whereby antecrysts from an earlier magmatic pulse are incorporated into and re-equilibrated within subsequent magma batches. Such textures and morphologies in plagioclase phenocrysts are common in homogeneous volcanic rocks produced by the mixing of magmas (*e.g.*, Kawamoto, 1992). Suite 1 rocks also have elevated Th and LREE, consistent with a mantle source that has been modified by slab fluids (Pearce, 2008). They are similar to calc-alkaline basalts (*e.g.*, CABA in Figure 7E), but have gentler multi-element slopes, lower $(La/Yb)_{PM}$ ratios, and they lack the Zr-Hf troughs that typically characterize mature magmatic arc rocks (Figure 7A *vs.* 7E). These mineralogical and chemical characteristics indicate a complex magmatic history, with magma replenishment resulting in a mixed or transitional composition that is closer to the calc-alkaline end member within the volcanic arc basalt-to-MORB spectrum (Pearce, 1996).

Suite 2 and 3 basalts have similar multi-element patterns, with suite 3 having slightly higher LREE contents than suite 2, as reflected by the slightly elevated $(La/Yb)_{PM}$ and $(La/Sm)_{PM}$ ratios (Table 1). Suite 3 displays more variable Th and Nb contents, a feature common in continental tholeiitic basalts (*e.g.*, Dupuy and Dostal, 1984). Suite 3 samples fall entirely within the continental-basalt field of Cabanis and Lecolle (1989), whereas suite 2 samples straddle the calc-alkali basalt – continental-basalt fields (Figure 8A). Suite 2 rocks plot close to the NMORB field of Wood (1980), whereas suite 3 rocks fall closer to the EMORB field (Figure 8B), owing to their higher Th contents. Both suites cluster close to or just above the mantle array, indicating a small component of lithospheric input (Pearce, 2008), with suite 2 rocks clustering slightly closer to NMORB (Figure 8C, D). Suite 2 rocks have flatter multi-element patterns, contain higher Mg#'s, Ni, Cr, V and Co and lower SiO_2, Zr and Th than suite 3 rocks, reflecting derivation from a more primitive source. This is consistent with petrographic observations of abundant primary clinopyroxene in suite 2 rocks (Plate 4C, D). The higher Zr content of suite 3 is particularly evident in Zr/Y *vs.* Zr space, and it is notable here that all sub-alkaline basalts from the Long Harbour Group plot in Pearce and Norry's (1979) 'within plate' field (Figure 8E). TiO_2/Yb ratios function as a proxy for depth of melting (Pearce, 2008; Pearce *et al.*, 2021) and the spread of suite 3 rocks reflects variable source depths, whereas suite 2 rocks all originated from a similar source depth (Figure 8D, F). In Th/Nb *vs.* TiO_2/Yb space (Figure 7F), suite 2 rocks cluster within the transitional field, whereas suite 3 rocks range from MORB + OPB (ocean plateau basalts) through the transitional field, to OIB + OPB, reflecting the wide range of melting depths for the latter suite (Pearce *et al.*, 2021).

The Hare Harbour basalt is similar to the alkali basalts near Rencontre East in terms of its smooth multi-element pattern (Figure 7), although it has a shallower slope ($(La/Yb)_{PM}$ of 5.00 *vs.* 9.56, and $(Gd/Yb)_{PM}$ of 1.89 *vs.* 2.48, respectively) (Table 1). Unlike the alkali basalts, the Hare Harbour basalt plots just outside the field for alkali basalts (Pearce, 1996; Figure 5B). In most discrimination diagrams, the Hare Harbour basalt falls between suite 3 and the alkali basalts, indicating a chemical affinity transitional between EMORB-like and OIB-like (or WPB and MORB of Pearce, 1996; Figure 8A-F). This rock has a considerably higher Mg#, Ni and Cr, and slightly lower SiO_2, Zr, Th and Nb than the alkali basalts, indicating its source is more primitive. The Ti–Yb proxy for melting depth (Pearce, 2008) indicates that the alkali basalt source is deeper than the source for the Hare Harbour basalt (Figure 8D, F). Therefore, the Hare Harbour basalt originated from a more primitive but shallower source relative to the alkali basalts.

Silicic rock samples from the Long Harbour Group are A-type, within-plate, alkaline volcanic rocks (Figure 9A, B). These chemical characteristics are consistent with emplacement into a tensional setting, either post-orogenic or in a continental-rift zone (Eby, 1990). Silicic rocks of the Long Harbour Group overlap in compositional space with the *ca.* 569 Ma alkali rhyolites of the Rocky Harbour Group of the northwestern Avalon Zone (Figure 9), which are also interpreted to reflect A-type, within-plate, alkaline magmas emplaced into an extensional setting (Mills *et al.*, 2021).

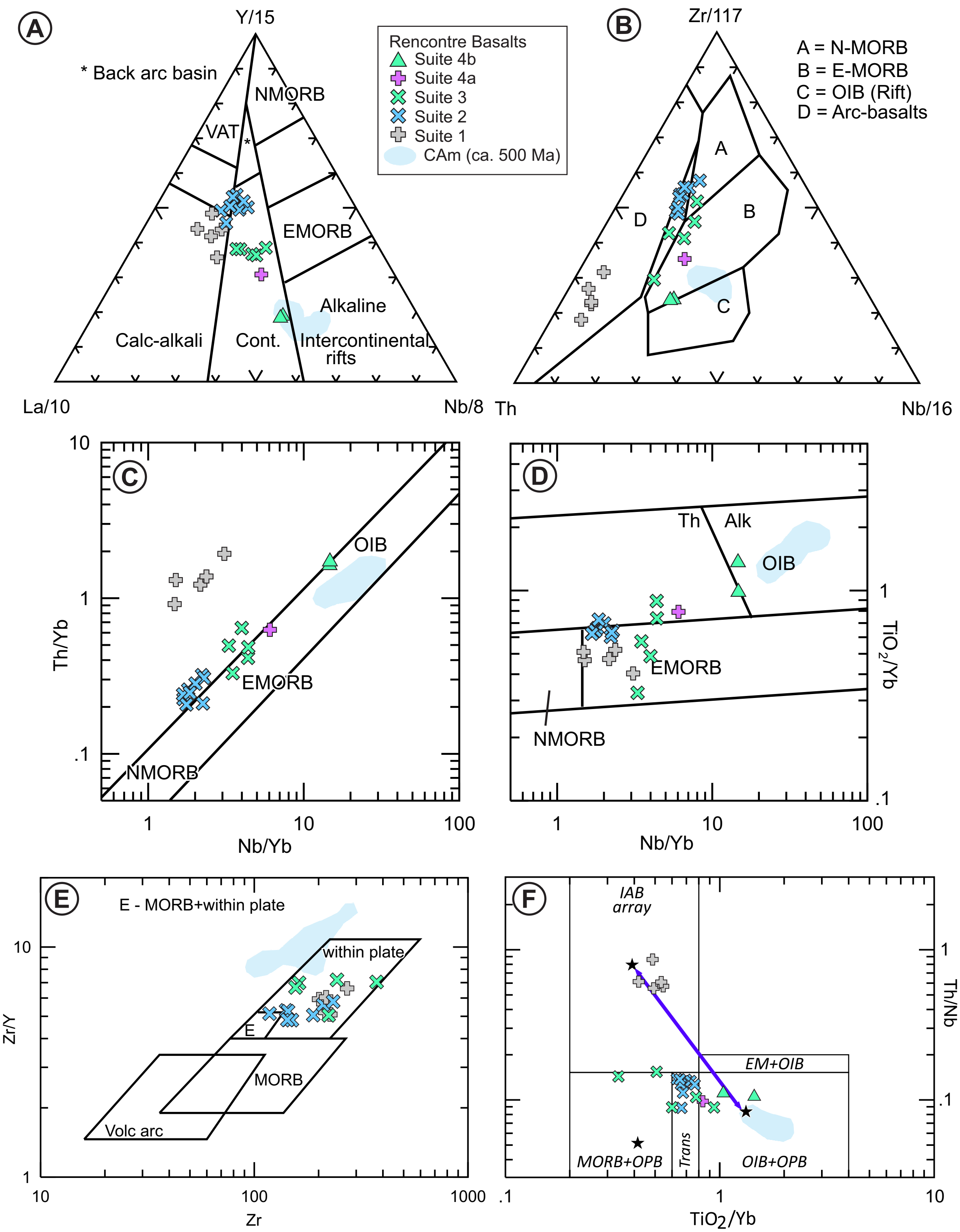

Figure 8. *Tectonic discrimination diagrams for mafic rocks from the study area. A) La/10–Y/15–Nb/8 (Cabanis and Lecolle, 1989); B) Th–Zr/117–Nb/16 (Wood, 1980); C, D) Th/Yb* vs. *Nb/Yb and TiO_2/Yb* vs. *Nb/Yb (Pearce, 2008); E) Zr/Y* vs. *Zr (Pearce and Norry, 1979); F) Th/Nb* vs. *TiO_2/Yb (Pearce* et al.*, 2021).*

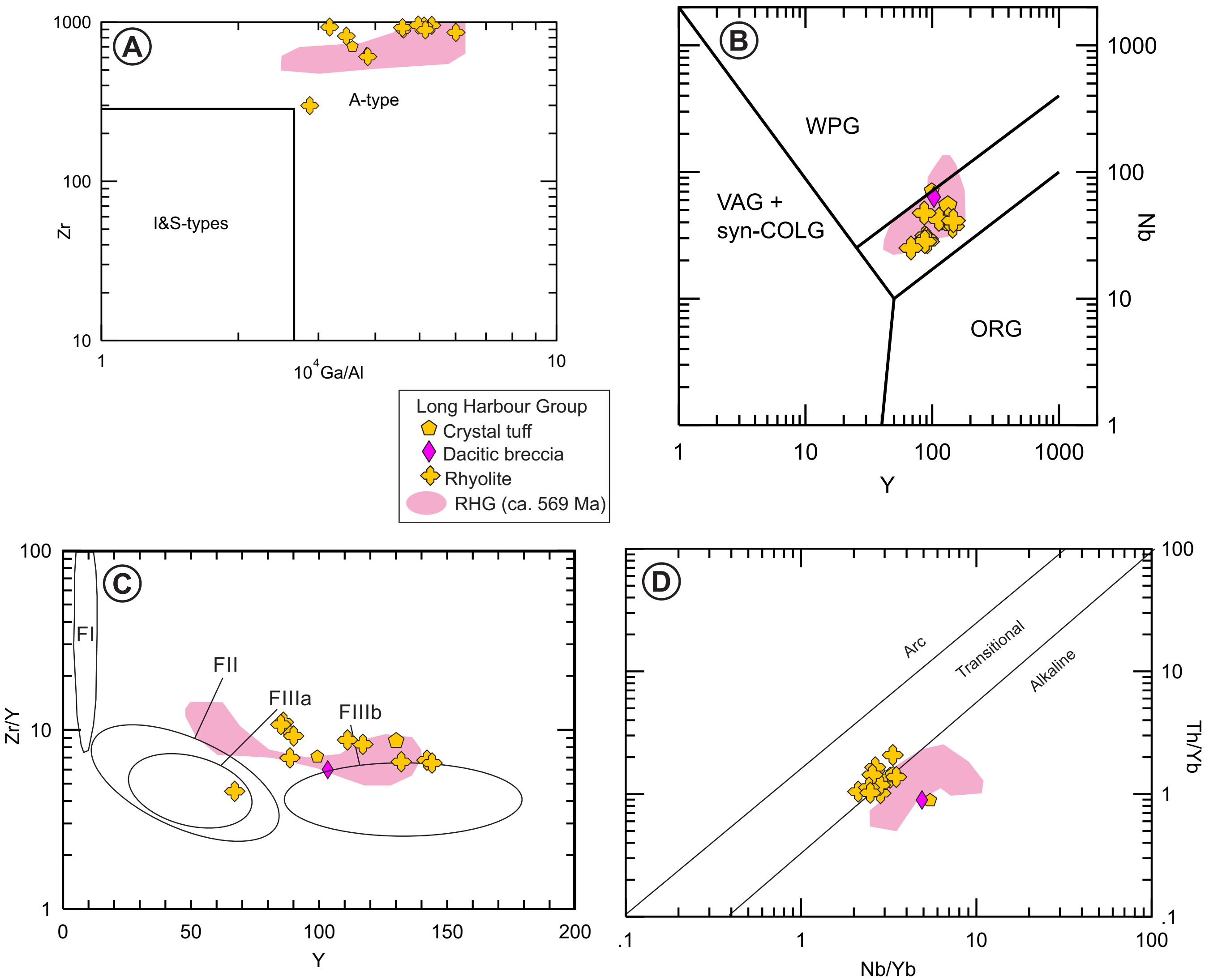

Figure 9. *Tectonic discrimination diagrams for silicic rocks from the study area. A) Zr* vs. *10^4 Ga/Al (Whalen* et al.*, 1987); B) Nb* vs. *Y (Pearce* et al.*, 1984); Zr/Y* vs. *Y (Lesher* et al.*, 1986); D) Th/Yb* vs. *Th/Yb (Pearce, 2008). Field for the* ca. *569 Ma Rocky Harbour Group (RHG;* see *Mills* et al.*, 2021) shown for comparison.*

DISCUSSION

The Long Harbour Group comprises voluminous bimodal volcanic rocks (Figure 5B), and this lack of intermediate compositions is consistent with an extensional tectonic setting (*e.g.*, Van Wagoner *et al.*, 2002). The oldest magmatic rocks from the study area are alkali rhyolites of the Belle Bay Formation (Figure 2). Their A-type, within-plate, alkaline affinity and multi-element patterns are similar to the *ca.* 569 Ma rhyolites of the Rocky Harbour Group in the northwestern Avalon Zone. Their shared chemical affinities and overlapping ages (within error) suggest that much of the western Avalon Zone of Newfoundland was under extension at that time.

The overlying (suite 1) basalts of the lower Mooring Cove Formation have considerable LREE enrichment, notable negative Nb anomalies, and are similar to calc-alkaline basalts (Figure 8A, B). However, their multi-element slopes are not as steep, and they lack the Zr–Hf troughs and depleted HREE contents that characterize most mature magmatic-arc basalts. Their Zr/Y ratios are similar to within-plate basalts, and to those of suites 2 and 3 (Figure 7E). Basalts of suites 2 and 3 are tholeiites, having gentler multi-element slopes, modest negative Nb anomalies, and lower Th contents relative to suite 1 rocks. They occur above suite 1 rocks in the Mooring Cove Formation at Long Cove and Doting Cove, but within the lower Rencontre Formation at Stone Cove. The LREE enrichment and elevated Zr/Y ratios of suites 1, 2 and 3 (Figure 8C, D), are consistent with a continental tholeiitic affinity (*see* Dupuy and Dostal, 1984,and Pe-Piper and Murphy, 1989). Suite 2 basalts originated from a source more primitive than that of suites 1 and 3, and at depths between the sources for suite 1 and suite 3 rocks. Suite 3 rocks, however, originated from a similar, more EMORB-like source, but at varying depths. Suite 4 basalts are alkaline (Figure 5B), OIB-like (Figure 8B–D), and originated from a deeper source (Figure 8D). These rocks are low-degree partial melts of a relatively deep source, likely associated with waning extensional tectonism.

The change from more arc-like (suite 1) to more NMORB- (suite 2) and EMORB-like (suite 3) transitional magmatism likely reflects, in part, a decreasing subduction zone input with time, as indicated by decreasing Th/Yb and Th/Nb ratios at higher stratigraphic levels. Suite 1 basalts occur at the lowest stratigraphic levels and have the highest Th/Yb (Figure 6C) and Th/Nb (Table 1) ratios, likely reflecting melting of an older arc-mantle infrastructure. At Stone Cove, suite 2 basalts occur above suite 1, interbedded with red conglomerates of the lower Rencontre Formation, and are succeeded by suite 3 basalts up-section. The presence of a suite 2 basalt at the top of the Stone Cove section may reflect that volcanism from the distinct sources of suite 2 and 3 overlapped in time. Both suites 2 and 3 are continental tholeiites derived from enriched, variably NMORB-like to EMORB-like, moderately deep sources. TiO_2/Yb values indicate a temporal progression from relatively shallow to deeper magmatic sources, likely reflecting an initially shallower melting zone due to asthenospheric upwelling resulting from crustal attenuation. Suite 4 rocks are the youngest of the volcanic rocks in the study area. These OIB-like, alkali basalts originated from partial melting of a relatively deep source. The overall temporal change reflects progressive deepening of the mantle source, resulting from late Ediacaran extension of an inherited lower Ediacaran volcanic arc. The low degree partial melting of a more deeply seated source, indicated by suite 4 alkali basalts, reflects the waning of this extensional pulse. Subsequent extension continued episodically, possibly evolving to rifting by Terreneuvian to Miaolingian times.

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