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WESTERN NEWFOUNDLAND: ALLOCHTHONS, OPHIOLITES AND OBDUCTION

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ABSTRACT

Research this past summer (2022) marked the initiation of a collaborative program between the Geological Survey of Canada, the Geological Survey of Newfoundland and Labrador, and multiple universities (led by Laval University). The program aims to upgrade the geoscientific knowledge of ophiolite complexes throughout Newfoundland, and stimulate mineral exploration. This project is supported by the Targeted Geoscience Initiative (TGI 6) of Natural Resources, Canada, the Geological Survey of Newfoundland and Labrador, and the Natural Science and Engineering Research Council. The objectives of the TGI initiative are to provide next-generation geological knowledge and innovative techniques to understand geological systems with a focus on critical minerals. Ophiolites are known to host many critical minerals such as chrome, PGE and cobalt (as well as base metals: copper, lead and zinc), which could provide a potential economic and stable source to transition to a greener economy. Newfoundland has world-class ophiolite complexes that are under-explored relative to the other global examples providing a perfect opportunity to refocus research.

This research upgrades our understanding of: a) Reactions between deep oceanic crust and seawater as Cu–Pb–Zn–Au–Co ore-forming environments, and as buffers of seawater and atmospheric chemistry; b) Interplays between fluid, magmatic, and mechanical/structural processes as rock-forming environments that can potentially revolutionize the understanding of oceanic crustal differentiation; c) How ophiolites accrete to continents to better constrain how the earliest stages of Appalachian orogenesis evolved. All three themes inform the mineral potential of the region.

This report provides the regional geological framework for these studies and a brief overview of proposed projects and researchers.

INTRODUCTION

The Laurentian continental margin preserved in western Newfoundland is part of the Humber (tectonostratigraphic) Zone (Figure 1, inset map; Williams, 1995). The Humber Zone is separated by the Long Range-Cabot Fault from the metamorphic equivalents of strata deposited on the hyperextended Laurentian margin, as well as microcontinents preserved within the Notre Dame and Dashwoods subzones (Waldron and van Staal, 2001; van Staal and Barr, 2012; van Staal and Zagorevski, 2022; van Staal and Dewey 2023). The composite fragments of the Notre Dame and Dashwoods subzones were accreted to the margin and deformed during three major orogenic episodes: the Taconic, Salinic, and Acadian (Williams, 1995; Hatcher, 2010). In Newfoundland, the western Appalachian fold belt largely escaped the penetrative effects of the younger Alleghenian orogeny (*i.e.*, the collision of Gondwana into the southern Appalachian belt) that resulted in brittle faulting of the Carboniferous basins (Williams, 1995; Murphy and Keppie, 2008; van Staal and Barr, 2012; Hinchey *et al.*, 2022).

In western Newfoundland, the Taconic orogeny had a long history beginning in the Cambrian (Furongian) with arc-continent collision that culminated in the obduction of allochthons by the Middle Ordovician (van Staal, 2007; van Staal and Zagorevski, 2022; van Staal and Dewey, 2023). The Taconic allochthons are composed of ophiolite complexes and sedimentary–volcanic nappes that collided with, and were obducted across, the Laurentian continental margin above an east-directed subduction zone (van Staal and Zagorevski, 2022 and references therein). The basal thrust of the obducted arc-ophiolites is the collision–obduction surface thought to be preserved at the base of the Coastal

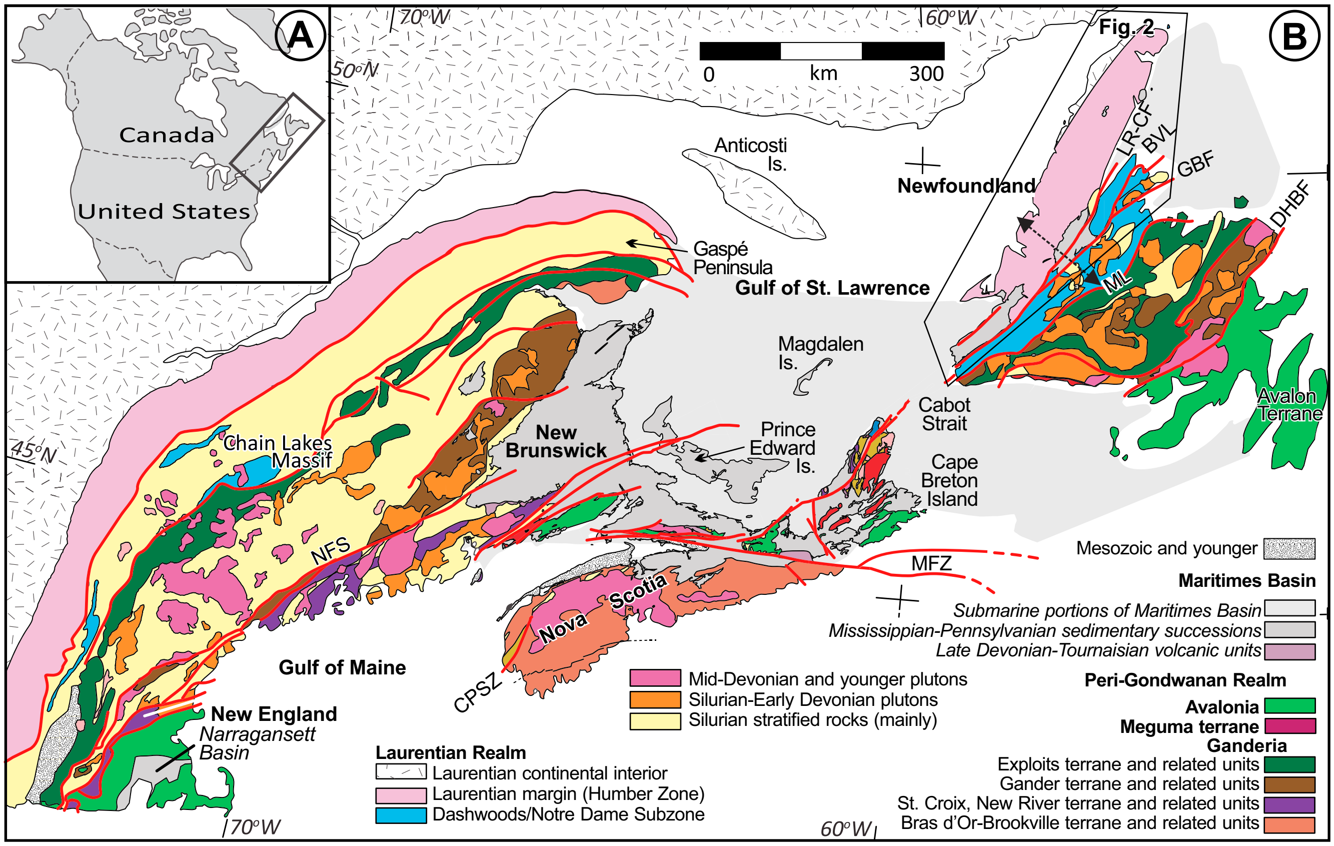

Figure 1. *A) Location of the northern Appalachian orogen within North America; B) Map showing the present-day distribution of terranes (zones), major rock units and major fault traces (red) in the northern Appalachian orogen (modified from Waldron* et al.*, 2015). Fault and other abbreviations (plain text): BVL=Baie Verte Line; LR-CF=Long Range-CabotFault; CPSZ=Chebogue Point shear zone; DHBF=Dover-Hermitage Bay Fault; GBF=Green Bay Fault; ML=Mekwe'jit Line (formerly Red Indian Line); MFZ=Minas Fault Zone; NFS=Norumbega fault system.*

Complex (CC) and the adjacent four ophiolites of the Bay of Islands Complex (BOIC: Table Mountain, North Arm Mountain, Blow Me Down, and Lewis Hills; Dewey and Casey; 2021 and references therein). Subsequent development of west-dipping subduction along the margin of Laurentia is preserved in the rocks of the Annieopsquotch accretionary tract (Williams, 1995; Zagorevski *et al.*, 2007; van Staal *et al.*, 2013). The middle to late Silurian Salinic orogeny was largely driven by the accretion of peri-Gondwanian terranes (Ganderia) to the Laurentian margin (van Staal *et al.*, 2009; Willner *et al.*, 2018). The accretion of the West Avalonia and Meguma terranes to the Laurentian margin led to the Early Devonian Acadian and Early to Late Devonian Neoacadian orogenies, respectively (van Staal and Barr, 2012; van Staal *et al.*, 2021). Carboniferous sedimentary rocks of the Bay St. George, Deer Lake and White Bay basins were both syndepositional with, and deformed by, repeated Alleghenian wrench movements along the Long Range-Cabot Fault system (Hyde, 1995; Dafoe *et al.*, 2016; Snyder and Waldron, 2021; Hinchey *et al.*, 2022).

REGIONAL GEOLOGY

THE EXTERNAL HUMBER ZONE

The focus here is on the unmetamorphosed to weakly metamorphosed western Humber Zone (the external Humber Zone) and the adjoining Appalachian foreland. The region includes six main geological divisions (Figures 2 to 4).

Basement Rocks

The Long Range Inlier of western Newfoundland is one of the largest exposures of Mesoproterozoic crystalline basement rocks within the Appalachian Orogen (Heaman *et al.*, 2002; Hinchey, 2010). It is not a simple stratigraphic inlier, but rather represents a massif of Grenvillian crust reactivated during the Appalachian Orogeny (Owen, 1991). The Long Range Inlier forms a structural culmination bounded to the north, south and locally to the east, by Proterozoic to Paleozoic cover rocks. The western boundary

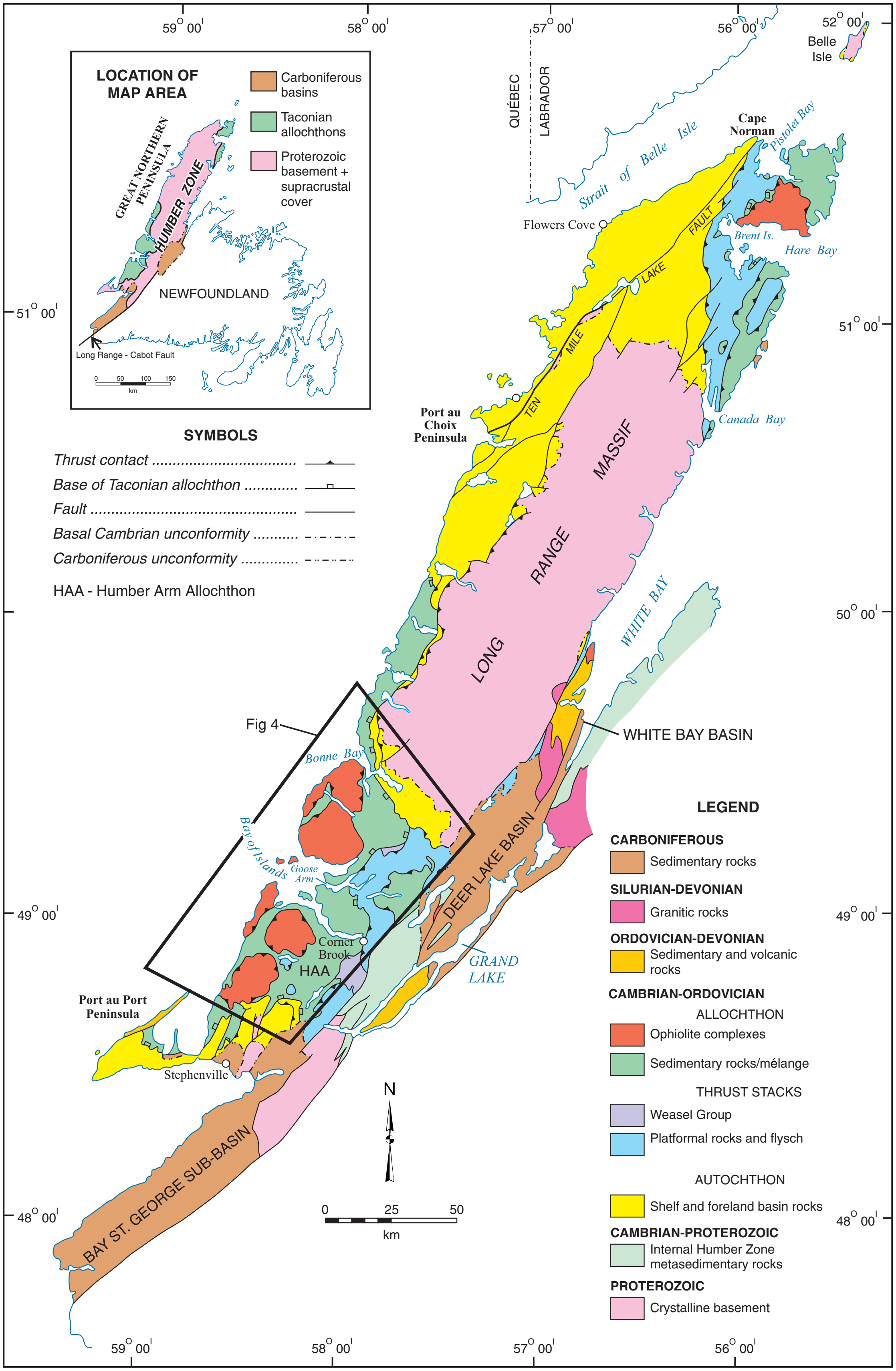

Figure 2. *Simplified geology of western Newfoundland (modified after Hinchey* et al.*, 2022).*

is marked by a southeast-dipping thrust fault (the Long Range frontal thrust) that placed Proterozoic crystalline rocks onto autochthonous Cambro-Ordovician platformal strata and Taconic allochthonous rocks (Owen, 1991; Hinchey and Knight, 2011a, b; Hinchey, 2020). Paleozoic deformation of the inlier is marked by low-grade metamorphism and tectonic overprinting along the Doucers Valley fault and emplacement of post-deformational intrusions *e.g.*, Devils Room granite and Taylor Brook gabbro (Owen, 1991; Hinchey, 2010).

Rift Rocks

The continental margin of Laurentia formed with the opening of the Iapetus Ocean between *ca.* 615 and 520 Ma (Kamo *et al.*, 1989; Waldron and van Staal, 2001; Robert *et al.*, 2021). Volcanic rocks and thick successions of sandstone, shale and conglomerate were deposited in narrow rift-valley basins and oceanic seaways (*e.g.*, the Taconic Seaway of van Staal and Barr, 2012) along the hyperextended margin of Laurentia. The abrupt facies and thickness variations at steeply dipping basement-involved faults are indicative of deposition on an uneven horst–graben topography (Williams and Hiscott, 1987). Thick rift successions of sandstone, shale and conglomerate (now deformed parts of the two Taconic allochthons) are discussed below, but autochthonous, late Neoproterozoic rift rocks, belonging to the lower part of the Labrador Group (Bostock *et al.*, 1983), are also confined to small areas on the Northern Peninsular. Coarse conglomeratic units of the Precambrian Bateau Formation (Labrador Group) contain boulders of basement gneiss near the base, with finer conglomerate and sandstone at higher structural levels. The Bateau Formation is overlain by the mafic volcanic units of the Lighthouse Cove Formation, in turn, overlain by red arkosic sandstone and conglomerate of the Bradore Formation that extend laterally onto the autochthonous basement. The Bradore Formation contains the lowest Olenellus Zone faunas supporting a Cambrian Series 2 (~515 Ma) age and these formations were deposited in a relatively shallow, nearshore marine environment (Williams and Hiscott, 1987).

Sedimentary Rocks of the Lower Paleozoic Continental Shelf

Sedimentary rocks of the lower Paleozoic continental shelf include shale, sandstone, limestone and dolostone deposited in shallow, continental shelf seas that stretched for over 400 km from southwest to northeast (Knight 1997). The shelf deposits which are about 1.5 km thick, were deposited from *ca.* 520 to 468 Ma, a period spanning much of the Cambrian and the Early Ordovician. Only the inner to middle shelf sequence is preserved in western Newfoundland; the outer shelf and the shelf margin were destroyed or deeply buried during Appalachian orogenesis. Contemporaneous lower Paleozoic sedimentary rocks, deposited on the shelf slope and deep-sea floor are preserved in the Taconic allochthons of western Newfoundland. They host, in the conglomerates, eroded blocks of the coeval ancient continental shelf margin that allow its paleo-reconstruction (James, 1981; James and Stevens, 1986). The shelf succession is little deformed except southwest and northeast of Corner Brook, near Deer Lake, Gros Morne and from Canada Bay, north to Pistolet Bay on the North Peninsula. The Cow Head Group is complexly folded and faulted within the Humber Arm Taconic allochthon (Hinchey *et al.*, 2015; Lacombe *et al.*, 2019).

The shelf succession, in western Newfoundland, is divided into three groups: the Labrador, Port au Port and St. George (Figure 3). The early-shelf clastic rocks are the upper units of the Labrador Group and are overlain by the carbonate shelf succession preserved in the Port au Port and St. George groups. Lower to Middle Cambrian, Labrador Group, comprises limestone and shale of the Forteau Formation and shallow-marine quartzite of the Hawkes Bay Formation. These formations are the base of the passive margin and were deposited in the Cambrian, Series 2 from *ca.* 516 to 511 Ma (Williams and Hiscott, 1987). They are overlain by a succession of middle Cambrian to Lower Ordovician carbonate rocks of the Port au Port and St. George groups deposited from *ca.* 510 to 470 Ma (Chow and James, 1987; Knight and James, 1987). The latter two groups formed a carbonate platform of shallow-water limestone and dolostone deposited in a variety of settings (James, 1981). When the sea level was high, the shelf was dominated by fine-grained carbonate mud rich in organisms; extensive barrier complexes of carbonate sand and algal–sponge mounds dominated large tracts of the shelf at various times. When the sea level lowered, shallow marine and peritidal rocks were deposited cyclically on a shallow shelf in lagoons, tidal flats and islands. Microbial mounds and shoreline carbonate sand bodies were also common along the shallow shoreline.

The St. George Unconformity, which marks the top of the Early Ordovician St. George Group, is correlated with similar sequence boundaries throughout eastern Laurentia as far south as Texas *e.g.*, Beekmantown and Knox unconformities, and likely marks a global sealevel lowstand at *ca.* 469–464 Ma (Knight and James, 1987; Knight *et al.*, 1991). Evidence in western Newfoundland indicates that the shelf top was exposed as the sea fell below the shelf edge, and the earliest events of the Taconic orogeny affected the shelf with the passage of a peripheral forebulge. Consequently, it was extensively faulted and warped prior to, and contemporaneous with, the formation of the unconformity (Lane, 1990; Knight *et al.*, 1991; Baker and Knight, 1993). Significant

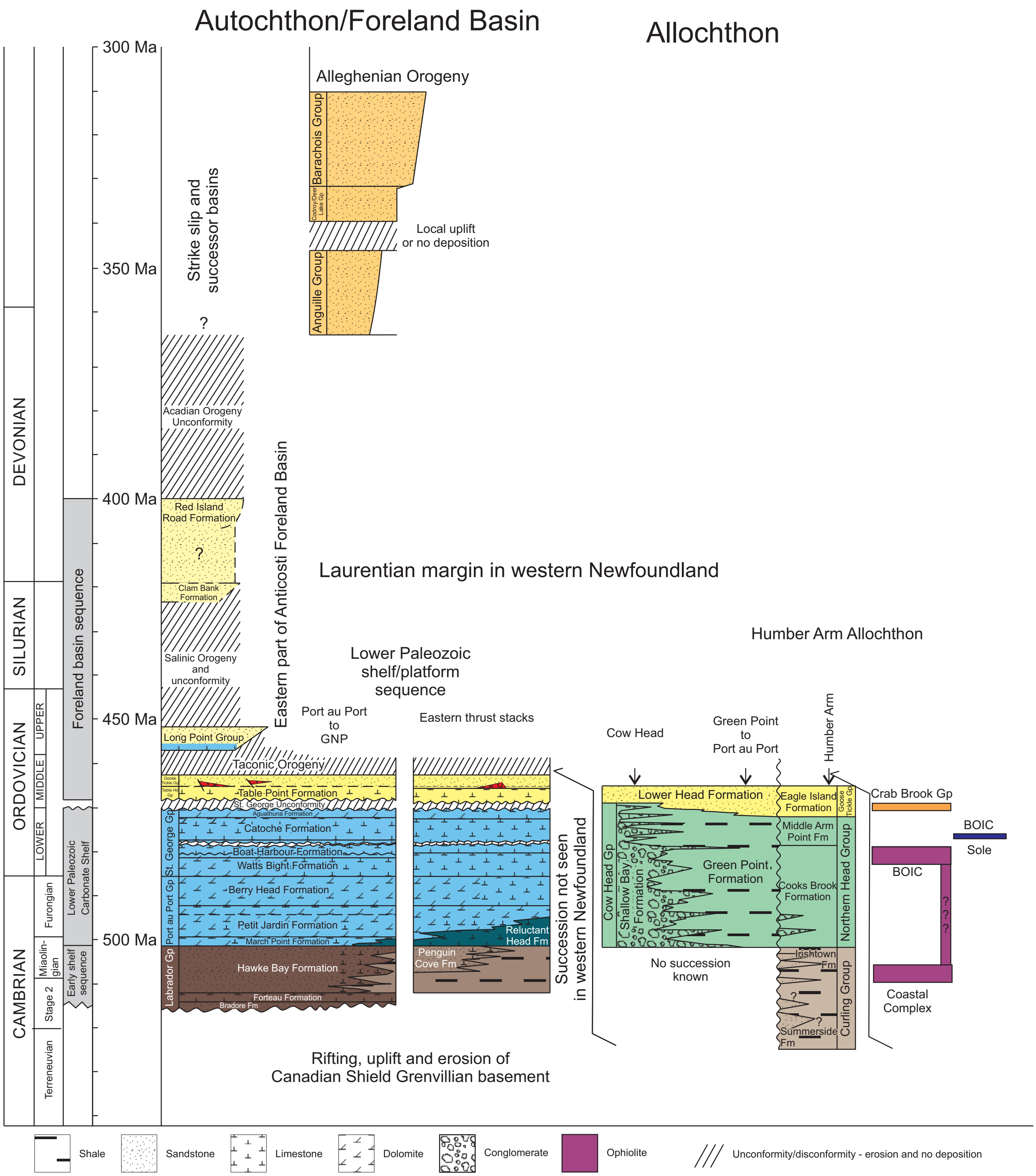

Figure 3. *Simplified stratigraphy of lower Paleozoic sequences in western Newfoundland (modified after Cooper* et al.*, 2001; van Staal and Barr, 2012; Hinchey* et al.*, 2015).*

relief developed on the exposed shelf due to local fault uplift and karst erosion that produced a hilly landscape; cave systems formed in the subsurface, particularly close to faults (*ibid.*). Evidence of this relief and the cave systems occurs on the Port au Port Peninsula, and near Port au Choix and Daniel's Harbour (Knight, 2007). Rock formations beneath the St. George Unconformity host reservoirs and are important to the hydrocarbon evolution of western Newfoundland; they include the Catoche and Aguathuna formations of the St. George Group (Baker and Knight, 1993; Cooper *et al.*, 2001). Sedimentary rocks deposited on the shelf slope and deep-sea floor (described below) are confined to the Taconic allochthons of western Newfoundland (Figures 2 and 3; James *et al.*, 1987).

Foreland Basin Rocks

The western Newfoundland foreland basin is the eastern part of the Anticosti Basin; the succession consists of limestone, shale, sandstone and conglomerate. Like its underlying shelf counterpart, the foreland basin occurs in both the autochthon and allochthon (Figure 3). The autochthonous part comprises several unconformity-bounded sequences that widely preserve Middle Ordovician (*ca.* 470 Ma) strata (Table Head Group and American Tickle Formation part of the Goose Tickle Group) throughout western Newfoundland (Klappa *et al.*, 1980; Stenzel *et al.*, 1990; Knight *et al.*, 1991). The Cape Cormorant Formation (base of the Table Head Group) is a limestone cobble-to-boulder conglomerate, with clasts derived from the underlying shelf succession. The formation was deposited into submarine fault scarps (Stenzel *et al.*, 1990) that developed because of extension during plate flexure and orogenic loading (Waldron *et al.*, 1993; White and Waldron, 2019). Overlying the Table Head Group is the Middle Ordovician Goose Tickle Group, a turbiditic siliciclastic unit that contains graded beds, Bouma sequences, and flute casts and grooves on basal surfaces, indicative of rapid and high-energy deposition by turbidity currents (Quinn, 1992).

Subsequent pulses of deposition, exposed only on the Port au Port Peninsula but easily correlated, seismically, westward into the offshore beneath the Gulf of St. Lawrence, occurred in the Late Ordovician (Long Point Group, *ca.* 455 Ma), and in the late Silurian (*ca.* 420 Ma, Clam Bank Formation) through to the late Early Devonian (Red Island Road Formation, *ca.* 400 Ma) indicating a prolonged evolution of the basin (Stockmal *et al.*, 1998; Cooper *et al.*, 2001; Quinn *et al.*, 2004; Lacombe *et al.*, 2020). Allochthonous rocks consist of Middle Ordovician clastic flysch and conglomerate of the Lower Head and Eagle Island formations, Goose Tickle Group, that conformably overlie rocks of the Laurentian slope sequences (Quinn, 1992). Based largely on the interpretation of offshore seismic data, the eastern Anticosti foreland basin is interpreted to have a northeast–southwest axis and the basin succession thinning to the west and north.

The foreland basin was initiated when the Appalachian mountain fold belt first began to form, and oceanic rocks, including rocks from the lower Paleozoic continental slope and sea floor, were thrust up over the shelf margin as several Taconic allochthons. The deepening-upward autochthonous Middle Ordovician succession consists of a lower carbonate shelf ramp (peritidal to subtidal limestone to slope limestone and shale, Table Head Group) overlain by a deep basinal shale (Black Cove Formation) and a younger clastic flysch (American Tickle Formation, Mainland Sandstone). The succession, deposited following the submersion of the St. George Unconformity, as eustatic- and tectonic-driven sealevel rose rapidly drowning the foundering Laurentian margin (Stenzel *et al.*, 1990; Quinn *et al.*, 1995). Common slump folds and scars deforming the succession of fossiliferous, subtidal, ramp limestone and shale of the Table Head Group and bodies of limestone conglomerate and breccia, enclosed within the overlying clastic flysch of the American Tickle Formation, indicate that tectonism was ongoing throughout the early development of the foreland basin. The limestone conglomerate and breccia were deposited in hanging-wall basins adjacent to active normal faults that uplifted and locally exposed the underlying carbonate shelf as well as, locally, the sub-St. George Unconformity platform to erosion. Such faults were later inverted, *e.g.*, Round Head Thrust (Stockmal *et al.*, 2004).

Detritus derived from erosion of the Taconic ophiolites was noted in the Middle to Late Ordovician flysch deposits (Stevens, 1970; Quinn *et al.*, 1995; White and Waldron, 2022). Shale pebbles of Green Point Formation (Cow Head Group) in the allochthonous conglomeratic flysch indicate that the underlying Lower Ordovician slope deposits were uplifted and eroded as the flysch was generated; Quinn (1992) also noted the presence of detritus in the Goose Tickle Group flysch that indicate that sediment was also sourced from a granitic basement terrain. The allochthonous equivalents of the flysch (Western Brook Pond Group), are generally finer grained and also preserve ophiolitic detritus (Stevens, 1970). This combined with the overall basin geometry indicates that flysch was derived from allochthonous rocks that were thrust onto western Newfoundland (White *et al.*, 2019; Lacombe *et al.*, 2020).

Taconic Allochthons: Humber Arm and Hare Bay

Allochthonous rocks form the Humber Arm and Hare Bay allochthons in western Newfoundland. The two allochthons consist of two parts: i) lower structural levels consist of sedimentary rocks deposited in rift basins

(Curling Group), on the continental shelf slope, adjacent ocean floor (*see* below), and during the early stages of the foreland basin (*see* above); ii) ophiolite complexes are emplaced above the sedimentary rocks; they include the Coastal Complex (CC) and the four adjacent ophiolite massifs of the Bay of Islands Complex (Table Mountain, North Arm Mountain, Blow Me Down and Eastern Lewis Hills; Figure 4). The ophiolite massifs are preserved from Port au Port Peninsula to Bonne Bay and as an isolated ophiolite near Hare Bay in the north of the Northern Peninsula. The sedimentary rocks are grouped into the Humber Arm Supergroup, which includes the Cow Head and Northern Arm groups, as well as flysch of the Lower Head and Eagle Island formations (Figure 3).

Rift-related rocks in the Humber Arm Allochthon include the Cambrian Summerside, and Blow-Me-Down Brook formations (Curling Group) that are considered to be distal time-equivalents of the Ladrabor Group (Botsford, 1987; Palmer *et al.*, 2001). The Ediacaran volcanic–volcaniclastic Skinner Cove Formation structurally overlies the Blow-me-Down Brook formation; whereas the Early to Middle Ordovician flysch (Western Brook Pond Group) preserves foredeep turbidites overlying the continental slope succession of the Cow Head Group (Botsford, 1987; Lacombe *et al.*, 2019). The timing of the transition to a tectonically active basin is ~469 Ma based on the preservation of graptolites in the Eagle Island formation, the oldest formation of the Western Brook Pond Group (Botsford, 1987).

OPHIOLITE COMPLEXES

TERMINOLOGY

Despite over 60 years of research in the well-preserved ophiolitic complexes of western Newfoundland, the formation, relationship and timing of obduction of various ophiolites are still widely debated (*see* Zagorevski and van Staal, 2015; Dewey and Casey, 2021; van Staal and Zagorevski, 2022; van Staal and Dewey, 2023). This report attempts to characterize the geology of the region, synthesize and standardize the terminology that is author-dependent. The Little Port Complex was originally defined by Williams (1973) as the group of rocks that form the structural slice immediately below the Bay of Island Complex. The Coastal 'Complex' was later proposed to include the Little Port Complex and the deformed ophiolites of the western Lewis Hills (Karson and Dewey, 1978; Casey *et al.*, 1985; Karson, 1984). The term was not universally accepted at the time because of uncertainty over the age of the Lewis Hills massif and Jenner *et al.* (1991) recommended that the term be abandoned. However, Kurth *et al.* (1998) demonstrated that the western Lewis Hills were synchronous with, and geochemically similar to, the Little Port Complex, which is 15–20 myr older than the BOIC. They proposed that the CC comprises the Little Port Complex, western Lewis Hill and the Mount Barren Complex. Subsequently, Kurth-Velz *et al.* (2004) termed all the ophiolites Bay of Island Ophiolite, then subdivided them into the: a) *ca.* 488 Ma BOIC; b) *ca.* 505 Ma CC, which includes the Little Port Assemblage (sometimes Complex) and western Lewis Hills; and, c) Mount Barren Complex. Though this terminology was not widely accepted, and many authors continue to use CC and Little Port Complex interchangeably (*see* Kerr, 2019; Yan and Casey, 2020; Dewey and Casey, 2021; van Staal and Dewey, 2023). We propose that the CC should be used to describe the older ophiolites of the Little Port Complex and the western Lewis Hills. The timing and the relationship of the Mount Barren Complex to either the BOIC or Little Port Complex remain unclear. Whereas some have proposed that the Mount Barren Complex preserves a fossil transform fault representing a transition zone between an arc and a marginal basement (Karson and Dewey, 1978; Karson, 1984; Kurth-Velz *et al.*, 2004) this is not universally accepted and the geochronological evidence is absent.

OPHIOLITE COMPONENTS

There are typically seven principal components recognized within ophiolites and equated with specific parts of the oceanic crust (Figure 5; summarized from Kerr, 2019). From the base to top, they consist of: a) Massive (but commonly deformed) ultramafic rocks (harzburgite to lherzolite tectonite, dunite and pyroxenite veins and layers) that represent the residual mantle material from partial melting that may have produced the overlying oceanic crust section; b) Ultramafic cumulate rocks (feldspathic dunite and olivine-rich gabbro), which define the transition between crust and mantle, *i.e.*, the Moho; c) Layered gabbros, which record cumulate processes in the deeper sections of mid-crustal magma chambers; d) More massive gabbroic rocks representing fractionated magma chambers, commonly with trondhjemitic to hornblenditic dyke-vein systems, and with an upwardly increasing proportion of microgabbroic to diabasic dykes; e) Diabase sheeted dykes, interpreted as the feeder systems to the overlying pillow lavas; f) Basaltic pillow lavas; and, g) Cherts or shales that were deposited on the lavas forming the deep-seafloor.

COASTAL COMPLEX

The Little Port Complex was originally defined by Williams (1973) as a northeast-trending belt along the coast from Little Port to Bonne Bay, and the islands at the mouth of the Bay of Islands (Figure 4). The oldest rocks in this belt consist of a polygenetic series of older foliated gabbros, peridotites and their altered equivalents that are intruded by quartz diorites and trondhjemites. All plutonic units that are

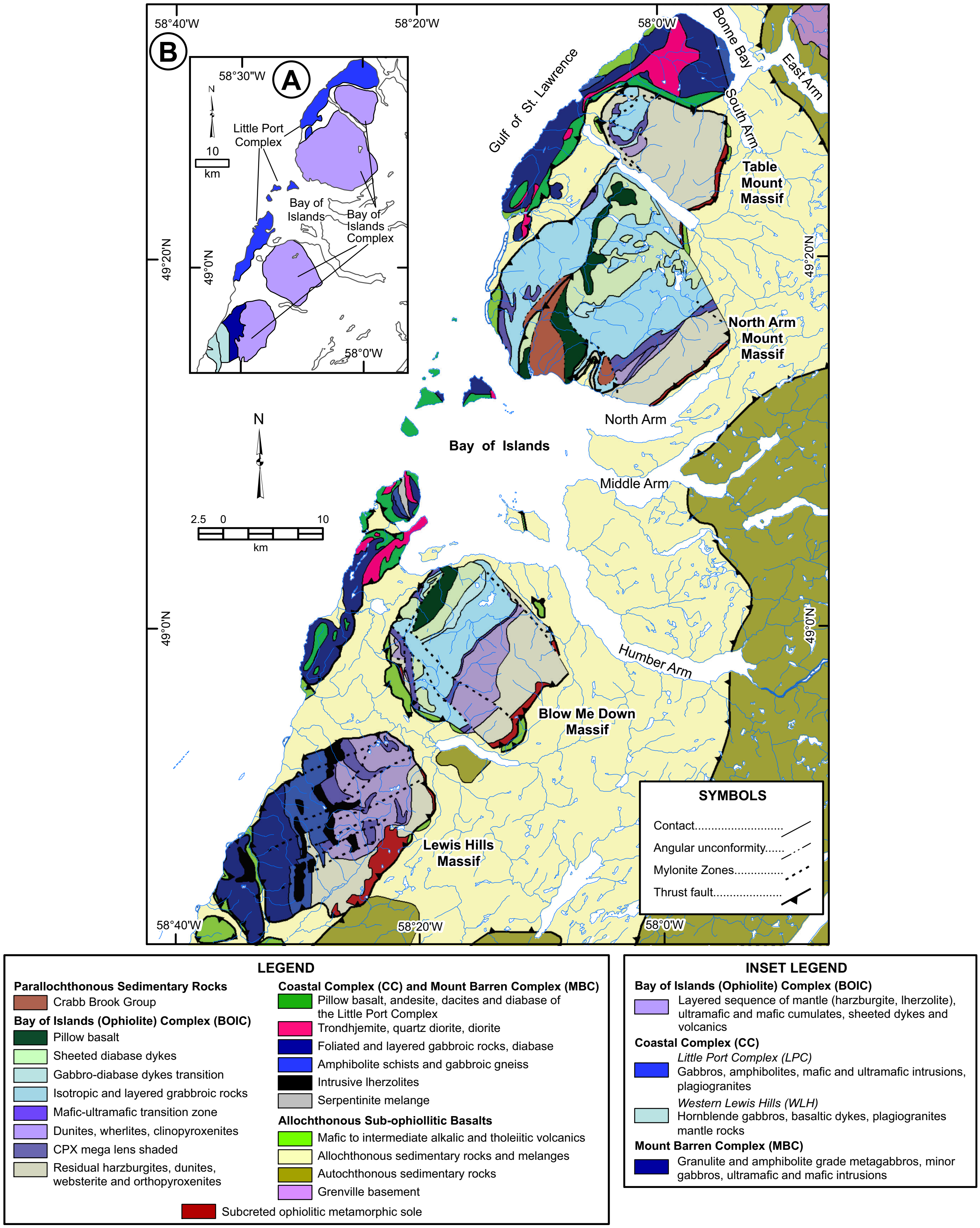

Figure 4. *Generalized regional geological map of allochthonous ophiolitic rocks of the Bay of Islands region of western Newfoundland, Canada (modified from Yan and Casey, 2020).*

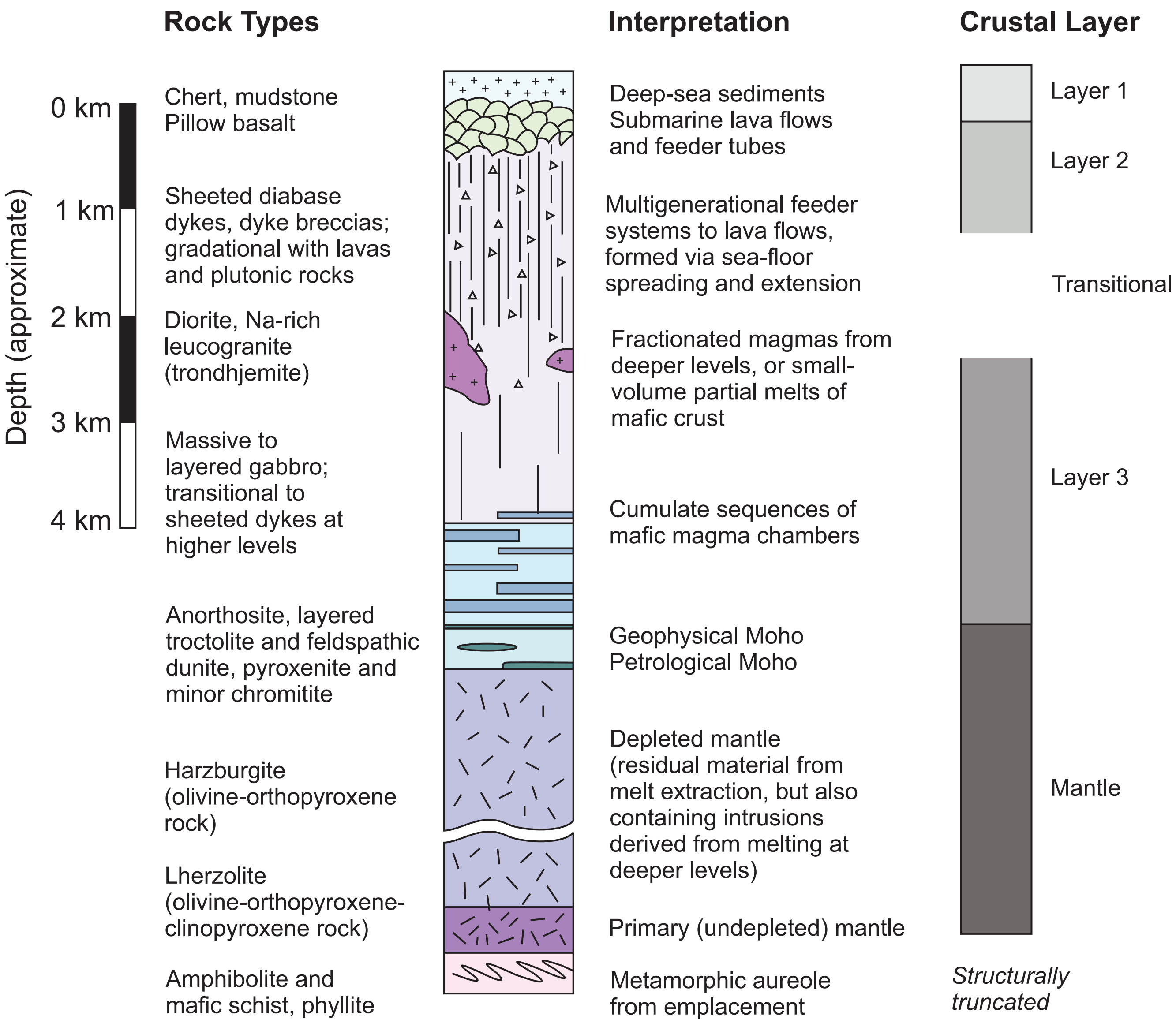

Figure 5. *The major components of the ophiolite suite, their interpretation and their relationship to layer structure defined in the modern oceanic crust by seismic and other geophysical methods (modified after Kerr, 2019).*

intruded by mafic dykes are variably metamorphosed and likely of multiple ages (Williams and Malpas, 1972). The volcanic rocks of the Little Port Complex are dominated by pillow lavas and pillow breccias, associated with red cherts and black shales (Williams, 1973). The U–Pb zircon TIMS dating of a trondhjemite in the Little Port Complex, near Trout River, gave a Cambrian age of 505 +3/-2 Ma (Jenner *et al.*, 1991). Lithogeochemisty and Nd isotopic systematics (εNd -1 to +1) of trondhjemites suggest that the Little Port Complex trondhjemites formed by partial melting of older arc-related crust (Jenner *et al.*, 1991). More recent LA-ICP-MS U–Pb zircon dating of plagiogranitic plutons provide an age range of 514.3–502.7 Ma for the formation of the Little Port Complex (Yan and Casey, 2022).

The western Lewis Hill preserves a 5–6-km-wide assemblage of mainly undeformed hornblende-bearing gabbroic rocks that include isotropic and layered gabbros, greenschist-facies metagabbros, trondhjemite bodies (up to 20 to 30 m wide), and vertical diabase dykes (Karson, 1984; Kurth-Velz *et al.*, 2004). Initial εNd values of plutonic rocks range from -2 to +2, and a U–Pb zircon TIMS age is 503.7 ± 3.2 Ma and 500.6 ± 2.0 Ma (Kurth *et al.*, 1998). Numerous plugs and larger dykes (up to a few hundred metres across) of peridotite intrude the gabbroic rocks and are cut by diabase dykes (Karson *et al.*, 1985). A large ultramafic exposure, the Springers Hill harzburgite, has been interpreted as representing an uplifted arc-related basement and is exposed on Springers Hill and in the eastern Lewis Hills (Suhr and Cawood, 2001).

MOUNT BARREN COMPLEX

The Mount Barren Complex is a 4–5-km-wide, structurally complex zone of metagabbros and amphibolites cut by syn- to post-kinematic mafic and ultramafic intrusive bodies (Karson, 1977). The structural complexity reflects a protracted history of deformation and magmatism (Karson and Dewey, 1978; Karson and Dick, 1983; Suhr 1992). Dominant amphibolite- to granulite-facies metagabbros have near-vertical, planar-deformed structures with shallow, plunging lineations, suggesting strong strike-slip deformation (Karson, 1977; Karson and Dewey, 1978; Casey *et al.*, 1985; Rosencrantz, 1983; Suhr, 1992).

This complex is proposed to have been deformed in a transform fault (Kurth-Velz *et al.*, 2004 and references therein). Numerous north–south-trending, foliation parallel mafic to ultramafic plutonic bodies occur within or at the eastern boundary of the complex (Karson and Dewey, 1978; Karson *et al.*, 1984; Suhr and Cawood, 2001). They consist mainly of olivine–clinopyroxene–orthopyroxene-bearing assemblages that are characterized by the late appearance of plagioclase (Suhr and Cawood, 2001). They are termed the Pyroxenite Suite because of the large occurrence of pyroxenites, which only locally grade into more olivine-rich facies like wehrlite, lherzolite and dunite (Suhr and Cawood, 2001). They have εNd values between -1.5 and +0.6 (Kurth-Velz *et al.*, 2004). These intrusions have been emplaced syn- to post-kinematically (Suhr and Cawood, 2001). The pyroxenites are cut by abundant basaltic dykes that are generally undeformed, and based on geochemical evidence, are divided into two groups (Group 1 has ~0.6 x MORB abundances and εNd from +5.4 to +7.5 and Group 2 has ~0.3 x MORB abundances and εNd from +5.4 to +5.9; (Casey *et al.*, 1985; Kurth-Velz *et al.*, 2004). Gabbros and metagabbros from the Mount Barren Complex have initial εNd values between +1.5 and +4.3 (Kurth *et al.*, 1998). The variability of the lithogeochemistry and isotopic signatures has been explained by invoking two compositionally distinct mantle sources, a sub-island lithospheric mantle, and an asthenospheric marginal basin mantle (Kurth-Velz et al., 2004).

BAY OF ISLANDS COMPLEX

The Bay of Islands Complex (BOIC) comprises four massifs, from north to south, Table Mountain (Tablelands), North Arm Mountain, Blow-Me-Down Mountain and the eastern Lewis Hills. The Bay of Islands ophiolite was tilted and broken up by faults during obduction and as such exposes a steeply dipping section through the lithosphere (Bédard, 1991). The North Arm and Blow Me Down mountains preserve a complete ophiolite suite from ultramafic mantle and cumulate rocks, through gabbros and sheeted dykes to mafic pillow lavas and capping sediments (Figure 5). At North Arm Mountain, the ophiolite suite is unconformably overlain by breccias of the Crabb Brook Group, which is an integral part of the North Arm Mountain massif (Casey and Kidd, 1981).

All four massifs have a complex mantle section. Suhr and Cawood (1993) divided the Table Mountain mantle section into multiple structural–compositional units that can be correlated with similar packages at North Arm Mountain. The harzburgite tectonite (referred to as the Wheeler's Brook assemblage in the Lewis Hills) is markedly thinner in the two southern massifs, which have extremely thick dunitic masses beneath the gabbroic/ultramafic/pyroxenitic cumulates. In eastern Lewis Hills, the dunites, wehrlites, troctolites and gabbros located to the east of the Mount Barren Complex are subdivided into early and late plutonic suites based on the degree of deformation, and crosscutting relationships (Williams, 1973; Cawood and Suhr, 1992). Apophyses of the plutonic suites are entrained syn-magmatically into the shallow-plunging Mount Barren Complex deformation. In Blow-Me-Down Mountain, the equivalent facies is a 5-km-thick dunite, with local chromitite schlieren, and common feldspathic domains near the contact with the layered gabbros. This dunite is interpreted either as a complex ultra-restite (Suhr and Edwards, 2000), or a cumulate (Stern, 2013).

A metamorphic sole(s?) of polydeformed granulites, amphibolites and greenschists occur at the stratigraphic base of the BOIC's mantle (Williams, 1973; Malpas, 1979). The most complete section through the metamorphic sole is preserved in the North Arm Massif, where a thin garnet–granulite-facies gneiss unit is underlain by amphibolites, greenschists, phyllites and unmetamorphosed sediments with a structural thickness of 130 m (Williams, 1995). At the contact between the amphibolites and ultramafic rocks, the P-T conditions were calculated at 750–850°C and 7–11 kbar (McCaig, 1983).

Yan and Casey (2020) reported an average age of the BOIC of 488 ± 1.5 Ma based on their new LAM-ICP-MS data coupled with re-calculated older TIMS ages of Mattinson (1976), Dunning and Krogh (1985), and Jenner *et al.* (1991), although they acknowledged that newer TIMS techniques would likely constrain the errors to less than 0.5 Ma. This is similar to previously reported ages of 484 ± 5 Ma for a gabbro from the Blow Me Down Mountain (Jenner et al., 1991), 485 +1.9/-1.2 for a trondhjemite from Blow Me Down Mountain (Dunning and Krogh, 1985) and 485.0 ± 1 Ma for a gabbro from eastern Lewis Hills (Kurth *et al.*, 1998).

TECTONIC EVOLUTION

Western Newfoundland preserved a Laurentian passive margin until the base of the Middle Ordovician (approximately 470 Ma) when tectonic loading due to allochthon emplacement was marked by the St. George unconformity that formed on a migrating peripheral bulge (Jacobi, 1981; Knight *et al.*, 1991). Prior to the obduction of the allochthons, the Laurentia margin was stable; however, outboard elements of the Laurentian realm were deformed and metamorphosed earlier. Plutons of the Notre Dame arc (part of the Notre Dame Subzone) had stitched ophiolitic and deformed Laurentian-derived metasedimentary rocks of the Dashwoods terrane, as early as 488 Ma (possible by 495 Ma; Swinden *et al.*, 1997; Waldron and van Staal, 2001; van Staal and Dewey, 2023). This suggests early Taconic deformation was accommodated by a southeast-dipping subduction zone that involved an arc-continent collision of an offshore microcontinent (Dashwoods Block; Waldron and van Staal, 2001; van Staal *et al.*, 2007). The sliver of the Iapetus Ocean separating the Laurentian margin from the Dashwoods Block is referred to as the Taconic Seaway (van Staal and Barr, 2012). Following the initial early Taconic arc-continent collision, convergence continued along this south-(southeast?) dipping subduction zone progressively consuming the Taconic Seaway (van Staal and Dewey, 2023). Tremadocian juvenile ophiolites were formed in this seaway in a suprasubduction zone setting and obducted onto the margin of Laurentian including the Coastal Complex and the BOIC in a fore-arc setting (Elthon, 1991; van Staal *et al.*, 2007).

Yan and Casey (2020) proposed that the spreading centre that formed the BOIC rifted an older Coastal Complex (*ca.* 508 Ma) ophiolitic fore-arc ocean basin and formed a welded composite fore-arc terrane that have disparate ages. They further proposed that the ophiolite formation and hot subcretion of sole rocks to the BOIC were simultaneous as spreading proceeded and that the sole began to immediately cool in an oceanic realm. Continued subduction of oceanic crust adjacent to the stable Laurentian margin eventually resulted in ophiolite obduction and a cooled sole near the ocean–continent transition to complete the igneous portion of allochthon (Dewey and Casey, 2021). This was followed by the complete assembly and final emplacement of the Humber Arm Allochthon during the Taconic orogeny. The final emplacement of the allochthons onto the inboard shelf is constrained to *ca.* 463 Ma, based on stratigraphic relationships in the Port au Port region (Lacombe *et al.*, 2020; White *et al.*, 2020).

CURRENT INVESTIGATIONS

Several research projects are evolving based on fieldwork from 2022. Below is a select list of research projects:

The Microstructure of the Peridotites and Lower Crust of the North Arm Massif (NAM), Bay of Islands, NL, Canada
H. Henry, G. Ceuleneer, M-A. Kaczmarek, J.H. Bédard, A.M. Hinchey and C.J. Lissenberg

Two research themes will be explored in the research project, 1) Revisit legacy outcrops showing melt-rock interaction and test their hypothesis of formation (plastic deformation *vs.* magmatic deformation *vs.* pure cumulative processes); 2) Investigate the possible strain partitioning in the upper mantle section of the NAM, and model the NAM seismic properties. This research will involve extensive textural characterization using Electron Backscattered Diffraction (EBSD) together with element mapping and chemical characterization using electron microprobe analysis (EPMA) and EBSD mapping.

Detrital Zircon Geochronology, Provenance and Paleomagnetism of the Crabb Brook Group, North Arm Mountain, Bay of Islands, NL, Canada
J.P. Butler, M. Maffione, A.M. Hinchey and C. Guilmette

The Crabb Brook Group (CBG: Casey and Kidd, 1981) is an approximately 1.5-km-thick sequence of sedimentary rocks unconformably overlying the BOIC on the southern end of NAM. It consists of a basal, ophiolitic breccia overlain by shale and sandstone, and is generally interpreted as the remnants of a piggy-back basin deposited during obduction of the ophiolite complex onto the Laurentian margin, although its age, and to some extent, its provenance remains poorly constrained. This research will use detrital zircon U–Pb geochronology, heavy-mineral concentrations, and paleomagnetic analysis to better constrain the age, provenance, and depositional paleolatitude of the CBG. Additionally, the magnetic remanence directions isolated from these rocks will provide insight into the regional tectonic rotations experienced by the ophiolite during its emplacement. These new data will be integrated with results from ongoing paleomagnetic studies in the crustal section of the Bay of Islands ophiolite to assess models for the late-stage tectonic evolution of the ophiolite complex.

Detrital Zircon Geochronology, Heavy-Mineral Composition and Provenance of the Humber Arm Allochthonous Sediment, Western Newfoundland, Canada
A.M. Hinchey, N. Rayner, J.P. Butler, J.F. Waldron, C. Guilmette and J.H. Bédard

The allochthonous, upper part of an intact sequence of Lower to Middle Ordovician deep-water sediments, at Lobster Cove Head, is interpreted as having been deposited downslope from a drowned carbonate platform margin (James *et al.*, 1987). A 50-m-thick section is correlated with the Cow Head Group, where the basal part of the section is a proximal facies of the Cow Head Group (Shallow Bay Formation, Factory Cove Member).The upper part, which consists of interbedded dolostone and shale, is defined as the Lobster Cove Head Member of the Shallow Bay Formation, Cow Head Group (James *et al.*, 1987). The break between the two formations marks the drowning of the carbonate platform coinciding with the onset of the Taconic orogeny in western Newfoundland. Above the Cow Head Group lies the sandstones of the Lower Head Formation, Goose Tickle Group. This research will combine high-resolution, heavy-mineral analysis and detrital zircon geochronology to solve stratigraphic and structural puzzles in the deformed sequence preserved at Lobster Cove Head. Specifically, looking for evidence of erosion of the obducted ophiolites in sedimentary units.

BOIC Differentiation Processes and Tectonic Environments
J.H. Bédard, C.J. Lissenberg, M. Jansen, H. Henry, G. Ceuleneer, L. Iacceri and C. Guilmette

Understanding the interplays between fluid, magmatic and mechanical/structural processes improves our understanding of oceanic crustal differentiation. Research will focus on detailed studies of cumulus and melt-reaction facies. Extensive sheeted dyke major- and trace-element data will provide benchmarks for the compositions of the plutonic suites, and enable a reconstruction of the evolution of mantle-source compositions during crustal accretion and thus underpin paleotectonic interpretations.

Potential for Low-grade Chromitite Ores in Ophiolites
J.H. Bédard, D. Paktunc, N. Rayner, A. Sultanmohammedi, C. Guilmette and A.M. Hinchey

This study explores the ore potential, regional extent, and mechanism of generating chromite-bearing feldspathic wehrlites in the lower crust. Research focuses on ore-processing constraints, mineral potential and PGE fractionation, in addition to regional correlations and timing of mineralizing events in the BOIC. Reactions between deep-oceanic crust and seawater as Cu–Pb–Zn–Au–Co ore-forming environments, and as buffers of seawater and atmospheric chemistry will also be evaluated.

The Metamorphic Sole and Subduction Initiation Processes
C. Guilmette, M. Coleman, F. Fournier-Roy, J. Wakabayashi, P. Agard, C. Prigent, M. Soret and L. Mérit

This research team will investigate the chronology of processes in the formation of the BOIC subophiolitic metamorphic sole. The sole likely accreted as a series of sheets offscraped from the lower plate, the structurally highest rocks, next to the mantle, having accreted first shortly after initiation of subduction. The team will investigate the metamorphic conditions recorded by each sole subunit (sheet), as well as the deformation mechanisms active during their accretion from the lower to the upper plate. The timing of accretion and exhumation will be constrained through multi-system petrochronology involving Lu–Hf on garnet and U–Pb on titanite, zircon and monazite geochronology. Geochemical isotopic-, trace- and major-element data from the sole subunits, inherited from their protolith, will also be integrated in the dataset to constrain the architecture of the lower plate prior to and during subduction initiation, as well as the processes in the evolution of an incipient subduction plane under the overlying ophiolitic complex. Such insights will inform on the architecture of the Taconic Seaway and its tectonic evolution, as well as on the tectonic setting and process of subduction initiation.

Siderophile Elements in the Mantle
B. O'Driscoll and C.J. Lissenberg

This project will evaluate the length-scales over which upper-mantle compositional heterogeneity occurs on ophiolitic mantle by combining field-based observations with geochemical studies. Fieldwork will focus on thick sections of harzburgite, initially in the North Arm Massif, using a grid-sampling approach that has been utilized by this team on other Iapetus-related ophiolites. Analytical techniques include major- and trace-element chemistry, Re–Os isotopes and HSE abundance measurements. Key goals are to better constrain the abundance of and geometry of refractory mantle domains (signified by >1 Ga Os isotope model ages), and assess the extent of any subduction zone overprint recorded by the HSE on this portion of mantle material.

Crustal Cumulates and Dykes
J.H. Bédard, J.Lissenberg, A. Sultanmohammedi and L. Iacceri

This research project will explore the mineral chemistry, major- and trace-element whole-rock lithogeochemistry and isotopic composition of the crustal cumulate rocks and associated dykes. The objectives are: to constrain the origin, relationships and magmatic affinities of the different facies of gabbroic rocks; the formation of potentially economic chromite mineralization; the processes involved in magmatic differentiation within the crust; and how residual melts migrate through the crust to feed lavas.

Implications on Regional Tectonics of Western Newfoundland
C. Guilmette, M. Maffione, E. Advokaat, J.H. Bédard, A.M. Hinchey and C. van Staal

By re-evaluating the paleo-orientation of BOIC and Costal Complex rocks using paleomagnetics, combined with other fabric elements: lineation in soles, lower crustal fabrics and dyke orientations, this research team will investigate the tectonic setting in which the ophiolites formed as well as the paleogeography of the Taconic Seaway. Such data will enable refining tectonic models of the Appalachian orogenesis and for the subduction and obduction processes in general.

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