Orogenic architecture diagrams to reconstruct paleogeography and plate tectonics: Newfoundland (Canada) as a case study

Abbreviated title: Orogenic architecture diagrams

Alice Maremmani[1*], Douwe J.J. van Hinsbergen[1], Eldert L. Advokaat[1], Alissa J. Kotowski[1], Carl Guilmette[2,3]

[1]*Department of Earth Sciences, Utrecht University, Princetonlaan 8A, 3584 CB Utrecht, Netherlands*

[2]*Département de Géologie et Génie Géologique, Université Laval, Québec, Canada*

[3]*Centre de Recherche sur la Géologie et L'ingénierie des Ressources Minérales (E4m), Québec, QC G1V 0A6, Canada*

ORCID ID: AM 0009-0005-9483-0746; DJJH 0000-0003-3410-0344; ELA 0000-0001-8239-0310; AJK 0000-0002-1257-4402; CG 0000-0001-7196-522X

*Corresponding author: Alice Maremmani, alimare99@gmail.com

ABSTRACT

Reconstructing paleogeography from accretionary records is challenging due to the difficulty of integrating data sources from different specialized fields. Here, we present the 'orogenic architecture diagram' method to systematically compile geological data in temporal and spatial context at the scale of nappes - the 'building blocks' of orogens - and to use their interpreted geological histories as a base for tectonic and paleogeographic reconstruction. We identify lower plate-derived Continental or Ocean Plate Stratigraphy, and upper plate-derived ophiolites and magmatic units. We apply this framework to the Newfoundland Appalachians, Canada, which record accretion of oceanic and Gondwana- and Laurentia-derived continental units to Laurentia during the Cambro-Ordovician closure of the Iapetus Ocean. Our diagrams allow for straightforward connection of modern geological records to opening and closure of marginal oceanic basins and illustrate that the Iapetus Ocean itself left little accretionary record. Our approach highlights the source of contrasting interpretations in Newfoundland reconstructions and may motivate targeted field campaigns to interrogate proposed models. Our application to Newfoundland also demonstrates that our protocol, based on the assumption of modern-style plate tectonics and orogenesis, still applies to early Paleozoic orogens and may provide a tool to reconstruct the emergence of plate tectonics.

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The destructive nature of subduction makes reconstruction of past paleogeography and plate kinematics challenging, but such reconstructions form the basis of paleo-environmental, paleo-climatic, and geodynamic research. The only direct observations for reconstructing the motions of subducted plates – and oceans, continents, and arcs built upon them – come from offscraped upper crustal rocks that comprise accretionary orogens (Şengör 1990; Cawood *et al.* 2009; van Hinsbergen and Schouten 2021). Orogenic reconstructions are based on interpretations of thrust packages which record features of paleogeographic and plate tectonic significance, such as sedimentation, paleontology, magmatism, geochemistry, paleomagnetism, deformation and metamorphism. In isolation, these sources of information permit a large variety of paleogeographic and plate tectonic scenarios (Fig. 1). As a result, it is challenging to navigate and interrogate interpretations derived from specialized fields. This complicates reproducibility of paleogeographic interpretations. Therefore, it is crucial to reassess the original, uninterpreted data in light of evolving understanding of plate tectonic processes.

There is a large interpretative step between detailed field observations and plate tectonic or paleogeographic reconstructions. If we integrate different data types related to paleogeography and tectonics on a more local scale and systematically organize data and examine first-order interpretations, then we can identify less controversial building blocks that then add up to less complicated orogens. Such analyses may restrict interpretation to the paleoenvironment recorded by individual nappes (e.g., passive margin, syn-rift, foreland basin, ocean basin, arc etc.) or their tectonic history (e.g., shortening, metamorphism, exhumation). This strategy organizes data sources into a regional geological history of sedimentation, paleontology, igneous history, deformation and metamorphism. Such organization of data has been done in the past in different ways (e.g., Handy *et al.* 2010; van Staal and Barr 2012; van Hinsbergen *et al.* 2020; van Hinsbergen and Schouten 2021; Wakabayashi 2021) but, so far, no explicit methodology for this approach was proposed.

In this paper, we describe the optimal construction of 'orogenic architecture diagrams', which summarize and interpret data from various fields into paleogeographic and tectonic building blocks. Each building block, which has been offscraped from a downgoing plate, and accreted to an overriding plate, has a specific architecture (i.e., tectonostratigraphy and internal features) and first-order geological history, which is typically more straightforward to interpret than at larger scales. We describe how to then zoom out and interpret the product of these building blocks – i.e., orogenic reconstruction.

As a case study, we selected the Newfoundland Appalachians, which has been extensively described and dated (e.g., Williams 1979, 1995; van Staal *et al.* 1998; van Staal and Barr 2012; White and Waldron 2022). Newfoundland has a well-defined structure comprising accreted continental and oceanic rocks, ophiolites, and records of arc magmatism and sutures, and contains a wide variety of paleogeographic and plate tectonic elements. Current interpretations posit that the Newfoundland Appalachians record evidence for several subduction systems, with models proposing anywhere from ca. 3 to 6 stages of both short- and long-lived subduction. We first explain the orogenic architecture diagram concept, and then present diagrams capturing a systematic review of the Newfoundland architecture. We then interpret paleogeography and plate tectonics from the diagrams (without influence of past research) and compare it with proposed models. Finally, we discuss the utility of the diagrams for building reproducible paleogeography and plate tectonic scenarios, and alternatively, as tools for interrogating past interpretations and identifying future research targets (e.g., regions with lower data quality or density, or with ambiguous interpretation).

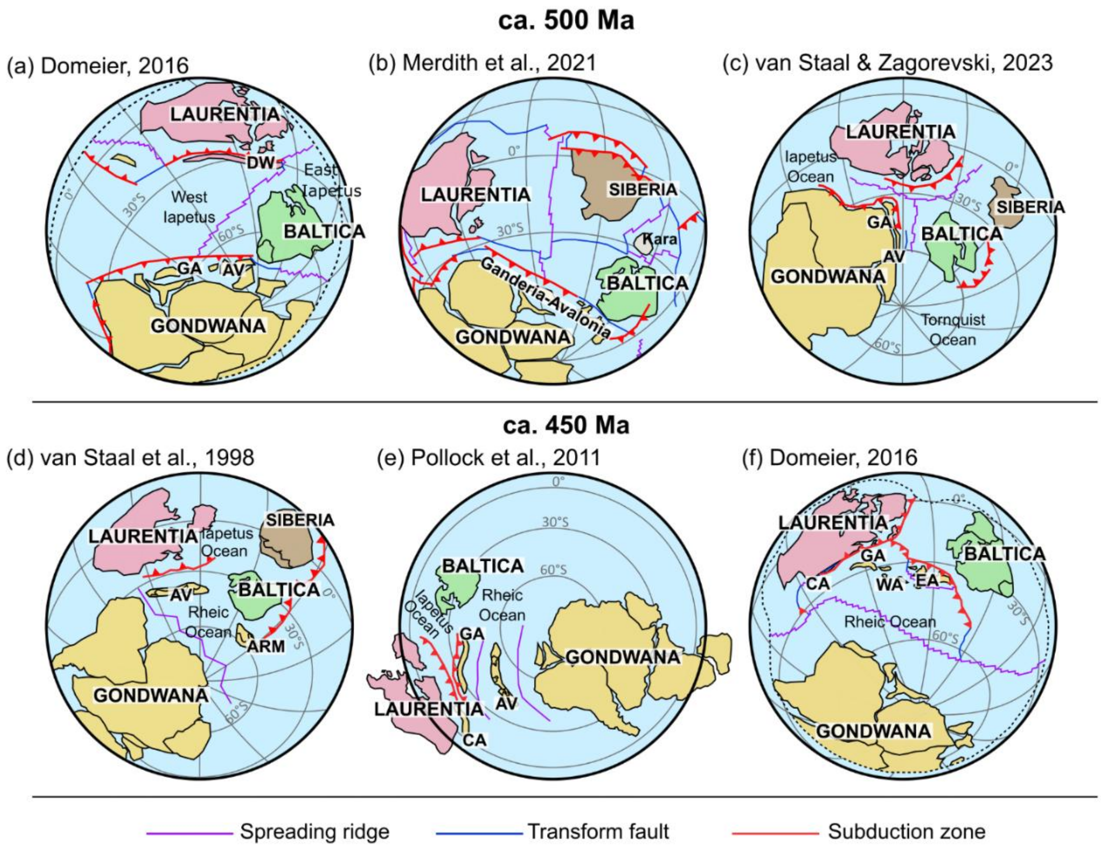

Figure 1 - Paleogeographic reconstructions at ca. 500 Ma (a, Domeier 2016; b, Merdith *et al.* 2021; c, van Staal and Zagorevski 2023; modified from Gasser *et al.* 2024) and at ca. 450 Ma (d, van Staal *et al.* 1998; e, Pollock *et al.* 2011; f, Domeier 2016). Projections are taken from the original authors and were not adapted. The reconstructions show different paleogeographic and subduction configurations for the same time step, as the interpretations derive from different datasets. Abbreviations for the microcontinents: ARM=Armorica; AV=Avalonia; CA=Carolina; DW=Dashwoods; EA=East Avalonia; GA=Ganderia; WA=West Avalonia.

OROGENIC ARCHITECTURE DIAGRAMS: THE APPROACH

Schematic visual representations of the building blocks of orogens have been used in many forms, and commonly summarize key observations that authors use as basis for their reconstructions. Those diagrams contain some combination of stratigraphy and lithology, metamorphism, magmatism, and the structural relationship between the building blocks, such as thrust vergence and timing of emplacement (e.g., Handy *et al.* (2010) for the Alps, van Staal and Barr (2012) for the North American Caledonides, van Hinsbergen *et al.* (2020) for the Mediterranean fold-thrust belts, Boschman *et al.* (2021) for Hokkaido, Japan, Advokaat and van Hinsbergen (2024) for the SE Asian orogen, and Wakabayashi (2021) for the Franciscan complex of California). The orogenic architecture concept is based on recognizing fault-bounded units in an orogen as distinct carriers of information on the paleogeography that existed on the tectonic plate they derive from, and on the motion of the tectonic plate. Therefore, distinguishing upper and lower plate units is crucial, as this allows to separately reconstruct the pre-orogenic paleogeography of the plates and the transfer of units from downgoing to overriding plates during accretion. It is important to note that this concept is developed under the paradigm of plate tectonics and the Wilson cycle (Wilson 1966), which are thus taken as the base assumptions. Herein we define the type-stratigraphy, -geochemistry and -metamorphic conditions characterising lower and upper plate units. The fault-bounded units form the 'building blocks' for the orogenic architecture diagrams (Fig. 2).

Upper Plate Units

Upper plates can consist of oceanic or continental lithosphere. Continental upper plates typically contain remnants of earlier accretionary orogens, as well as younger magmatic rocks and sedimentary basins. Continental upper plates have a large preservation potential in the geological record. Particularly, records of final ocean closure and continent-continent collision are typically well-preserved.

On the other hand, oceanic upper plates are more likely to subduct and disappear. However, if accretionary orogens formed below oceanic upper plates, their forearc may become uplifted and escape subduction. Such slices of oceanic forearcs may then be preserved as ophiolites, which represent the most complete remains of oceanic upper plates. Given their significance for reconstructing past intra-oceanic subduction, we identify upper plate ophiolites as distinct units in orogenic architecture diagrams (Fig. 2).

Ophiolites. Ophiolites offer several key diagnostic features to reconstruct oceanic upper plates and subduction history. Ophiolites in their most complete sequence comprise, from bottom to top, peridotites, gabbro, a sheeted dike complex and pillow basalts, overlain by chert and/or pelagic sediments (i.e., the 'Penrose' sequence; Anonymous 1972). Deep-water sediments may be overlain by forearc deposits derived from an intra-oceanic arc or a nearby continental margin (Fig. 2). U-Pb igneous zircon crystallization ages and cross-cutting relationships constrain the ages of upper plate spreading to produce the ophiolite sequence. Many ophiolites exhibit a SSZ (supra-subduction zone) geochemical signature, indicating that they formed above a subduction zone, typically during (e.g., Stern and Bloomer 1992) or shortly after subduction initiation (Guilmette *et al.* 2018, 2023). Subduction initiation-related ophiolites are commonly floored by a metamorphic sole, derived from the subducting plate (see below). Where ophiolites have MORB geochemistry, they may represent ocean floor that (long) predates subduction initiation (e.g., the Jurassic Masirah MORB ophiolite of east Oman that was uplifted above a late Cretaceous subduction zone; Peters and Mercolli 1998). In the orogenic architecture diagram, the ophiolite's age, geochemical composition, and sedimentary cover can be documented, as well as intervals where paleomagnetic data exist.

Arcs, basins, and upper plate deformation. Magmatic arcs typically form ~100-250 km inboard of a trench, above a subducting plate, whereby the arc-trench distance is a measure for slab dip (e.g., Stern 2002). Arcs may not be preserved in the geological record of ocean-ocean subduction, because the width of oceanic (i.e., ophiolite) belts thrust onto continental margins rarely exceeds 150 km (e.g., van Hinsbergen *et al.* 2015). Where preserved, however, we treat them as separate units intruding ocean floor or continental crust, or accreted units (Fig. 2).

Upper plates may record shortening, extension, and/or strike-slip deformation, which needs to be restored to correctly identify the geometry and location of accretion of the oceanic and continental lower plate units. Details of restoring upper plate deformation is beyond the scope of this paper, but systematic reconstruction protocols were developed and applied that restored upper/intraplate deformation in order of decreasing certainty from extensional (whereby a complete geological record is preserved at the end of the tectonic event), through transcurrent, to contractional deformation (where only a minimum record is preserved (e.g., van Hinsbergen and Schmid 2012; Boschman *et al.* 2014; van Hinsbergen *et al.* 2014, 2020).

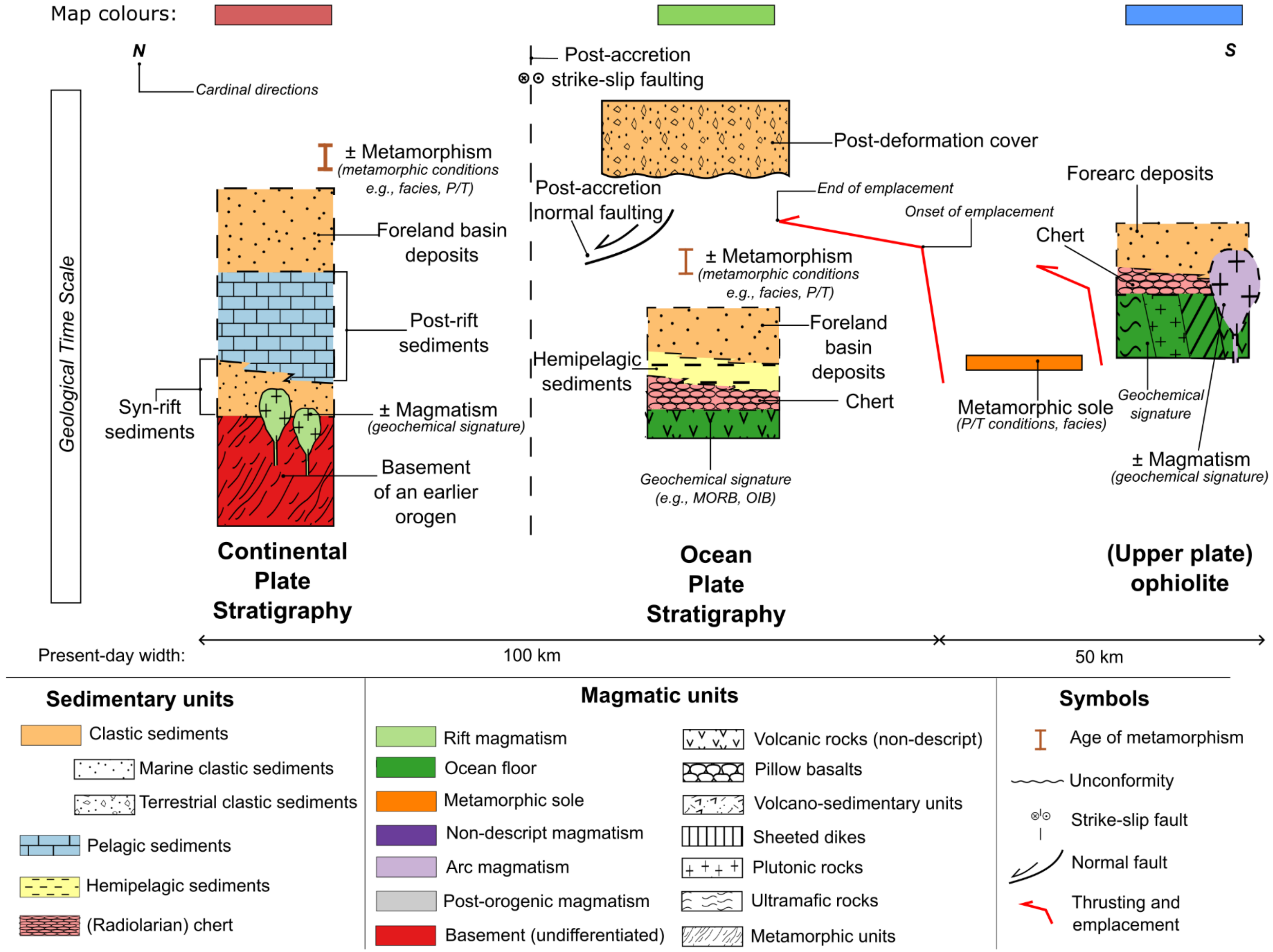

Figure 2 - Example of the elements making up an orogenic architecture diagram, and of the type-tectonic units with paleogeographic significance which can be found in an orogenic belt. The 'Map colours' at the top of each column refer to the colours each fault-bounded unit is assigned in a map of the region of interest. The colours and patterns presented in this infographic only serve as an example of lithological classification and interpretation, and can be adjusted.

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Lower Plate Units

During subduction, the upper units of the downgoing plate may accrete to the upper plate. We analyse nappe records to reconstruct the pre-accretionary history of the lower, subducting plate. Accreted units can be either oceanic (Ocean Plate Stratigraphy (OPS); Isozaki *et al.* 1990) or continental in nature (Continental Plate Stratigraphy (CPS); van Hinsbergen and Schouten 2021). OPS accretion is rare, since the default behaviour of oceanic lithosphere is to subduct, but blueschists and eclogites are locally recorded in orogenic systems (Brown 2007). On the other hand, the paradigm that historically underlies paleogeographic reconstruction is that continental lithosphere does not subduct but rather docks and is accreted (van Hinsbergen and Schouten 2021); however, we now know that continental units can be brought to (ultra) high-pressure conditions before being exhumed and accreted to the upper plate (Brown 2007). If continental lithosphere subducts, then it acquires a diagnostic metamorphic signature.

Ocean Plate Stratigraphy (OPS). The concept of Ocean Plate Stratigraphy was introduced by Isozaki *et al.* (1990), who inferred that oceanic plates record characteristic sequences of igneous rock types from ridge spreading to entering a trench. A complete OPS (Fig. 2) consists of remains of ocean floor magmatic rocks (typically pillow basalts, but in some cases also lower crustal rocks), overlain by deep-marine radiolarian chert, followed by distal hemipelagic sediments and then increasingly proximal foreland basin deposits ('flysch') deposited as the sequence approached the trench where it accreted. Biostratigraphic ages of the pelagic sediments (and, in rare cases, U-Pb zircon ages of gabbros and plagiogranites in the crustal sequences) constrain the maximum age of formation of the ocean floor, and the biostratigraphic or detrital zircon ages of foreland basin deposits constrain timing of arrival at the trench and the maximum age of accretion. The age gap constrains the age of the oceanic lithosphere that subducted when the OPS accreted (Isozaki *et al.* 1990). Geochemistry reveals if the oceanic crust formed at a mid-ocean ridge (MORB), hotspot or seamounts, or an intra-oceanic arc. If geochemistry indicates an ocean island basalt (OIB) or island arc tholeiite (IAT), the age of the magmas represents only a minimum age of the ocean floor. Such seamounts may be overlain by shallower-marine sedimentary facies such as carbonate reefs. If present, the tectonostratigraphic level where paleomagnetic data constrains paleolatitude can be added (e.g., van de Lagemaat *et al.* 2024). In our case study, we have not included a review of available paleomagnetic constraints.
The completeness of an accreted stratigraphy depends on the depth of a decollement, which for oceanic plates typically occurs around the sediment-crust interface (van Hinsbergen and Schouten 2021). OPS may develop coherent nappes, or more chaotic assemblages in mélanges (e.g., Wakita 2015; van Hinsbergen and Schouten 2021 and references therein). However, even in the latter case, composite stratigraphies tend to still retain first-order coherence, and may still be useful to restore subducting plate history (e.g., Wakabayashi 2021; Kotowski *et al.* 2022). Where rocks are frontally accreted, they will not metamorphose as long as they are unaffected by upper plate thickening. If they accrete at depth below the orogen, they may become metamorphosed, typically under high-pressure/low-temperature (HP/LT) conditions, which provide minimum estimates for the conditions of accretion. Radiogenic isotopes analyses of the metamorphic assemblages may quantify the minimum timing of accretion (e.g., Kotowski *et al.* 2022).

A special type of OPS are metamorphic soles, or thin, high-grade metamorphic rocks derived from subducted oceanic crust that accreted to the mantle base of supra-subduction zone ophiolites during subduction initiation (e.g., Jamieson 1981; Hacker and Gnos 1997; Wakabayashi and Dilek

2000). Soles are diagnostic features that confirm ophiolites are upper plates. Soles are the oldest, and highest structural units of the accretionary orogen that formed below the ophiolite, and their metamorphic ages indicate minimum ages of subduction initiation (e.g., Guilmette *et al.* 2018, 2023). Lu-Hf garnet ages of metamorphic soles record initial burial, whereas U-Pb zircon ages record upper plate extension and may post-date the garnet ages (Guilmette *et al.* 2018). For the orogenic architecture diagrams, we define metamorphic soles as separate accreted 'nappes' consisting of OPS, and indicate their metamorphic grade and age (Fig. 2). Further details may include protolith age or composition, if known.

Continental Plate Stratigraphy (CPS). Continental-affinity accreted units are typically organized in fault-bounded, coherent nappes (Fig. 2). In its most complete form, a CPS contains a continental basement of an earlier orogenic event, which is typically heterogeneous and is made up of (metamorphosed) OPS, CPS, or magmatic units. The basement is commonly overlain by clastic syn-rift sedimentary rocks from continental break-up, often associated with bimodal magmatism. Syn-rift sequences are then overlain by fining-upward post-rift passive margin sediments that are usually pelagic or hemipelagic; the base of this sequence represents the transition from rifting to drifting. Finally, the passive margin sediments are overlain by coarsening upward active margin foreland basin deposits (i.e., flysch), which indicate proximity to and subsequent arrival at the trench and provide a maximum age of accretion. This simple stratigraphy may be more complex if margins underwent multiple phases of rifting, or due to climate or sea level changes, influencing specific alternations of rock types and paleo-stratigraphy. Such complexities aid the interpretation of pre-orogenic paleogeography and may be incorporated into orogenic architecture diagrams. Similar to OPS, nappes buried below the upper plate may record metamorphism (high-pressure/low-temperature for thinned continental margins, or medium-pressure/high-temperature for thicker margins, cf. van Hinsbergen *et al.* 2024). This metamorphism gives a minimum age for accretion. Ages of exhumation constrained from cooling histories help reconstruct upper plate deformation. Like OPS, accretion of CPS usually occurs after subduction of an oceanic basin, and the amount of accreted material depends on the depth of decollement from the subducted lithosphere. Such detachment horizon may localize at the brittle-ductile transition, or at the interface between the sediment column and underlying crystalline basement, with the deeper parts having a smaller chance of accretion (van Hinsbergen and Schouten 2021, and references therein).

REVIEW OF THE GEOLOGY OF NEWFOUNDLAND

The geologic architecture of the Appalachians comprises tectonostratigraphic slices that are interpreted as the ancient margins of Laurentia (the Humber zone of Williams 1979), of sedimentary and igneous relicts of oceanic basins (the Dunnage zone of Williams 1979, interpreted as the relicts of the Iapetus Ocean or other oceanic basins), and continental stratigraphy and igneous rocks that do not resemble Laurentia, interpreted as ‘exotic’ microcontinents (e.g., Ganderia, Avalonia) that accreted to Laurentia upon closure of the Iapetus Ocean (Fig. 3). All units are interpreted to have amalgamated between the Ordovician and the early Devonian (e.g., van Staal and Barr 2012). The orogen is intruded by Silurian to Devonian granites that may have resulted from melting of the orogenic crust due to thickening, or slab break-off (Whalen *et al.* 1996, 2006).

In the next section we review the geology of Newfoundland from theNW to the SE. We subdivide it in fault-bounded units corresponding to tectonic columns in the orogenic architecture diagrams (Fig.

4).

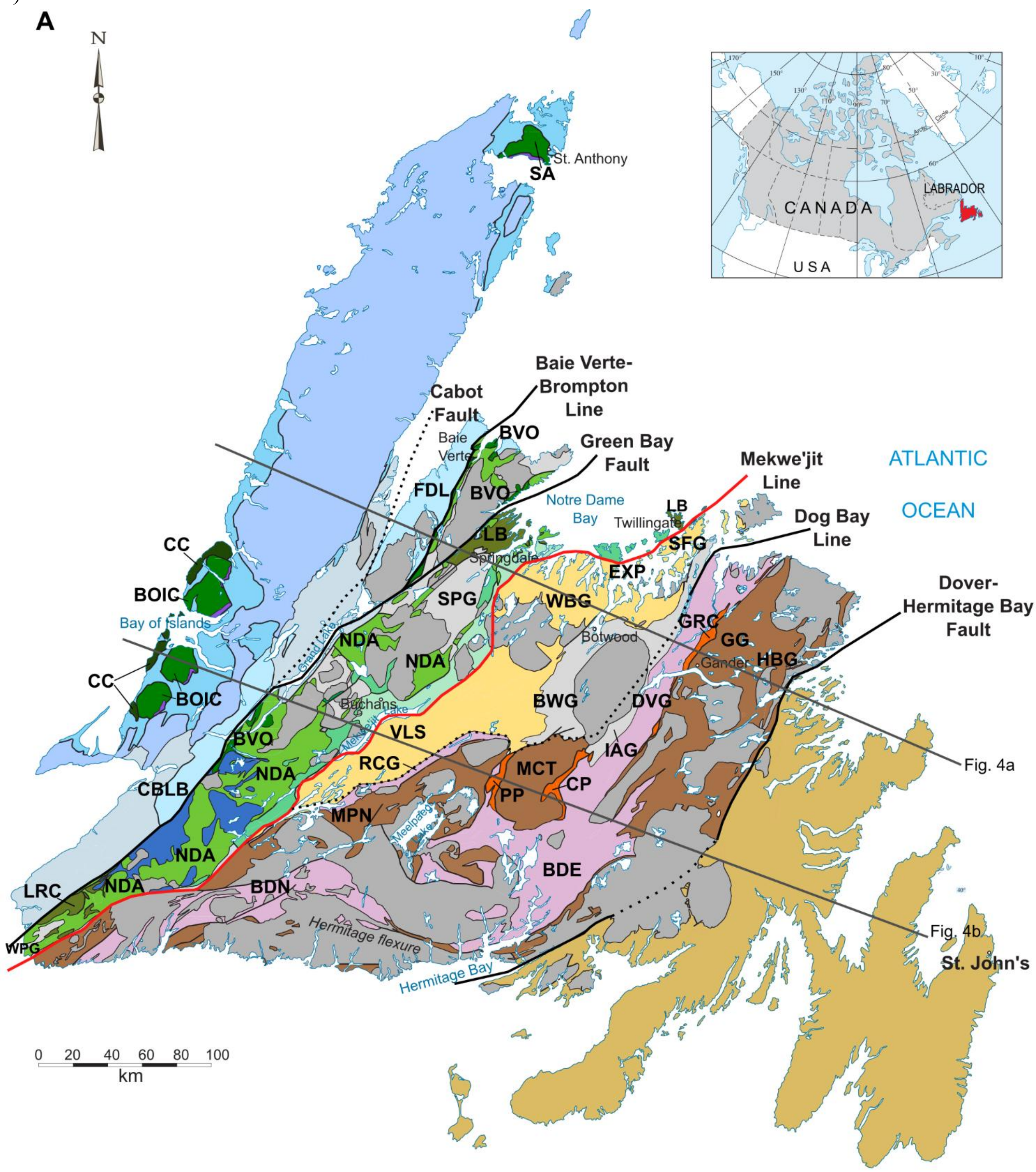
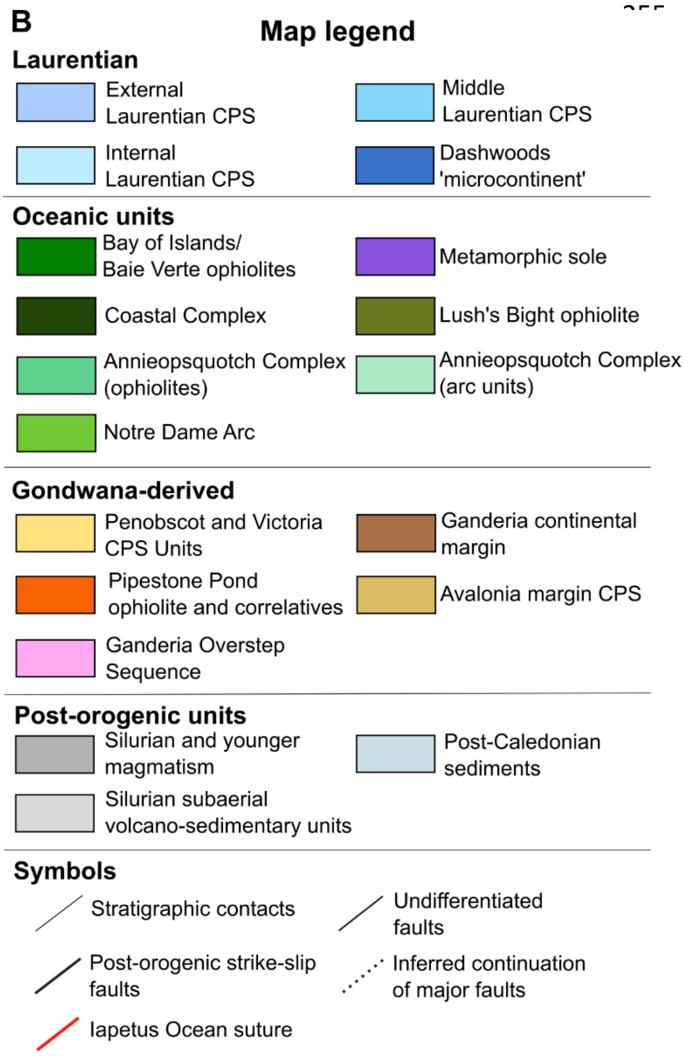


Figure 3 - A) Simplified geological map of Newfoundland, adapted from Colman-Sadd *et al.* (2000). Trace of the major NE-SW structural features is from Waldron *et al.* (2015); Willner *et al.* (2022). The two northwest-southeast lines represent the trace of the orogenic architecture diagrams of Fig. 4a, 4b. Note that each colour and pattern (see legend in B, in the next page) represents one of the tectonic units described in the text, and represented by a column in Fig. 4. Abbreviations: BDE=Baie d'Espoir Group, BDN=Bay du Nord Group, BOIC=Bay of Islands Complex, BVO=Baie Verte Ophiolite, BWG=Botwood Group, CBLB=Corner Brook Lake Block, CC=Coastal Complex, CP=Coy Pond ophiolite, DVG=Davidsville Group, EXP=Exploits Group, FDL=Fleur de Lys Supergroup, GG=Gander Group, GRC=Gander River Complex, HBG=Hare Bay Gneiss, IAG=Indian Islands Group, LB=Lush's Bight ophiolite, LRC=Long Range mafic-ultramafic Complex, MCT=Mount Cormack Terrane, MPN=Meelpaeg Nappe, NDA=Notre Dame Arc PP=Pipestone Pond ophiolite, RCG=Red Cross Group, SA=St. Anthony ophiolite, SFG=Summerford Group, SPG=Springdale Group, VLS=Victoria Lake Supergroup, WBG=Wild Bight Group, WPG=Windsor Point Group.



Laurentian Units (CPS)

Western Newfoundland comprises a ~60 km-wide stack of west-verging thrust slices, of which the Laurentian continental margin is preserved in the three bottom nappes (Fig. 3, Fig. 4). The Laurentian margin units record a Continental Plate Stratigraphy (CPS) that shows little variability throughout the Appalachian Mountains in Canada and New England (e.g., White and Waldron 2022).

External Laurentian CPS. The External Laurentian CPS (EL-CPS) is the lowest structural unit and comprises a crystalline basement with igneous and metamorphic rocks ('Long Range Inlier') yielding U-Pb zircon crystallization ages of 1530-985 Ma (Heaman *et al.* 2002). These rocks are correlated to the Pinware terrane in Labrador (Fig. 3) and are likely part of the Grenville Province (Hoffman 1988; Owen 1991; Waldron and Stockmal 1994; Cawood *et al.* 2001; Heaman *et al.* 2002). The crystalline basement is unconformably overlain by the 'autochthonous' continental margin of Laurentia (Cawood *et al.* 2001). The stratigraphy contains coarse basal conglomerates, arkosic sandstones and local mafic volcanic units of the 'Bateau' and 'Lighthouse Cove' formations of the Labrador Group (Waldron *et al.* 2022 and references therein; White and Waldron 2022, and reference therein). The mafic volcanic rocks are chemically identical to mafic dikes ('Long Range dykes') that yield U-Pb zircon and baddeleyite ages of 615 ± 2 Ma that intrude the crystalline basement in Labrador (NW of Newfoundland; Fig. 3) (Kamo *et al.* 1989). The mafic volcanic and intrusive rocks are interpreted to form during incipient rifting of the Laurentian margin (Cawood *et al.* 2001; White and Waldron 2022; Williams and Hiscott 1987). The overlying 'Bradore Formation' of the Labrador Group is a clastic sedimentary succession of early Cambrian age (~530-515 Ma based on fossil biozones; White and Waldron 2022 and references therein), which contains detrital zircons with Laurentian provenance (Hibbard *et al.* 2006, 2007). Some authors interpret the base of the Bradore formation as representing the rift-drift transition, as the formation does not contain any record of syn-rift igneous activity (e.g., Cawood *et al.* 2001); several authors, on the other hand, place the transition at the top of the formation, corresponding to the change from siliciclastic to carbonate depositition (e.g., Williams and Hiscott, 1987; White and Waldron 2022).

The rift succession grades upward into transgressive limestones and mudstones (upper Labrador Group, 'Port au Port Group' and 'St. George Group') that represent carbonate platform and shelf deposits of a passive margin (Hibbard *et al.* 2006). This passive margin sequence spans from the middle Cambrian to the Lower Ordovician (~520-469 Ma fossil ages; White and Waldron 2022 and references therein).

A regional unconformity spanning 469-464 Ma then breaks the sedimentation ('St. George unconformity'; Waldron 2019; White and Waldron 2022). Then, the 'Table Head Group' records short-lived limestone deposition, locally alternating with conglomerates that rework the underlying platform sequence (Stenzel *et al.* 1990). These limestones grade upward into a fine-grained, Middle Ordovician (~464-460 Ma) siliciclastic turbidite succession (flysch of the 'Goose Tickle Group') containing undifferentiated ophiolite-derived detritus (e.g., ultramafic debris containing chromite; (Stevens 1970; Hiscott 1984; Kerr 2019; White and Waldron 2022). The St. George's unconformity is interpreted as uplift and erosion due to the passage of a forebulge during SE-dipping subduction of the passive margin, and the following succession is interpreted as foreland basin sediments, testifying proximity to the trench (Knight *et al.* 1991; White and Waldron 2022).

Middle Laurentian CPS. The flysch of the External Laurentian CPS is structurally overlain by tectonic slices containing continental margin units, often referred to as 'allochthons' (Stenzel *et al.* 1990; Batten Hender and Dix 2008; White and Waldron 2022) and here named 'Middle Laurentian CPS' (ML-CPS). Their stratigraphy is largely correlative to the 'autochthonous' Laurentian margin they have been thrust upon. It comprises latest Proterozoic mafic units ('Skinner Cove formation' of ca. 556-550 Ma U-Pb zircon age, Hodych *et al.* 2004; McCausland *et al.* 1997), with alkaline and subalkaline geochemical signature (Baker 1979) and Cambrian clastic rocks ('Summerside' and 'Blow Me Down Brook' formations), overlain by limestones and shales ('Irishtown Formation' and 'Cow Head Group') spanning the middle Cambrian-Middle Ordovician (ca. 510-470 Ma; Lacombe *et al.* 2019; White and Waldron 2022). These rocks are interpreted as deeper-water equivalents of units belonging to the 'autochthonous' passive margin succession (James and Stevens 1986; Waldron and Palmer 2000; White and Waldron 2022). This sequence is overlain by coarse-grained siliciclastic turbidites of the 'Western Brook Pond Group', containing chromite-bearing ophiolite detritus (Hiscott 1984; Lindholm and Casey, 1989; White and Waldron 2022; Yan and Casey 2023 and references therein), dated through fossil biozones at ca. 470-465 Ma (Lacombe *et al.* 2019 and references therein). The Middle Laurentian CPS sedimentary units locally occur as blocks in disrupted successions (mélanges) that also contain mafic rocks (Karson and Dewey 1978). These mélanges have gradational contacts with the coherent sedimentary units and may have formed as olistostromes during emplacement of the Middle Laurentian CPS (Lacombe *et al.* 2019). The Middle Laurentian CPS units are folded and duplexed, structures which are attributed to their emplacement on top of the correlative Laurentian-proximal units during the Middle Ordovician (Waldron and Palmer 2000; White and Waldron 2019). However, the absolute timing of deformation remains unconstrained.

The Middle Laurentian CPS margin units are disconformably overlain by the Long Point Group, comprising a thick Upper Ordovician limestone unit (ca. 458-453 Ma graptolite age; Bergström *et al.* 1974) grading into a coarsening upward sandstone succession reaching Katian (i.e., ca. 453-445 Ma) age and containing volcanic clasts (Stenzel *et al.* 1990; Quinn *et al.* 1999). This disconformity corresponds to a hiatus of ca. 5 Ma, which is inferred as the time of emplacement of the Middle Laurentian CPS 'allochthons' towards the west ('Taconian unconformity'; Batten Hender and Dix 2008; Cooper *et al.* 2001).

Internal Laurentian CPS. East of the Middle Laurentian CPS are several meta-sedimentary units (e.g., 'Fleur de Lys Supergroup', 'Corner Brook Lake Block', Fig. 3), recording low-grade metamorphic signatures. This 'Internal Laurentian CPS' (IL-CPS) sequence is interpreted as the metamorphic equivalent to the 'autochthonous' External Laurentian CPS (Williams 1995; Waldron and van Staal 2001; de Wit and Armstrong 2014), and representing the continental margin of Laurentia that was hyperextended and then partly subducted (van Staal *et al.* 2013). In northern Newfoundland, the post-orogenic, dextral strike-slip Cabot fault produced minor displacements on the order of ca. 35 km (Waldron *et al.* 2015) and represents the boundary between the Middle Laurentian CPS in the west and the Internal Laurentian CPS metamorphic units in the east. Farther south, a (probably) normal fault (Cawood *et al.* 1996) is the boundary between the carbonate sequence of the External Laurentian CPS 'autochthonous' Laurentian margin in the west and metasedimentary units of the Internal Laurentian CPS ('Corner Brook Lake Belt/Block') in the east.

The metamorphic units are made up of a basal unit comprising gneisses yielding a U-Pb zircon age of 555 +3/-5 Ma ('Lady Slipper pluton'), metamorphosed magmatic rocks (serpentinite, actinolite/tremolite schist, amphibolite, metabasalt, metagabbro yielding a U-Pb zircon age of 558.3 ± 0.7 Ma (Hibbard 1983; Cawood *et al.* 1996; van Staal *et al.* 2013) and a Proterozoic crystalline basement (Cawood *et al.* 1996; Skulski *et al.* 2010). In the Corner Brook Lake Block of southwestern Newfoundland, in particular, results from U-Pb geochronological studies on zircons (Fig. 3) show an apparent lack of Grenvillian signature in its crystalline basement (Cawood *et al.* 1996; Lin *et al.* 2013 and references therein), although such signature is present in the overlying sedimentary cover (Lin *et al.* 2013). Furthermore, the lithologies of the Corner Brook Lake Block lack any Ordovician metamorphism, but rather $^{40}Ar/^{39}Ar$ on hornblende reveal early Silurian metamorphism (430 ± 4 Ma; Lin *et al.* 2013). Lin *et al.* (2013) thus interpreted this metamorphic unit as being a Laurentian block transported from the north by dextral convergence. This basal sequence is uncomformably overlain by a metasedimentary cover sequence, comprising lower metaconglomerates, quartzites, schists, mica schists, and upper metacarbonate units made up of marble, calc-schist, pelitic schist, and limestone conglomerate (Cawood *et al.* 1996; Lin *et al.* 2013; White and Waldron 2022). No biostratigraphic age exists for these metasediments, but they are stratigraphically correlated to unmetamorphosed equivalents of the Laurentian margin (e.g., White and Waldron 2022). Metamorphic conditions reached amphibolite to eclogite facies (Lin *et al.* 2013). Metamafic and metapelitic rocks of the Fleur de Lys Supergroup in northern Newfoundland yield pressures of 6.7-11.2 kbar and temperatures of 315-600 °C (Willner *et al.* 2022). Metamorphic ages are scarce, mostly hindered by younger deformation and overprinting (Willner *et al.* 2022). However, dating of eclogites (U-Pb zircon and Rb-Sr multimineral isochrons), granites (U-Pb zircon), and mafic schists ($^{40}Ar/^{39}Ar$ white mica and amphibole) beneath the metasedimentary units yield metamorphic ages of ca. 483-460 Ma, constraining regional metamorphism to the Lower-Middle Ordovician (Castonguay *et al.* 2014; de Wit and Armstrong 2014; Willner *et al.* 2015). This is broadly consistent with peak metamorphism inferred at ca. 466 Ma from a U-Pb monazite age in a paragneiss (van Staal *et al.* 2007). Overlying units of Upper Ordovician-Devonian ages lack metamorphism and deformation (Dubé *et al.* 1996) and confirm the metamorphic ages must be Middle Ordovician.

Coastal Complex

Structurally above the southwestern Middle Laurentian CPS units are the Coastal Complex and the Bay of Islands Ophiolitic Complex, which are the two structurally highest units of the west-verging thrust stack (Fig. 4b). The two complexes are geographically close (Fig. 3), and several authors report an igneous contact between them, with the younger Bay of Islands Ophiolite intruding into lithologies of the Coastal Complex (e.g., Karson and Dewey 1978; Karson *et al.* 1983; Yan and Casey 2022). This intrusive relationship is not accepted by all authors (e.g., Jenner *et al.* (1991), who argue for a structural contact).

The Coastal Complex consists of a narrow 5-10-km wide, highly deformed, thrusted, and variably metamorphosed sequence of foliated gabbro, amphibolite, tholeiitic pillow lavas and volcaniclastic rocks (Jenner *et al.* 1991; Kerr 2019; Waldron 2019). No protolith or metamorphic ages are available for these metamorphosed ocean floor rocks. The deformed lithologies of the Coastal Complex were then intruded by leucocratic rocks with arc signature (trondhjemites, diorite, quartz-diorites; Casey *et al.* 1985; Jenner *et al.* 1991; Kerr 2019) with U–Pb zircon ages spanning 514-503 Ma (Yan and Casey 2022), providing a minimum age for the deformation, metamorphism, and thrusting of the oceanic floor lithologies of the Complex. Geochemistry of the basalts and diabases and of the trondhjemites intruding the Coastal Complex indicate arc tholeiitic, suprasubduction zone signatures (Jenner *et al.* 1991). The Coastal Complex is thrust atop undifferentiated deep-water sediments of the Middle Laurentian CPS nappes (White and Waldron 2019; Yan and Casey 2022).

Ophiolites

Bay of Islands Ophiolite. The Bay of Islands Ophiolite Complex is a ~25 km wide klippe located <5 km east-southeast of the Coastal Complex (Fig. 3) and preserves a coherent section of oceanic lithosphere containing, from bottom to top, harzburgite tectonite, peridotite, pyroxenite, foliated and isotropic gabbro, plagiogranite intrusions with a U–Pb zircon age of 488.3 ± 1.5 Ma (Yan and Casey 2020), sheeted dykes, and pillow basalts (Casey and Karson 1981; Casey *et al.* 1983; Yan and Casey 2020). A metamorphic sole at the base of the mantle section comprises uppermost garnet-clinopyroxene granulite and garnet-clinopyroxene amphibolite, a middle unit of common amphibolites with U–Pb zircon ages of 489–484 Ma (Yan and Casey 2023) and U–Pb titanite ages of 486 ± 7 Ma and 484 ± 5 Ma (Fournier-Roy *et al.* 2024) and a lower greenschist unit (Fournier-Roy *et al.* 2024; Yan *et al.* 2025). Geochemistry indicates the upper part of the sole formed from mafic rocks with a MORB affinity (Fournier-Roy *et al.* 2024). Biotite and muscovite in a biotite-garnet metasedimentary schist found within amphibolite facies portions of the sole yielded ages of 480 ± 2 and 479 ± 2 Ma, respectively, recording cooling below ~ 340°C and thus exhumation of the high-grade sole by that time (Yan *et al.* 2025). Greenschist-facies metasedimentary rocks from the middle unit yield youngest U-Pb detrital zircon age of ca. 490 Ma, which is interpreted as the maximum depositional age (Fournier-Roy *et al.* 2024); the detrital zircon analyses also exhibit a subtle peak in Proterozoic ages and a dominant peak in Cambro-Ordovician ages, pointing to contributions from Laurentian lithologies and a Cambro-Ordovician arc, respectively (Fournier-Roy *et al.* 2024). Because of the overlap in metamorphic titanite and detrital zircon ages, Fournier-Roy *et al.* (2024) interpreted the metasedimentary rocks as representing trench-fill sediments which were buried almost immediately after deposition and accreted as a successive slice below older slices of the metamorphic sole; deposition and subduction were thus nearly coeval. The Bay of Islands Ophiolite has a supra-subduction zone (SSZ) geochemical signature (Elthon 1991) and is interpreted to have formed by spreading above a nascent subduction zone (Fournier-Roy *et al.* 2024; Yan and Casey 2023).

The Bay of Islands Ophiolite is thrust over Middle Ordovician (ca. 470-465 Ma) turbiditic sequences of the Middle Laurentian CPS (Yan and Casey 2023) and is unconformably overlain by a Middle

Ordovician (Darriwilian, ca. 467-458 Ma) succession of sedimentary breccia containing ophiolite-derived clasts (red jasper, basalt, diabase clasts, with minor trondhjemite, gabbros, and serpentinized ultramafic clasts), olistostromal shale/mudstone, and coarse red calcareous sandstone (Casey and Kidd 1981). These are interpreted as a syn-obduction sedimentary cover and, together with the foreland basin deposits, they show that the complex emerged by 467 Ma.

Another ophiolitic complex is thrust on top of sedimentary Middle Laurentian CPS units in NW Newfoundland ('St. Anthony Complex'; Dallmeyer 1977; Jamieson 1981) (Fig. 2) and comprises peridotite and an underlying metamorphic sole of metagabbro, granulite, amphibolite, greenschist, and undeformed volcanic rocks at its base (Jamieson 1981). Hornblende $^{40}Ar/^{39}Ar$ ages in amphibolites yield 480 ± 5 Ma ages, and metamorphic zircons in the aureole return U-Pb ages of ca. 495 Ma (Jamieson 1988). Correlations and interpretations of the geological history of this complex are difficult and more data is needed.

Baie Verte ophiolites. East of the Internal Laurentian CPS in northwestern Newfoundland, oceanic units are juxtaposed with Internal Laurentian CPS metasediments along a post-orogenic strike-slip fault, the Baie Verte-Brompton Line (e.g., Waldron *et al.* 2015) (Fig. 3). The Baie-Verte Brompton Line reactivates a crustal-scale, oblique-dextral ductile shear zone. The structure crosscuts a 455 ± 12 Ma syn-tectonic pegmatite dike in the older shear zone, and a 446 ± 1 Ma granodiorite constrains minimum timing of deformation along this fault zone (Brem *et al.* 2007).

The Baie Verte-Brompton Line, together with the Cabot Fault, comprise a strike-slip fault system that separates the western part of Newfoundland comprising the Laurentian CPS units from the eastern domain. Oceanic units exposed east of the Baie Verte-Brompton Line are deemed the 'Baie Verte Oceanic Tract' (Hibbard 1983). This tract is ~5 km wide and includes ultramafic rocks (harzburgite, pyroxenites), gabbros yielding U-Pb zircon ages of 489 +3/-2 Ma, mafic dikes, plagiogranites yielding U-Pb zircon ages of 490 ± 4 Ma, and boninites (e.g., Dunning and Krogh 1985; Cawood *et al.* 1996; Skulski *et al.* 2010). Volcanic rocks have MORB, IAT and OIB geochemical signatures (Swinden *et al.* 1997). Units of the Baie Verte Oceanic Tract all contain elements of oceanic lithosphere and yield similar ages to the Bay of Islands Complex and are therefore interpreted as ophiolites belonging to the same original forearc as the BOIC, but having formed after the formation of the BOIC metamorphic sole (Swinden *et al.* 1997; van Staal *et al.* 2014). The Baie Verte Oceanic Tract units are unconformably overlain by volcano-sedimentary rocks comprising a basal conglomerate with ophiolite-derived (gabbro, basalt and rare boninite) clasts, tholeiitic to calc-alkaline basalts, felsic tuffs of ca. 470 Ma (unpublished age reported in Skulski *et al.* 2010), tuff breccias, and sedimentary rocks including wackes, siltstones, and shales of Early Ordovician age (Skulski *et al.* 2010; Williams 1992). A U-Pb zircon age of a gabbro sill underlying the sequence, and an unpublished felsic tuff age in the sequence, constrains sedimentary deposition between ca. 483 Ma (Ramezani 1992) and 467 Ma, respectively (Skulski *et al.* 2010). This volcano-sedimentary sequence is interpreted as an arc correlated to a magmatic arc preserved farther south (i.e., the Notre Dame Arc, described below; Brem *et al.* 2007).

Lush's Bight ophiolite (northern Newfoundland). In northwestern Newfoundland, the post-orogenic, dextral strike-slip Green Bay Fault exhibits minor displacement (Coyle and Strong 1986; Waldron *et al.* 2015) and separates the Baie Verte ophiolites from other units of oceanic affinity to the east (Fig. 3). These oceanic rocks are commonly grouped as the 'Lush's Bight Oceanic Tract' (Kean *et al.* 1995;

Szybinski 1995; van Staal *et al.* 2007; van Staal and Barr 2012). The Lush's Bight units span a ~20 km-wide zone and their relationships with underlying lithologies are obscured by later faults and igneous intrusions (e.g., Zagorevski *et al.* 2024). The Lush's Bight units dominantly comprise sheeted dikes, plagiogranites, and pillowed lavas of island arc tholeiitic to boninitic affinity, overlain by epiclastic rocks, with minor ultramafic and gabbro sills and dikes (Szybinski 1995; Swinden *et al.* 1997; van Staal and Barr 2012). The magmatic rocks have not been dated but are interpreted as middle-late Cambrian (510-501 Ma; e.g., van Staal *et al.* 2007, 2012) based on crosscutting relationships with younger calc-alkaline dykes ($^{40}Ar/^{39}Ar$ hornblende ages of 504-495 Ma; Szybinski 1995 and references therein). Recently, Yan and Casey (2022) obtained a U-Pb zircon age of 504.3 ± 1.8 Ma for a plagiogranite intrusion ('Twillingate granite'; Fig. 3) cross-cutting the mafic volcanic sequences correlative to the Lush's Bight tract, which may provide a minimum age for the oceanic crust. Geochemistry of the Lush's Bight rocks reveals boninite and island arc tholeiite signatures, with some rocks in the upper part of the sequence yielding MORB signatures (Szybinski 1995; Swinden *et al.* 1997). This is interpreted as a suprasubduction zone setting (Szybinski 1995). The geochemistry of cross-cutting calc-alkaline dikes exhibit a considerable contribution from continental lithosphere; correlation with modern geochemical equivalents led authors to interpret the dykes as deriving from assimilation of continental crust by a mantle-derived magma, and thus to indicate the presence of continental crust at depth (Szybinski 1995; Swinden *et al.* 1997 and references therein). Therefore, the Lush's Bight rocks are interpreted to have been emplaced onto continental crust and then crosscut by continental crust-derived melts (Szybinski 1995; Swinden *et al.* 1997). However, this signature could have also been acquired due to close proximity to continental crust or from subducted Laurentian sediments. We interpret the oceanic Lush's Bight units as ophiolites (without soles) based on their internal stratigraphy.

The Lush's Bight ophiolite is observed in fault contact (Szybinski 1995; Swinden *et al.* 1997) with overlying bimodal volcanic rocks ('Upper Western Arm Group' and 'Catchers Pond Group'), which contain high proportions of felsic pyroclastics and epiclastics, chert, limestone and limestone breccia (Szybinski 1995; Swinden *et al.* 1997). Volcanic ages span 479 ± 4 to 465 ± 1 Ma (U-Pb zircon age and $^{40}Ar/^{39}Ar$ hornblende age of tuffs, respectively; Szybinski 1995), consistent with limestone breccias that are interlayered within the volcanic units and contain fossils indicating Lower-Middle Ordovician deposition (Szybinski 1995 and references therein). The mafic rocks have calc-alkaline signatures (Swinden *et al.* 1997) and felsic rocks show a Nd concentration and Sm/Nd ratios indicative of contamination from continental crust, which is attributed to proximity to the Laurentian continental margin (Szybinski 1995). The volcano-sedimentary sequence is interpreted as renewed volcanism in an island arc setting (Szybinski 1995; Swinden *et al.* 1997), which we here correlate to the volcano-sedimentary units similarly overlying the Baie Verte ophiolites, and to the Notre Dame magmatic arc farther to the south (see next section).

Dashwoods Microcontinent and Notre Dame Arc (Southern Newfoundland)

East of the post-orogenic Cabot-Baie Verte-Brompton strike-slip fault system in southwestern Newfoundland, rocks are mostly continental in nature (Fig. 3). These continental units occupy a 40-km wide zone and are thought to have been located paleogeographically eastward of the oceanic basin that produced the ophiolitic Lush's Bight and Coastal Complex OPS units described above. Only one oceanic complex comprising lower crustal and mantle rocks – gabbro, trondhjemite, and peridotite tectonite (Zagorevski *et al.* 2024) – is reported in southwest Newfoundland (Fig. 3, 'Long Range mafic-ultramafic Complex' of van Staal *et al.* 2007) but lacks any age constraint. Because of its position directly east of the post-orogenic Baie Verte-Brompton Line, this complex has been correlated to oceanic units in similar structural positions in the north of Newfoundland, either to the Lush's Bight ophiolites (van Staal *et al.* 2007; Zagorevski *et al.* 2024) or the Baie Verte ophiolites (e.g., Willner *et al.* 2022), or to oceanic units farther east ('Annieopsquotch Complex', described below; e.g., Dunning and Chorlton 1985).

Dashwoods microcontinent. In the 40-km wide zone east of the Cabot-Baie Verte Brompton fault system, and only in southwestern Newfoundland, metasedimentary rocks are found that are interpreted to make up the 'Dashwoods microcontinent' (Waldron and van Staal 2001) (Fig. 3). These are continent-derived metasedimentary units that comprise metaclastic rocks, marble, migmatized paragneiss yielding U-Pb monazite ages of 466.5 ± 1.8 Ma (van Staal *et al.* 2007), and garnet-muscovite schists yielding U-Pb monazite ages of ca. 460 Ma (McNicoll *et al.* 2007, personal communication reported in Lin *et al.* 2013; Waldron and van Staal 2001 and references therein). Both monazite and zircon ages are interpreted as the ages of peak regional metamorphism, which reached granulite facies (van Staal *et al.* 2007). Although no Precambrian basement is exposed in this southern region, the metasedimentary units are interpreted as correlative to the metamorphic sedimentary units of the Laurentian continental margin (i.e., Fleur de Lys Supergroup; Currie *et al.* 1992; Waldron and van Staal 2001; Brem *et al.* 2007). The contact between the metasedimentary units in southwestern Newfoundland and the oceanic units (i.e., Lush's Bight Ophiolite) in northern Newfoundland is a reverse E-W trending thrust fault ('Little Gran Lake Fault') which thrusts metasedimentary rocks towards the north over oceanic units (Brem *et al.* 2007). Dextral transpression occurred between 463-440 Ma as indicated by U-Pb zircon and $^{40}Ar/^{39}Ar$ muscovite ages of a mylonitized granite (Brem *et al.* 2007).

Notre Dame Arc. The 40-km wide zone east of the Cabot-Baie Verte Brompton fault system is dominated, both in its southern and northern parts, by felsic intrusions which are collectively called the 'Notre Dame Arc' (e.g., van Staal *et al.* 2007) (Fig. 3). The felsic plutons lie ~60 km east of the Bay of Islands ophiolite (Fig. 3) and intrude continental metasedimentary and oceanic units, exposed in southwestern and northern Newfoundland, respectively Fig. 3). The intrusions thus constrain a minimum age for metamorphism of the sedimentary package (Hodgin *et al.* 2022 and references therein). The oldest plutons are pre-tectonic, contain mafic enclaves, and are metamorphosed to high grade (locally up to granulite facies; van Staal *et al.* 2007). They are exposed in southwest Newfoundland, where they intrude the metasedimentary units and the only reported oceanic complex (i.e., the Long Range Complex). U-Pb zircon ages of felsic rocks (tuffaceous schist, tonalitic orthogneiss, and granodiorite) range between 493-489 Ma (Dubé *et al.* 1996; van Staal *et al.* 2007). A second pulse of magmatism, intruding both the metasedimentary units and older intrusions, was more widespread in southwest and north Newfoundland, and ranges in ages between 469 and 459 Ma (tonalite, granodiorite, and charnockite U-Pb zircon ages; Dubé *et al.* 1996; van Staal *et al.* 2007). These plutons are metamorphosed up to amphibolite facies and are interpreted as syn-tectonic (van Staal *et al.* 2007).

The 493-489 Ma *and* the 469-459 Ma felsic intrusive suites both contain inherited zircons and geochemical signatures indicating intrusion into old continental crust with Grenvillian signature (van Staal *et al.* 2007; Whalen *et al.* 1997). Therefore, van Staal *et al.* (2007) interpreted these two

magmatic phases as arc magmatism, built on continental crust. In contrast, Hodgin *et al.* (2022) attributed the Laurentian signature to subducted detritus which does not require the presence of a continental basement.
The timing of metamorphism of late Cambrian-Middle Ordovician intrusions is not well constrained but is inferred to occur at the same time as metamorphism of the units they intrude (i.e., Middle Ordovician). Upper Ordovician-Devonian sedimentary successions that contain deformed felsic clasts at their base (van Staal *et al.* 2007) are not themselves deformed or metamorphosed, which further constrains peak deformation and metamorphism of the underlying units to the Middle Ordovician (Waldron and van Staal 2001). Furthermore, a U-Pb zircon age of 460 ± 10 Ma obtained for a granulite facies meta-granite (Currie *et al.* 1992) is interpreted as the age of peak metamorphism (Brem *et al.* 2007; Currie *et al.* 1992) and indicates that magmatism was syn-tectonic.

Collectively, these late Cambrian-Middle Ordovician plutons are interpreted as a continental magmatic arc, the 'Notre Dame Arc' (e.g., van Staal *et al.* 2007; Whalen *et al.* 1997). The geochemical signature and inherited zircons in the magmas, which were derived from a Precambrian basement, and the presence of metasedimentary units correlated to the Laurentian continental margin, led several authors to infer that a 'Dashwoods microcontinent' had rifted off the Laurentian margin in the Cambrian and then reaccreted during the Early-Mid Ordovician (Waldron and van Staal 2001). The Notre Dame Arc is therefore thought to be in part built on this microcontinent.

Upper Ordovician magmatism in (south)western Newfoundland is limited, but one such restricted volcano-sedimentary group ('Windsor Point Group', ~2 km wide; Fig. 3) unconformably overlies older magmatic units (Dubé *et al.* 1996). The Windsor Point Group comprises felsic and mafic volcanic rocks (453 +5/-4 Ma rhyolite U-Pb zircon age), conglomerates, greywackes, and siltstones (Dubé *et al.* 1996). No geochemical analyses are available for this group, but Dubé *et al.* (1996) related the volcanic rocks to an extensional event, because of the extension-dominated control observed in the distribution of the conglomerate facies. Furthermore, Brem *et al.* (2007) reported a 446 ± 1 Ma U-Pb zircon age for a restricted granodiorite sheet in southern Newfoundland, for which no geochemical analyses are available.
An early-middle Silurian bimodal magmatic pulse is more widespread in northern Newfoundland, constrained by 440-427 Ma granodiorite, quartz-diorite and granite U-Pb zircon ages (Cawood *et al.* 1996; Whalen *et al.* 1987, 2006; Brem *et al.* 2007). Geochemical analyses reveal an arc signature for felsic intrusions dated 440-435 Ma (Whalen *et al.* 2006), which some authors interpret as representing another phase of Notre Dame Arc magmatism (van Staal *et al.* 2007). A mixed arc- and non-arc- (e.g., post-collisional, within-plate) signature is recorded by younger (ca. 432-427 Ma) bimodal magmatics, which Whalen *et al.* (2006) interpreted to result from slab break-off. Silurian magmatism is coeval with a mid-Silurian volcano-sedimentary succession ('Springdale Group'; Fig. 3, Fig. 4) comprising arc to bimodal subaerial magmatic rocks (429 +6/-5 Ma U-Pb zircon age on rhyolite; Chandler *et al.* 1987), polymictic conglomerate with clasts derived from the underlying rocks, and red sandstones (Zagorevski *et al.* 2008). The Springdale Group overlies units of Dashwoods, Lush's Bight, and the Notre Dame Arc, as well as those of the Annieopsquotch Complex (described in the next section), with a sub-Silurian unconformity separating this succession from older rocks (Dunning *et al.* 1990). The Springdale Group is interpreted as an overlap sequence, with within-plate magmatism attributed to thermal adjustments (Chandler *et al.* 1987; Whalen *et al.* 2006).

Annieopsquotch Complex

To the east, structurally beneath the metasedimentary and igneous rocks of the Dashwoods microcontinent and Notre Dame Arc and the oceanic units of the Lush's Bight ophiolite, four mafic and felsic tectonic slices comprise a ~10-km wide, NW-dipping thrust stack (Zagorevski *et al.* 2008). Previously called the 'Annieopsquotch Accretionary Complex' (van Staal *et al.* 1998), herein we call it the 'Annieopsquotch Complex' (Fig. 3). The western contact of this complex is an oblique sinistral NW-dipping shear zone made up of amphibolites and mylonites called the Lloyd's River Fault Zone (Lissenberg and Van Staal 2002). Along this fault, oceanic rocks of the Annieopsquotch Complex are thrust beneath igneous and metasedimentary rocks of the Dashwood microcontinent and Notre Dame arc to the west (Lissenberg and van Staal 2002; Lissenberg *et al.* 2005b). This fault was active from ca. 471 Ma (^{40}Ar/^{39}Ar hornblende age of an amphibolite) to ca. 459 Ma (U-Pb zircon age of a syn-kinematic – with respect to the fault – intrusion) (Lissenberg *et al.* 2005b).

Annieopsquotch Ophiolite Belt. The structurally highest and westernmost unit of the Annieopsquotch Complex below the Lloyd's River Fault Zone is an oceanic complex ('Annieopsquotch ophiolite belt') made up of gabbro sills, mafic cumulates, sheeted dikes, and plagiogranitic bodies yielding U-Pb zircon ages of 477.5 +2.6/-2 and 481 +4/-2 Ma (Dunning and Krogh 1985) and pillow lavas. Pillows show three magmatic phases with boninitic, tholeiitic and MORB signatures (Lissenberg *et al.* 2005a, b). The Annieopsquotch ophiolite belt is crosscut by (deformed) plutons of mafic to granodioritic with crystallization and/or deformation ages ranging from 464 to 459 Ma. Similar geochemical signature and ages of these plutons led to correlations with the Notre Dame Arc (Lissenberg *et al.* 2005a).

Lloyd's River Complex. The sinistral transpressive, greenschist to amphibolite facies shear zone 'Otter Brook shear zone' (Lissenberg *et al.* 2005a) separates the Annieopsquotch ophiolite belt from the structurally underlying oceanic 'Lloyd's River Complex' to the east. The Otter Brook shear zone comprises mylonites, phyllonites, and micaschists with a NW-dipping foliation, deformed rhyolites, micaschists, and amphibolites (Lissenberg *et al.* 2005a; Zagorevski and van Staal 2002; Zagorevski *et al.* 2006). The Lloyd's River Complex comprises gabbro (473 ± 3.4 Ma U-Pb zircon age; Zagorevski *et al.* 2006), anorthosite, sheeted diabase dikes, and pillow lavas with a tholeiitic geochemical signature that is distinct from the overlying Annieopsquotch ophiolite belt (Lissenberg *et al.* 2005a; Zagorevski *et al.* 2006). The Otter Brook shear zone, Annieopsquotch ophiolite belt, and Lloyd's River Complex are all intruded by syn-kinematic – with respect to the shearing – mafic rocks (gabbro) and granodiorites (468 ± 2 Ma U-Pb zircon age; Lissenberg *et al.* 2005a) thereby constraining a minimum age of emplacement of the Lloyd's River Complex below the Annieopsquotch ophiolite belt by 468 Ma. Both the Annieopsquotch ophiolite belt and the Lloyd's River Complex are interpreted as the deformed remnants of upper plate ocean floor.
The Lloyd's River Complex is bounded to the SE by brittle-ductile thrust faults (Lissenberg *et al.* 2005b) that juxtapose it against bimodal volcaniclastic rocks of the two deepest structural units of the Annieopsquotch Complex. No radiometric dates of these faults is available.

Buchans Group. The Buchans Group lies east of and structurally below the Lloyd's River Complex, and comprises pillow basalts, breccia, diabase, dacites, and rhyolites yielding U-Pb zircon ages of

473 +3/-2 Ma (Dunning *et al.* 1987), felsic tuff yielding U-Pb age of 473.4 ± 1.2 Ma, and cherts (Dunning *et al.* 1987; Zagorevski *et al.* 2006). Geochemical and isotopic characteristics of the felsic and mafic volcanic rocks indicate contributions from continental material, leading Zagorevski *et al.* (2006) to interpret the Buchans Group as either a continental magmatic arc or as an oceanic arc having acquired the signature from subducted continental crust. Detrital zircon U-Pb ages and Lu-Hf isotopic signatures in sedimentary rocks of the Buchans Group yield characteristics like sedimentary units of the continental Laurentian margin farther to the west, i.e., Fleur de Lys Supergroup (Willner *et al.* 2014), which indicate that this unit was located close to the continental margin of Laurentia. Structural relationships and geochemical analyses of the Buchans Group led Lissenberg *et al.* (2005b) to posit 467 Ma as a minimum age of its westward accretion beneath the Lloyd's River Complex.

Mekwe'jite'wey Group. The Buchans Group is juxtaposed against the structurally lowest and easternmost Mekwe'jite'wey Group (herein using its indigenous name; previously called the 'Red Indian Lake Group', Matthews *et al.* 2018) along a seismically imaged km-scale fault (Thurlow *et al.* 1992). The Mekwe'jite'wey Group contains the youngest rocks of the Annieopsquotch Complex (Lissenberg *et al.* 2005a; Zagorevski *et al.* 2006). It comprises pillow basalts (MORB to IAT to andesitic composition) associated with red shale, jasper, limestone, diabase, gabbro, and plagiogranites intruding mafic rocks (U-Pb zircon age of 464.8 ± 3.5 Ma; Zagorevski *et al.* 2006), and felsic tuff. This sequence is overlain by a volcanogenic conglomerate (467 ± 4 Ma U-Pb zircon age interpreted as its maximum deposition age; Coombs *et al.* 2012) and hematized calc-alkaline pillow basalts interlayed with tuffs yielding U-Pb zircon ages of 465-462 Ma, rhyolites, volcaniclastic sandstone, shales, and cherts (Zagorevski *et al.* 2006). Geochemical signatures of the mafic units indicate a volcanic arc and back-arc setting for the tholeiitic basalts and a continental arc setting for the overlying calc-alkaline basalts (Zagorevski *et al.* 2006). Inherited zircons in the conglomerate and tuffs (Zagorevski *et al.* 2006; Coombs *et al.* 2012) indicate contribution from Laurentian continental rocks, although a basement is nowhere exposed. Some volcanic clasts in the conglomerate show Laurentian zircon signatures (Coombs *et al.* 2012), which may be derived from subducted continental material.

The Mekwe'jite'wey Group is thrust southeastward on top of magmatic units with exotic affinity (see next section) (Fig. 3) along the 'Mekwe'jit Line' (White and Waldron 2022; previously called the 'Red Indian Line', Williams *et al.* 1988). Its trace is locally marked by highly tectonized Upper Ordovician black shale mélange (Rogers and van Staal 2002; Zagorevski *et al.* 2006). Seismic imaging reveals this is a crustal scale structure (van der Velden *et al.* 2004). The black shale mélange is interpreted as syn-collisional, and the associated shear zone is interpreted as having sinistral oblique SSE-directed movement, displacing the Mekwe'jite'wey Group above the exotic units (Zagorevski *et al.* 2008).

Williams *et al.* (1988) initially defined the Mekwe'jit Line based on faunal differences. Brachiopods and trilobites of Celtic affinity occur in the 'Summerford Group' sediments (description below), located just east of the Mekwe'jit Line and structurally below the Annieopsquotch Complex (e.g., Neuman 1984; Williams 1995; Harper *et al.* 2009). These taxa are inferred to originate from Gondwana and lived offshore near island arcs (van Staal *et al.* 1998 and references therein; Harper *et al.* 2009 and references therein) which constrains this group as Gondwana-derived. The conformable Ordovician to Silurian marine sedimentary cover overlying the exotic units to the east of the Mekwe'jit Line (see detailed description in the next section) differs from the unconformable, terrestrial Silurian cover of the Notre Dame Arc and Annieopsquotch Complex to the west. Westward accretion of these exotic units below the Mekwe'jite'wey Group is not precisely dated but it is inferred to have occurred between ca. 455-450 Ma, based on the youngest magmatic age of the Victoria arc (description below) located east of the Annieopsquotch Complex and thrust beneath it (Lissenberg *et al.* 2005b and references therein). As such, most studies interpret the Mekwe'jit Line (Fig. 2, 3) as the location of the main Iapetus suture between Gondwana- and Laurentia-derived continental and oceanic domains (Williams *et al.* 1988; van Staal *et al.* 1998, 2012; Zagorevski *et al.* 2008).

Penobscot and Victoria CPS Units

Several fault-bounded units are present SE of the Mekwe'jit Line. Herein, we subdivide a northern Newfoundland sequence (transect in Fig. 4a) and a central Newfoundland sequence (transect in Fig. 4b) but group them as a single unit in Fig. 3.

Penobscot and Victoria units in northern Newfoundland (CPS). SE of the Mekwe'jit Line and structurally below the Annieopsquotch Complex, magmatic and sedimentary sequences are interpreted as magmatic arc units. These include the Summerford Group, the Wild Bight Group, and the Exploits Group (Fig. 3). The northernmost is the Summerford Group, a ~5-km wide, fault-bounded unit made up of mafic volcanic rocks (pillow lavas, lapilli tuffs, tuff breccia) interbedded with limestone, arkosic sandstone, mafic-derived sandstones, argillite, felspathic wacke and shale (Jacobi and Wasowski 1985; Zagorevski *et al.* 2012). (Fig. 3). The limestones contain Lower to Middle Ordovician fossils (Tremadocian-Darriwilian; Horne 1970; Elliott *et al.* 1989), and endemic trilobite Celtic fossils interpreted to come from the Gondwana margin; Laurentian fossils are absent. Based on the faunal argument, the Mekwe'jit line is interpreted as a suture (Harper *et al.* 2009). Basalts are tholeiitic to alkaline and exhibit geochemical characteristics of within-plate and transitional arc environments (Jacobi and Wasowski 1985; Zagorevski *et al.* 2012). The Summerford Group was first interpreted as an accreted seamount (Jacobi and Wasowski 1985) but has recently been correlated to the Victoria Lake Supergroup, interpreted as a magmatic arc (Zagorevski *et al.* 2012). SE of the Summerford Group, a small unit ('Dunnage Mélange') contains magmatic blocks with similar geochemical characteristics to the Summerford Group (Wasowski and Jacobi 1985), as well as sedimentary clasts containing fossils indicative of Gondwanan proximity and mostly Lower Ordovician and Cambrian ages (Dean 1985; Hibbard *et al.* 1977; Zagorevski *et al.* 2012). The Dunnage Mélange is intruded by a porphyritic granite yielding a U-Pb zircon age of 469 ± 4 Ma (Zagorevski *et al.* 2012), which has no correlatives anywhere in this part of Newfoundland. The granite contains inherited zircons derived from Gondwana continental crust, taken as further evidence of peri-Gondwana origin for the mélange unit and the Summerford Group (Zagorevski *et al.* 2012).

South and west of the Summerford Group, the ~20-km wide Wild Bight group occupies a similar structural position east of the Mekwe'jit Line below the Annieopsquotch Complex (Fig. 3). The Wild Bight group is subdivided into 'lower' and 'upper' units. The lower unit comprises a bimodal volcanic sequence with pillow lavas (tholeiitic and boninitic composition), pillow breccias, and porphyritic rhyolites; a 486 ± 4 Ma U-Pb zircon age from a mafic dike (MacLachlan and Dunning 1998b) cross-cutting the felsic breccia, tuff, argillite, and chert constrains a minimum formation age. The lower package occurs as fault-bounded slices intercalated within the upper package, but these (thrust) faults are not well exposed (MacLachlan *et al.* 2001). Geochemical characteristics of the lower mafic and felsic rocks indicate a depleted mantle source and a subduction influence (MacLachlan and Dunning 1998b), interpreted to form in an extensional, suprasubduction zone setting (MacLachlan and Dunning 1998b). The lower Wild Bight Group is correlated to another faut-bounded unit in the same area, the 'South Lake Igneous Complex' (MacLachlan and Dunning, 1998b), which is made up of gabbro, gabbroic pegmatite (U-Pb zircon age of 489 ± 3 Ma) and sheeted dikes intruded by diorite and tonalite plutons (U-Pb zircon ages of 489 ± 2 and 486 ± 3 Ma for the plutons, respectively; MacLachlan and Dunning 1998b). The mafic rocks are island arc tholeiites that resemble the older magmatic units of the Wild Bight Group (MacLachlan and Dunning 1998b) and are interpreted to have formed in a suprasubduction zone setting (Zagorevski *et al.* 2010).

The upper Wild Bight Group unconformably overlies the lower unit and is a volcano-sedimentary sequence comprising tuffaceous sandstone, greywacke, polylithic conglomerate, mafic volcanic flows, intermediate-felsic sills and dikes, and argillite and chert. The argillite and chert are interleaved at the top of the succession with pillow basalt sills, pillow basalt breccia, intermediate to felsic sills and dikes and mafic agglomerate (MacLachlan and Dunning 1998a; MacLachlan *et al.* 2001). Diabase and gabbro dikes (472 +2/-9 and 471 ± 4 Ma U-Pb zircon and baddeleyite ages) intrude the whole succession (MacLachlan *et al.* 2001; MacLachlan and Dunning 1998a). Tuffs within the volcaniclastic units yield U-Pb zircon ages of ca. 472 Ma (MacLachlan and Dunning, 1998a) and 458 ± 3 Ma (Zagorevski *et al.* 2008). Clasts of the lower Wild Bight Group occur in volcaniclastic units of the upper sequence, indicating that the upper sequence developed on a substrate made up of the lower Wild Bight Group (MacLachlan *et al.* 2001; MacLachlan and Dunning 1998a). Geochemistry varies from calc-alkaline compositions in mafic flows with crustal contamination, to enriched tholeiitic to alkaline basalts with within-plate affinities in the volcanic sills (MacLachlan and Dunning 1998a). Based on the geochemistry, the upper Wild Bight Group is interpreted to represent a magmatic arc (MacLachlan and Dunning 1998a).

To the east and structurally above the Wild Bight Group (MacLachlan *et al.* 2001; O'Brien *et al.* 1997), and south of the Mekwe'jit Line (e.g., O'Brien *et al.* 1997; McNicoll *et al.* 2006), the ~50-km wide Exploits Group (Fig. 3) comprises a lower magmatic package of porphyritic basalt (island arc tholeiites enriched in REEs; Zagorevski *et al.* 2010), calc-alkaline mafic extrusions, dikes, rhyolites, felsic pyroclastic rocks (486 ± 3 Ma U-Pb zircon age; O'Brien *et al.* 1997) andesitic tuff, diabase intrusions, pillow lavas (tholeiite) and breccia, intercalated with limestones, chert and rare epiclastic turbidites (O'Brien *et al.* 1997, Zagorevski *et al.* 2010). This succession is overlain by a sedimentary package with argillaceous red cherts, oxide-facies iron formation related to the underlying basalts, sandstones, mudstones and conglomerates with Lower Ordovician graptolites and volcaniclastic rocks (O'Brien *et al.* 1997). The sedimentary package is overlain by an upper volcano-sedimentary succession comprising pillow lava and interstitial chert and turbidites yielding a Lower to Middle Ordovician graptolites and conodonts, diorites, subvolcanic dikes, pillow basalt breccias, and massive basalt with intervals of cherts and limestones (O'Brien *et al.* 1997). The mafic rocks in the upper succession yield MORB, transitional tholeiitic, and alkalic geochemical signatures (O'Brien *et al.* 1997). The Exploits Group is interpreted to represent a suprasubduction zone oceanic island arc, expressing a lower magmatic package evolving to arc rifting formation of an oceanic basin. It is correlated to successions with similar geochemistry in the Wild Bight Group (O'Brien *et al.* 1997).

Based on geochemistry and inherited zircon provenance, the lower magmatic sequence (i.e., middle-late Cambrian) in the Wild Bight and Exploits Groups have been interpreted as an oceanic magmatic arc (‘Penobscot Arc’ of van Staal *et al.* 1998) that formed on the Gondwana side of the Iapetus Ocean. These units record a pre-Caledonian geological history and therefore we interpret them as the basement of the younger volcano-sedimentary sequences; in our nomenclature this unit qualifies as a CPS (Fig, 4a, referred to as ‘Penobscot and Victoria CPS’). The younger Ordovician sequence in the Wild Bight, Exploits and Summerford Groups, and other units to the south, is deemed the ‘Victoria Arc’ and is interpreted to have been built on the remains of the Penobscot Arc (van Staal *et al.* 1998). The two sequences are separated by a ~15 Ma magmatic hiatus spanning ~485-470 Ma (Fig. 4).

‘Victoria Lake Supergroup’ in central Newfoundland (CPS). The ‘Victoria Lake Supergroup’ occurs about 60 km south of the Wild Bight and Exploit Groups, to the east of the Mekwe’jit Line and structurally below rocks of the Annieopsquotch Complex (Evans and Kean 2002, Zagorevski *et al.* 2010) (Fig. 3; Fig. 4). It is made up of several fault-bounded units occupying a total width of ~50 km. The faults are interpreted as thrusts (e.g., Zagorevski *et al.* 2007) but have not been dated. These units have similar characteristics and are therefore grouped together in a singular sequence in Fig. 4b.

At the bottom of the Victoria Lake Supergroup is a ~5-km wide continental-affinity Neoproterozoic unit (‘Sandy Brook Group’; Fig. 3; Fig. 4b) that lies structurally below the easternmost fault-bounded unit of the Victoria Lake Supergroup (McNicoll *et al.* 2008). The stratigraphy of the Sandy Brook Group is not well defined, but it is made up of volcanic rocks (basalts, mafic tuffs, andesite, cherty rhyolite; U-Pb zircon age of 563 ± 2 Ma; Rogers *et al.* 2006) associated with minor siliciclastic sedimentary rocks (Rogers *et al.* 2006) and several magmatic intrusions ranging in composition from pyroxenite, gabbro to diorite, quartz-monzonite (563 ± 2 Ma U-Pb zircon age; Evans *et al.* 1990), monzonite (565 +4/-3 Ma U-Pb zircon age; Evans *et al.* 1990) and granite (Evans and Kean 2002, Rogers *et al.* 2006). Geochemical analyses indicate an arc signature for both the felsic and mafic rocks of the Sandy Brook Group (Rogers *et al.* 2006). U-Pb dating of monazite in a quartz-monzonite yielded an age of 545 ± 3 Ma, which is interpreted as a metamorphic age (Evans *et al.* 1990). Although the contact with units to the west is faulted, the Sandy Brook Group yields identical inherited zircon ages as the fault-bounded units of the Victoria Lake Supergroup and is thus interpreted as the basement on which the Victoria Lake Supergroup was built (McNicoll *et al.* 2008; Rogers *et al.* 2006).

The fault-bounded units overlying the Sandy Brook Group comprise a basal bimodal sequence made up of felsic tuff, tuff and volcanic breccia (487 ± 3 Ma U-Pb zircon age; Zagorevski *et al.* 2007), ash tuff, subvolcanic intrusions (491 ± 3 Ma U-Pb zircon age; Hinchey and McNicoll 2009), rhyolite (498 +6/-4 Ma U-Pb zircon age; Evans *et al.* 1990), pillow basalt, diabase, andesite, dacite (514 ± 7 Ma U-Pb zircon age; McNicoll *et al.* 2008), mafic-derived sedimentary rocks, volcaniclastic rocks (U-Pb zircon age of 506 ± 3 Ma Zagorevski *et al.* 2010) and minor breccia (Zagorevski *et al.* 2010). Magmatic rocks in these units reveal an island arc signature (Rogers *et al.* 2006; Zagorevski *et al.* 2010), with juvenile island-arc tholeiite to, in some cases, calc-alkaline geochemistry (Zagorevski *et al.* 2010). Because of similar geochemical characteristics and ages, this basal bimodal sequence of ca. 514-486 Ma age is considered equivalent to the Penobscot arc lithologies in northern Newfoundland (Zagorevski *et al.* 2010).

The Penobscot arc is unconformably (McNicoll *et al.* 2008; Zagorevski *et al.* 2007, 2008) overlain by younger volcano-sedimentary sequences comprising felsic (U-Pb zircon ages ranging between 457-453 Ma; Zagorevski *et al.* 2007, 2008) and mafic tuff, rhyolite (462 +4/-2 Ma; Dunning *et al.* 1987), felsic dikes, gabbro sills, basalt flows, epiclastic volcanic rocks, volcanogenic greywacke, siltstone and shale, breccia and conglomerate (McNicoll *et al.* 2008; Zagorevski *et al.* 2007, 2008).

Volcanic and epiclastic components decrease towards the top and are overlain by black shale with minor volcanogenic siltstone and sandstone (McNicoll *et al.* 2008; Zagorevski *et al.* 2007, 2008). The magmatic rocks have within-plate trending to continental arc signatures (Zagorevski *et al.* 2007), and mafic rocks are E-MORB (Evans and Kean, 2002; Zagorevski *et al.* 2010). This led Zagorevski *et al.* (2007) to interpret these units as a continental arc and back-arc basin. These younger (i.e., 462-453 Ma) sequences are interpreted as part of the Victoria arc (Zagorevski *et al.* 2010), correlative to the Ordovician volcano-sedimentary sequences in the Wild Bight, Summerford and Exploits Groups in northern Newfoundland, which yield similar magmatic ages and geochemical characteristics (e.g., O'Brien *et al.* 1997; Zagorevski *et al.* 2010). Similarly to the Penobscot and Victoria CPS in northern Newfoundland, the Victoria arc units of southern Newfoundland are built on a basement with pre-Caledonian history (i.e., the Sandy Brook Group and Penobscot arc); thus, the 'Victoria Lake Supergroup' sequence also qualifies as a CPS (Fig. 4b, referred to as 'Victoria Lake CPS').

Both the Penobscot and Victoria CPS in northern Newfoundland and the Victoria Lake CPS in central Newfoundland are conformably overlain by a widespread black shale unit (often simply referred to as 'Caradoc black shale') of Upper Ordovician age (Sandbian-early Katian, ca. 458-450 Ma, graptolite age; Currie 1995; Williams *et al.* 1993; Waldron *et al.* 2012). This shale unit differentiates the "exotic" units assigned to the Penobscot and Victoria arcs from the ones lying west of the Mekwe'jit Line which lack a conformable marine cover (van Staal *et al.* 1998; Waldron *et al.* 2012; Zagorevski *et al.* 2007). The Caradoc black shale marks the magmatism cessation of the Victoria arc (Zagorevski *et al.* 2007). It is gradually overlain by a coarsening-upwards, Upper Ordovician-to-lower Silurian marine siliciclastic sedimentary sequence ('Badger Group'; Fig. 4). The Badger Group comprises greywackes grading into conglomerates and greywackes at its base, and olistostromes and siltstones towards the top (Arnott, 1983; Waldron *et al.* 2012; Williams *et al.* 1993). Zircon U-Pb analyses at the bottom and top of the Badger Group indicate sediment derivation from the Laurentian margin, so it is interpreted as a foreland basin succession deposited upon arrival of the underlying sequences at the margin of Laurentia (McNicoll *et al.* 2001; Waldron *et al.* 2012; Zagorevski *et al.* 2007 and references therein). The Badger Group exhibits folding that is not recorded in overlying mid-Silurian structures (Waldron *et al.* 2012), which is the structural signature of accretion in the early Silurian (Waldron *et al.* 2018). The Badger Group is disconformably (e.g., van Staal *et al.* 2014 and references therein) or conformably (e.g., Williams, 1991) overlain by a widespread mid-late Silurian subaerial volcano-sedimentary succession ('Botwood Group'; Williams *et al.* 1993) comprising subaerial basalt flows, volcaniclastic rocks and red sandstone (Pollock *et al.* 2007; van Staal *et al.* 2014). The Botwood Group was regionally deformed before being intruded by gabbroic and granitic plutons of the 'Mount Peyton Intrusive Suite' at ca. 424 Ma, i.e., in the mid-late Silurian (McNicoll *et al.* 2006). The Botwood Group is correlated with the Silurian volcano-sedimentary Springdale Group which unconformably overlies the Notre Dame Arc and Annieopsquotch Complex west of the Mekwe'jit Line and therefore postdates orogenesis (Chandler *et al.* 1987; Williams *et al.* 1993) (Fig. 4a, b).

Ganderia Continental Margin: Meelpaeg CPS; Mount Cormack CPS; Ganderia CPS; Avalonia margin CPS And Hermitage Flexure

Several metamorphic continental units occur east of the Victoria Lake CPS that are interpreted as the microcontinent Ganderia (e.g., van der Velden *et al.* 2004; van Staal and Barr 2012; van Staal *et al.*

1998, 2021a). The metamorphic units are exposed in tectonic windows beneath ophiolites and overlain by an unmetamorphosed cover sequence (Fig. 4).

Crystalline Basement: Hermitage Flexure. The crystalline basement of the metamorphosed continental units contains lithologies present in a restricted area of southwestern Newfoundland named the Hermitage Flexure, which comprises several Neoproterozoic tectonic windows making up an E-W trending belt (Dunning *et al.* 1990; Valverde-Vaquero *et al.* 2006b) (Fig. 3). This Hermitage Flexure is made up of ortho- and paragneiss (675 +12/-11 Ma; Valverde-vaquero *et al.* 2006b), low-grade Ediacaran volcano-sedimentary rocks and felsic and mafic intrusive rocks (e.g., Roti Intrusive Suite) with 578 ± 10 to 495 ± 2 Ma (U-Pb ages of granodiorites and gabbro; Dunning and O'Brien 1989; O'Brien *et al.* 1991; Dubé *et al.* 1995). These intrusions are cross-cut by oblique-convergent deformation (O'Brien *et al.* 1993). Contacts between the Hermitage Flexure and surrounding lithologies are mostly obscured by younger intrusions (Conliffe *et al.* 2024) (Fig. 3). This region was previously proposed to be a basement of the microcontinent Avalonia because of a similar Neoproterozoic geological history (e.g., Valverde-Vaquero *et al.* 2006b). In contrast, other authors argue that this region is the basement of the microcontinent Ganderia, based on reflection seismic studies, the difference in metamorphism with the basement of Avalonia, and correlations with other Ganderian terranes in mainland Canada (e.g., van der Velden *et al.* 2004; van Staal *et al.* 2021a; Waldron *et al.* 2022). Hermitage Flexure lithologies are correlated with the Sandy Brook Group at the base of the Victoria Lake CPS (Rogers *et al.* 2006) (Fig. 3; Fig. 4b) described in section 3.6. Our compilation supports that the Hermitage Flexure represents the basement of Ganderia.

Ganderia Continental Units (CPS). The most complete sequence of metamorphosed continental units is a ~60-km wide belt of deformed metasedimentary and igneous rocks in the east (Fig. 3). The metasedimentary units belong to the Gander Group, which comprises quartz-rich sandstones, siltstones and shales now metamorphosed to psammitic and pelitic schists of middle-upper greenschist facies, with minor mafic dikes and greenschist horizons that were originally tuffs (Bazinet 1980; Currie 1995; Nance *et al.* 2008). No fossils occur in this unit, but its maximum age is inferred at 545 Ma based on the age of a detrital titanite in the bottom part of the section. It is older than 474 Ma based on cross cutting relationships with intrusive granites (van Staal *et al.* 1996 and references therein). Deformation structures are different compared to the overlying units that contain Middle-Late Ordovician fossils which indicates the minimum age of the Gander Group must be Lower Ordovician (Bazinet 1980). Metamorphic conditions are not well-quantified but are roughly greenschist facies (Bazinet 1980). The metamorphic grade of the Gander Group increases to the east, reaching amphibolite conditions in pelitic gneisses of the Square Pond Gneiss (Blackwood 1977; O'Neill 1992). The Gander Group is interpreted as deposition at a continental margin on the eastern (present coordinates) side of the Iapetus Ocean (Bazinet 1980; van Staal *et al.* 2014, 2021a). Clastic syn-rift sequences are capped by pelagic sediments representing a deeper marine environment and the end of rifting (van Staal *et al.* 2021a). Detrital zircons indicate that the sediment source was continental Gondwana (Currie 1995 and references therein). East of the Gander Group, a band of gneissic units ('Hare Bay Gneiss', Fig. 3) are interpreted as part of the same succession, since there is no evidence for deformation or unconformities (Holdsworth 1994). The Hare Bay Gneiss comprises upper amphibolite-facies metasediments (paragneiss and migmatites) interpreted as high-grade equivalents of the Gander Group; greenschist-facies orthogneiss with granitic to tonalitic composition; and amphibolites interpreted as metamorphosed mafic intrusions (Blackwood 1977; D'Lemos *et al.* 1997; Holdsworth 1994; Langille 2012). The orthogneisses yield 510 ± 4 and 491 ± 4 Ma U-Pb zircon ages (Langille 2012) but lack any geochemical study. The Hare Bay Gneiss is intruded by several granitic bodies that are lithologically indistinguishable from the Cambrian orthogneiss (Holdsworth 1994). Apart from two Middle Ordovician ages (465 ± 2 and 460 ± 2 Ma U-Pb zircon ages of a granitic orthogneiss and leucogranite, respectively), intrusions in this area yield middle Silurian (428-412 U-Pb zircon ages of leucogranites, tonalites, granites) to Middle Devonian ages (387 ± 2 Ma U-Pb zircon age of a late pegmatite) (Langille 2012). The granites are foliated and thus interpreted as deformed during formation of the Wing Pond Shear Zone, which separates these units from the Avalonia CPS (see below) (Holdsworth 1994; D'Lemos *et al.* 1997). Orthogneisses and later intrusions show similar geochemical signatures that suggest melting of sedimentary crustal material (Langille 2012).

The Gander Group and Hare Bay Gneiss present features of Continental Plate Stratigraphy and we thus interpret this nappe as a CPS (Fig. 4, referred to as 'Ganderia CPS').

The Gander Group and Hare Bay Gneiss are bounded to the east by the steeply dipping Dover-Hermitage Bay Fault (Fig. 3), a dextral ductile shear zone that overprints the wider, sinistral Wing Pond shear zone (Langille 2012; Kellet *et al.* 2016). Seismic imaging indicates this fault-and-shear is a crustal-scale structure that offsets the Moho and separates crustal terranes with different seismic characteristics (Keen *et al.* 1986). The Wing Pond Shear Zone likely operated after the Caledonian orogeny, in the late Silurian to Devonian (between 422-394 Ma), based on U-Pb dating on monazite and $^{40}Ar/^{39}Ar$ dating on white mica in granites close to the Dover Fault (Kellett *et al.* 2016). The younger Dover Fault was active in the middle to late Devonian, between ca. 385 Ma ($^{40}Ar/^{39}Ar$ on white mica; Kellet *et al.* 2016) and 377 ± 4 Ma (age of a granite stitching the fault; O'Brien 1998 reported in Lynch *et al.* 2009). Total displacement along this fault zone is not constrained.

Avalonia Margin (CPS). The lithologies east of the Dover-Hermitage Bay Fault are offset compared to their position in the Late Ordovician-early Silurian, but their basement is different from the units to the west, and therefore are not a repetition of the Ganderia units located to the west. These units comprise 'Avalonia' (Williams 1979), exhibiting a Neoproterozoic basement with a complex tectonic history, and a variety of sedimentary and magmatic arc-related rocks ranging from ca. 760 to 545 Ma (O'Brien *et al.* 1996; Nance *et al.* 2002; van Staal *et al.* 2021b) that are interpreted to indicate subduction below the Gondwana margin (Nance *et al.* 2002). The magmatic rocks are overlain, in many areas unconformably, by ca. 575-545 Ma volcanic and volcaniclastic units that are bimodal (i.e., both mafic and felsic) in nature (Nance *et al.* 2002). The sedimentary rocks transition from marine to terrestrial in the latest Neoproterozoic (O'Brien *et al.* 1996). The magmatic units display calk-alkaline and arc tholeiite bimodal geochemistry (O'Brien *et al.* 1996; Nance *et al.* 2002). The terrestrial rocks conformably transition to a lower Cambrian (fossil age; Rast *et al.* 1976; Landing, 1996) sequence comprising quartz-arenites to fine grained, deeper marine sediments to near-shore sediments (O'Brien *et al.* 1996). The lower Cambrian succession unconformably overlies the basement in locations where the terrestrial units are absent. The Neoproterozoic basement and Cambrian sedimentary sequence have been correlated to units in North Africa with Gondwanan affinity (O'Brien *et al.* 1983), similar to the sedimentary units of Ganderia and associated terranes to the west. The latest Precambrian to early Cambrian sequence is interpreted to record the evolution from subduction with a well-developed arc to platformal sedimentation without robust evidence for continental collision (O'Brien *et al.* 1996; Nance *et al.* 2002). The lower Cambrian marine sediments shift into middle Cambrian siliciclastic pelagic sediments, locally with basalts and sills (Landing, 1996; O'Brien *et al.* 1996; Pohlner *et al.* 2020). Shale deposition continued into the Lower Ordovician, grading to sandstone, siltstone and quartz arenite and then, in upper part of the Lower Ordovician, to quartz-arenites, micaceous sandstones, siltstones and oolitic hematite (O'Brien *et al.* 1996). Fossil fauna in these marine sediments is interpreted as peri-Gondwanan until the Early Ordovician (Nance *et al.* 2002 and references therein). Cambrian to Lower Ordovician platformal sedimentation is attributed to intracontinental rifting or transtensional pull-apart basins (O'Brien *et al.* 1996); the Middle Cambrian bimodal volcanism is possibly consistent with intracontinental rifting (Nance *et al.* 2002). The Lower Ordovician coarser sediments have not been paleogeographically interpreted, but they might represent foreland basin deposits, deposited on top of shales of a passive margin. Younger geological records do not exist for this area of eastern Newfoundland, although seismic profiles and drilled cores offshore show that Ordovician-Silurian shales are overlain by post-Caledonian Devonian redbeds (Holdsworth 1994 and references therein). Similarly to the Ganderia CPS, we interpret units to the east of the Dover-Hermitage Bay Fault as representing Continental Plate Stratigraphy ('Avalonia CPS' in Fig. 4).

Tectonic Windows: Meelpaeg and Mt. Cormack (CPS). Several correlative units are preserved to the west of the Gander Group in tectonic windows (i.e., 'Meelpaeg Metamorphic Nappe' and 'Mount Cormack Terrane'; Fig. 3).

The '**Meelpaeg** Metamorphic Nappe', or 'Meelpaeg Metamorphic allochthon', is a ~40-km wide metamorphic continental unit (Fig. 3) bounded by shear zones with a sharp metamorphic transition from greenschist- to amphibolite-facies both in the west and east (van der Velden *et al.* 2004; Valverde-Vaquero and van Staal 2001; Valverde-Vaquero *et al.* 2006a). The western boundary is interpreted as an east-dipping thrust (Valverde-Vaquero and van Staal 2001) and the eastern boundary as an east-dipping, low angle normal fault (van der Velden *et al.* 2004 and references therein). The Meelpaeg Nappe is made up of metapsammites, semipelites, quartzites, orthogneiss and migmatitic gneiss interpreted as continental margin units of Ganderia (Valverde-Vaquero *et al.* 2006a). Early Devonian metamorphism (420-411 Ma monazite U-Pb age on metamorphic rocks and syn-metamorphic plutons) intensifies towards the core of the nappe (Valverde-Vaquero *et al.* 2006a and references therein). The Meelpaeg Nappe is interpreted to record deep burial followed by extrusion towards the NW in the early Devonian (van der Velden *et al.* 2004).

Along the western boundary of the nappe, a narrow (~3-km wide) belt of high-grade metamorphic volcano-sedimentary rocks called the 'Howley Waters Complex' (Valverde-Vaquero and van Staal 2001) comprises pelite, psammite, and greywacke interlayered with minor felsic porphyrys (467 ± 3 Ma U-Pb zircon age; Valverde-Vaquero *et al.* 2006a), calcsilicate, marble and amphibolite. The contact between the Howley Waters Complex in the west and the Meelpaeg Nappe to the east is a band of granite intrusives of ca. 467-468 Ma (U-Pb zircon age; Valverde-Vaquero *et al.* 2006a). These intrusions appear to stitch the original contact between the nappes and provide a minimum age for deposition of the Howley Waters Complex protoliths (Valverde-Vaquero *et al.* 2006a). Due to lithological similarities and the Ordovician age of the porphyry, the Howley Waters Complex is correlated with units of the widespread cover sequence ('Ganderia Overstep Sequence', see detailed description in section 3.9) which overlies Cambrian continental and ophiolitic units (Valverde-Vaquero *et al.* 2006a; Fig. 4). This cover sequence is unmetamorphosed, whereas the Howley Waters

Complex shows high-grade metamorphism. Metamorphic ages of this complex have not been determined but could be related to the Devonian metamorphism recorded in the underlying Meelpaeg Nappe, i.e., Devonian in age (Valverde-Vaquero *et al.* 2006a) and post-Caledonian.

To the east of the Meelpaeg sequence, metasedimentary rocks called the Spruce Brook formation occupy the '**Mount Cormack** Terrane'. Structural relationships are unknown, because they lie below the younger Ganderia Overstep Sequence (see below). The Mount Cormack Terrane makes up a concentric metamorphic zone with greenschist-facies conditions at the edge to migmatite-facies towards the core, with paragneiss, migmatite, tonalite, and amphibolite (Jenner and Swinden 1993; Valverde-Vaquero *et al.* 2006a). In areas with low-grade metamorphism, the original composition of the Spruce Brook Formation is described as light grey quartz-rich sandstone and grey and black shales with laminae and intercalations of siltstone and fine-grained sandstone (Colman-Sadd and Swinden 1984). The formation has not been dated, but correlations with other formations in eastern Newfoundland and New Brunswick suggest a minimum Lower Ordovician depositional age (Dec and Colman-Sadd, 1990; van Staal *et al.* 2021a). U-Pb dating of monazite and titanite in migmatite and amphibolite yielded metamorphic ages of ca. 462-460 Ma (Valverde-Vaquero *et al.* 2006a), consistent with zircon and monazite dating of a migmatitic gneiss (465 ± 2 Ma; Colman-Sadd *et al.* 1992a, reported in Valverde-Vaquero *et al.* 2006a), thus constraining metamorphism to the Middle Ordovician. Colman-Sadd and Swinden (1984) interpreted the Spruce Brook formation as a tectonic window into the Ganderia basement, because of its lithological correlations with sedimentary units (Gander Group) to the east. Rocks equivalent to the 'Mount Cormack Terrane' are also thought to form the basement of the Red Cross Group (Fig. 3), which has been interpreted as part of the widespread overstep cover sequence (Valverde-Vaquero *et al.* 2006a; van Staal *et al.* 2021a).
Due to their correlation with the Gander Group, we interpret both the Meelpaeg Nappe and the Mt. Cormack Terrane as CPS sequences ('Meelpaeg CPS' and 'Mt. Cormack CPS' in Fig. 4b).

Ophiolites: Pipestone Pond; Coy Pond; Gander River

Ophiolite klippe structurally overlie the continental units described above. They are interpreted as remnants of a single ophiolitic sheet that formed behind the Penobscot arc and that was thrust eastwards over the Gander Group and correlative Meelpaeg Nappe and Mount Cormack Terrane (Fig. 4) (Colman-Sadd and Swinden 1984; Colman-Sadd *et al.* 1992; Jenner and Swinden 1993; Zagorevski *et al.* 2010; Sandeman *et al.* 2012). Metamorphism of these nappes may therefore record their burial beneath the ophiolites.

To the east of the Meelpaeg Nappe in central Newfoundland is the ~5-km wide **Pipestone Pond** Complex (Fig. 3), which is separated by a poorly defined contact interpreted as a fault (Colman-Sadd and Swinden 1984). The Pipestone Pond Complex structurally overlies the Spruce Brook formation of the Mount Cormack Terrane to the east (Colman-Sadd and Swinden 1984). The complex consists of a disrupted sequence comprising harzburgite, cumulate pyroxenite, layered and massive gabbro intruded by pegmatitic gabbro, diabase dykes, plagiogranite (494 ± 2.5 Ma U-Pb zircon age; Dunning and Krogh 1985) and pillow lava (Jenner and Swinden 1993). Gabbro geochemistry indicates a suprasubduction zone setting; diabase and plagiogranite exhibit island arc tholeiite affinity; and the basalts have a MORB affinity (Jenner and Swinden, 1993).

To the east of the Mount Cormack Terrane lies the ~5-km wide **Coy Pond** Ophiolite (Fig. 3) (Sandeman *et al.* 2012). This unit contains harzburgite, pyroxenite, mafic dykes, plagiogranite (510 ± 4 Ma U-Pb zircon age; Sandeman *et al.* 2012), as well as diabase, gabbro and mafic pillow lavas, which are conformably overlain by argillite, sandstone and polymictic conglomerate (Zagorevski *et al.* 2010; Sandeman *et al.* 2012). Geochemical analyses on this complex are scarce, but basalts exhibit tholeiitic affinity, and felsic rocks have primitive arc affinity (Zagorevski *et al.* 2010). The Coy Pond complex is stitched to the Mount Cormack Terrane by a granitic intrusion dated at 474 +6/-3 Ma (U-Pb zircon age; Colman-Sadd *et al.* 1992), which constrains obduction of the ophiolites over continental rocks of the Ganderia continental margin to the Lower Ordovician.

The **Gander River** Ultramafic Complex, or Gander River Complex (Currie 1995; Williams 1995) occupies a ~5-km wide, NNE-SSW band in northern-central Newfoundland (Fig. 3), and structurally overlies metasediments of the Gander Group to the east (Bazinet, 1980; O'Neill, 1990 and references therein). The Gander River Complex is a deformed sequence of dominantly ultramafic rocks (pyroxenite, serpentinite), gabbro, diorite, and minor plagiogranites and mafic volcanic rocks (Bazinet 1980; O'Neill and Blackwood 1989; O'Neill 1990). Studies on this complex are scarce and it has not been dated, but geochemical analyses by O'Neill (1991) showed that mafic rocks have an island arc tholeiitic signature. Based on its structural position it has been correlated with the Pipestone Pond and Coy Pond Complexes farther to the west (Colman-Sadd and Swinden 1984; Jenner and Swinden 1993).

Ganderia Overstep Sequence

The units interpreted as the Ganderia continental margin and overlying ophiolites are overlain by a widespread sedimentary sequence of Middle Ordovician to late Silurian age (Bazinet 1980; Williams *et al.* 1993; Currie 1995; Valverde-Vaquero *et al.* 2006a; van Staal *et al.* 2014; Westhues and Hamilton 2018), which we name the 'Ganderia Overstep Sequence' (after Valverde-Vaquero *et al.* 2006). The Ganderia continental margin units and the ophiolites represent an earlier orogenic event and therefore served as the 'basement' upon which the Ganderia Overstep Sequence was deposited. Therefore, we consider the overstep to be a CPS sequence. The westward extent of the Ganderia Overstep Sequence is in tectonic contact with the Victoria Lake CPS (Fig. 3). Initial deposition of the Ganderia Overstep Sequence was contemporaneous with metamorphism of the Mount Cormack Terrane in the Middle Ordovician and local plutonic magmatism; since the latter processes are attributed to metamorphic core complexes and rifting (Valverde-Vaquero *et al.* 2006a and references therein), deposition of the Ganderia Overstep Sequence might be the upper crustal or surficial record of regional rifting. On its western side, the Overstep Sequence is a ~10-km wide volcano-sedimentary unit named the '**Red Cross Group**' (Fig. 3) that is emplaced via a post-Caledonian (Devonian) NW-directed thrust over the Victoria Lake Supergroup (Valverde-Vaquero *et al.* 2006a,b). The Red Cross Group comprises volcanic tuff, tuffaceous sandstone, siltstone, felsic porphyry (466 ± 3 Ma U-Pb zircon age), rhyolite, basalt with E-MORB and minor calc-alkaline geochemistry, and pillow basalts with MORB to island arc tholeiitic signature interleaved with limestone and black shale (Valverde-Vaquero *et al.* 2006a). The black shale is likely Upper Ordovician in age based on similarities with the widespread 'Caradoc black shale' cover of the Victoria Lake Supergroup (Valverde-Vaquero *et al.* 2006a). A gabbro intruding volcano-sedimentary rocks of the Red Cross Group dated 457 ± 6 Ma (U-Pb zircon age; Valverde-Vaquero *et al.* 2006a) constrains the minimum age for the group. The magmatic arc signature may indicate proximity to the Victoria Lake CPS (Fig. 3). Valverde-Vaquero *et al.* (2006a) interpret volcanism in the Red Cross Group as opening of a back-arc basin behind the Victoria arc, based on the intermediate signature of the volcanic lithologies between MORB and island arc and correlations with bimodal geochemistry in Ordovician volcanic rocks of the Wild Bight Group (refer to section 3.6).

In northern Newfoundland, the western boundary of the Overstep Sequence is represented by the Dog Bay Line (e.g., Williams *et al.* 1993; Fig. 3). The Dog Bay Line is a high-strain zone with tectonic mélange comprising mafic volcanic rocks and gabbros in disrupted black shale and exhibits dextral and transpressive displacements (Williams *et al.* 1993; Pollock *et al.* 2007). It separates siliciclastic and subaerial volcanic units of the Badger and Botwood Groups in the west (i.e., foreland basin units overlying the Victoria Arc, and the post-Caledonian volcanic cover sequences, respectively; see section 3.7), and units of the Ganderia Overstep Sequence in the east. The Dog Bay line was defined based on contrasts in the stratigraphy and level of deformation on either side (Williams *et al.* 1993; McNicoll *et al.* 2006; van Staal and Barr 2012), and is speculated to represent a suture along which a back-arc basin, located behind the Victoria arc, was subducted (e.g., Currie, 1995; Valverde-Vaquero *et al.* 2006a; Williams *et al.* 1993). However, no oceanic units are preserved along this structure, and the units on either side have different zircon provenance. Therefore, it may have acted as a barrier for sedimentation leading to two separate sedimentary settings (Pollock *et al.* 2007).

East of the Dog Bay Line in northern Newfoundland, the sedimentary rocks of the Ganderia Overstep Sequence comprise a local unit of Caradoc black shale overlain by Middle-Late Ordovician (fossil ages; Currie, 1995 and references therein) limestone, shale, sandstone, and debris flow conglomerates of the **Davidsville Group** (Pollock *et al.* 2007). Clasts in the conglomerates of the Davidsville Group are derived from ophiolitic rocks of Ganderia (Pollock *et al.* 2007). The Davidsville Group is conformably (McNicoll *et al.* 2006) or unconformably (Currie 1995) overlain by a succession of shale and limestone passing upwards to subaerial redbeds ('Indian Islands Group'; Boyce *et al.* 1993; Williams *et al.* 1993; McNicoll *et al.* 2006; Pollock *et al.* 2007) of lower Silurian to uppermost Silurian-Lower Devonian age (fossil ages; Pollock *et al.* 2007 and references therein). The bulk of the Indian Islands Group is middle Silurian (McNicoll *et al.* 2006), and the timing of change from marine to subaerial sedimentation is not well defined. The Indian Islands Group exhibits deformation through slaty cleavage which formed before intrusion of gabbro dikes of ca. 411 Ma, therefore constraining a minimum deformation age to the early Devonian (McNicoll *et al.* 2006). This contrasts with units of the Botwood Group which lie west of the Dog Bay Line and were deformed in mid-late Silurian, indicating different post-Caledonian deformation histories (e.g., Honsberger *et al.* 2023). Therefore, the Middle-Late Ordovician Davidsville Group (and correlative Red Cross Group) predates the arrival of Ganderia at the Laurentian margin as marked by the Badger Group (Fig 4). In contrast, the early Silurian-Early Devonian Indian Islands Group in northern Newfoundland post-date it and is thus post-Caledonian.

The Davidsville Group has been correlated to other groups with greater proportions of volcano-sedimentary material in central and southern Newfoundland (i.e., Baie d'Espoir Group, Bay du Nord Group; van Staal *et al.* 2021a; Waldron *et al.* 2022). The Baie d'Espoir Group (Fig. 3) has not been well described due to poor exposure and isoclinal folding which precludes thickness evaluation (Sandeman *et al.* 2012). It comprises felsic volcanic flows with minor mafic and intermediate volcanic rocks, tuffs, polymictic conglomerate, and volcaniclastic sandstones and clastic sedimentary rocks (Sandeman *et al.* 2012; Westhues and Hamilton 2018). Geochemical analyses indicate that the volcanic rocks are sub-alkaline, and mafic rocks exhibit volcanic arc, MORB and OIB signatures (Westhues and Hamilton 2018). These signatures support correlations between the Red Cross Group and justify interpreting the Baie d'Espoir magmatism as rifting of a backarc basin (Valverde-Vaquero *et al.* 2006a). Like the Baie d'Espoir Group, the Bay du Nord Group of southern Newfoundland (Fig. 3) is a composite group comprising volcano-sedimentary rocks that were metamorphosed to upper greenschist and amphibolite facies (Tucker *et al.* 1994). This group is bounded by Silurian intrusions and by a Silurian strike-slip fault zone in the north (Lin *et al.* 1994) and Silurian south-dipping reverse fault in the south (O'Brien and O'Brien 1990; Tucker *et al.* 1994) (Fig. 3). The original relationships of the Bay du Nord group with the surrounding lithologies are therefore unclear. This group comprises felsic volcano-sedimentary rocks, felsic tuff (466 ± 2 Ma; Dunning *et al.* 1990), minor psammite, pelite, and conglomerate (Tucker *et al.* 1994) and has been correlated with the Davidsville Group (e.g., van Staal *et al.* 2021a). Metagabbro is locally imbricated with these lithologies and is interpreted as the basement of the Bay du Nord Group; it may have been a backarc basin to the Penobscot arc which closed by the Early Ordovician (Tucker *et al.* 1994; van Staal *et al.* 2021a). In contrast to unmetamorphosed units of the Ganderia Overstep Sequence, the Bay du Nord Group is metamorphosed, likely during the Devonian (Dunning *et al.* 1990; van Staal *et al.* 2024). This event would be coeval with thrusting of the Red Cross Group and Meelpaeg Nappe to the west (Valverde-Vaquero *et al.* 2006a) (see section 3.7) and thus post-dates the Caledonian orogeny.

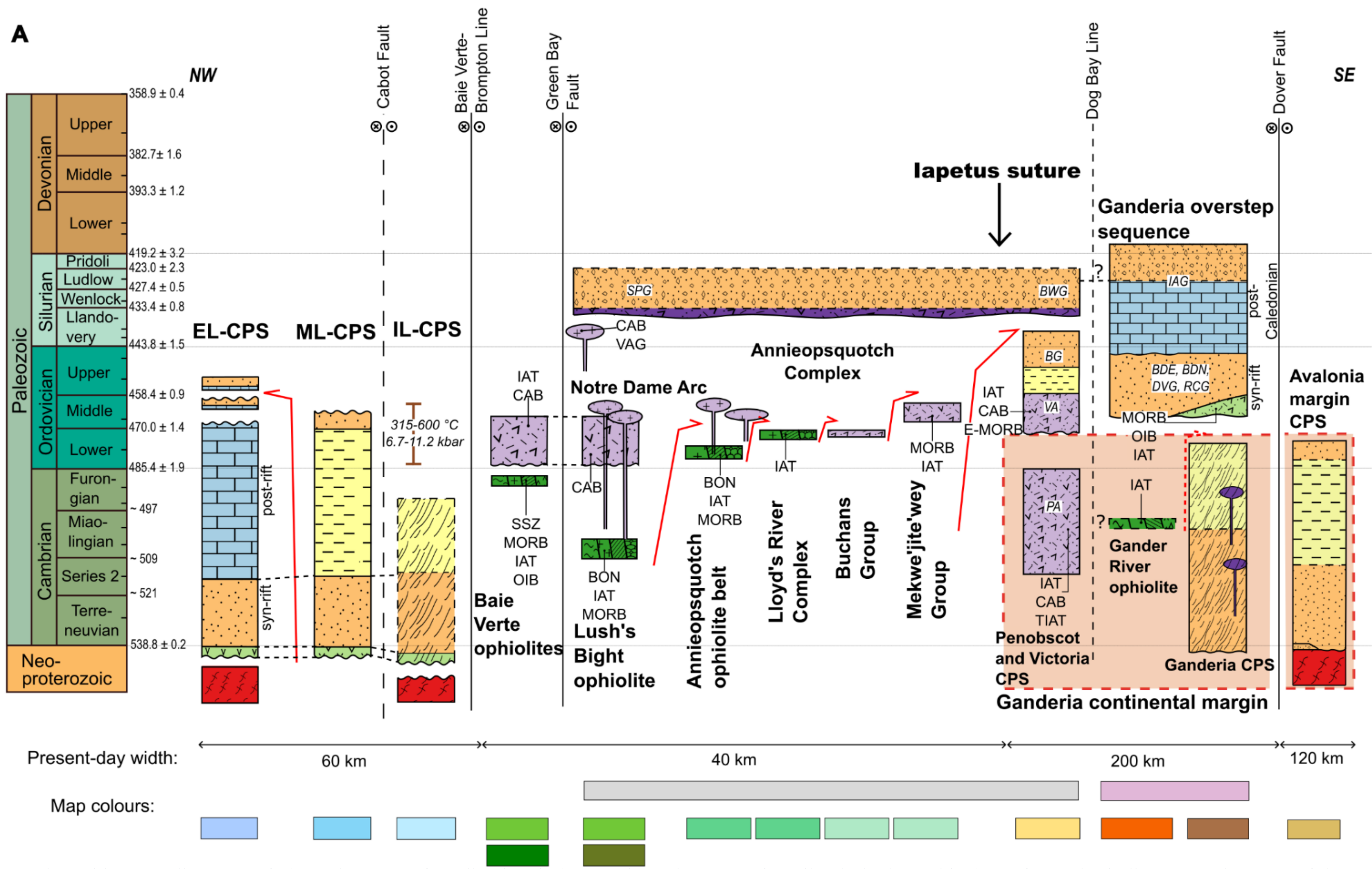
INTERPRETATION OF OROGENIC ARCHITECTURE DIAGRAMS

Our orogenic architecture diagrams display summaries of the compiled data, including interpretations of whether units are continental plate stratigraphy (CPS), oceanic plate stratigraphic (OPS), or continental or oceanic upper plate units (Figs. 4a, b). The Laurentian continental margin and Gondwana-derived units occupy the west-northwest and east-southeast sides of the orogen in present-day coordinates, respectively. They are illustrated on the left and right sides of the orogenic architecture diagrams (Figs. 4a, b). Below, we use these diagrams to develop a reconstruction of the paleogeographic and tectonic evolution that led to the Caledonian orogeny in Newfoundland along a roughly west-east cross section (Fig. 5). Our model includes rifting and drifting phases and associated igneous and sedimentary processes, and subsequent convergence and stages of orogenesis. For this interpretation, we deliberately *only* refer to our diagrams, to evaluate the utility of the methodology proposed above. In Section 5, we compare our orogenic architecture interpretation with previously proposed models to evaluate strengths and limitations of our approach.

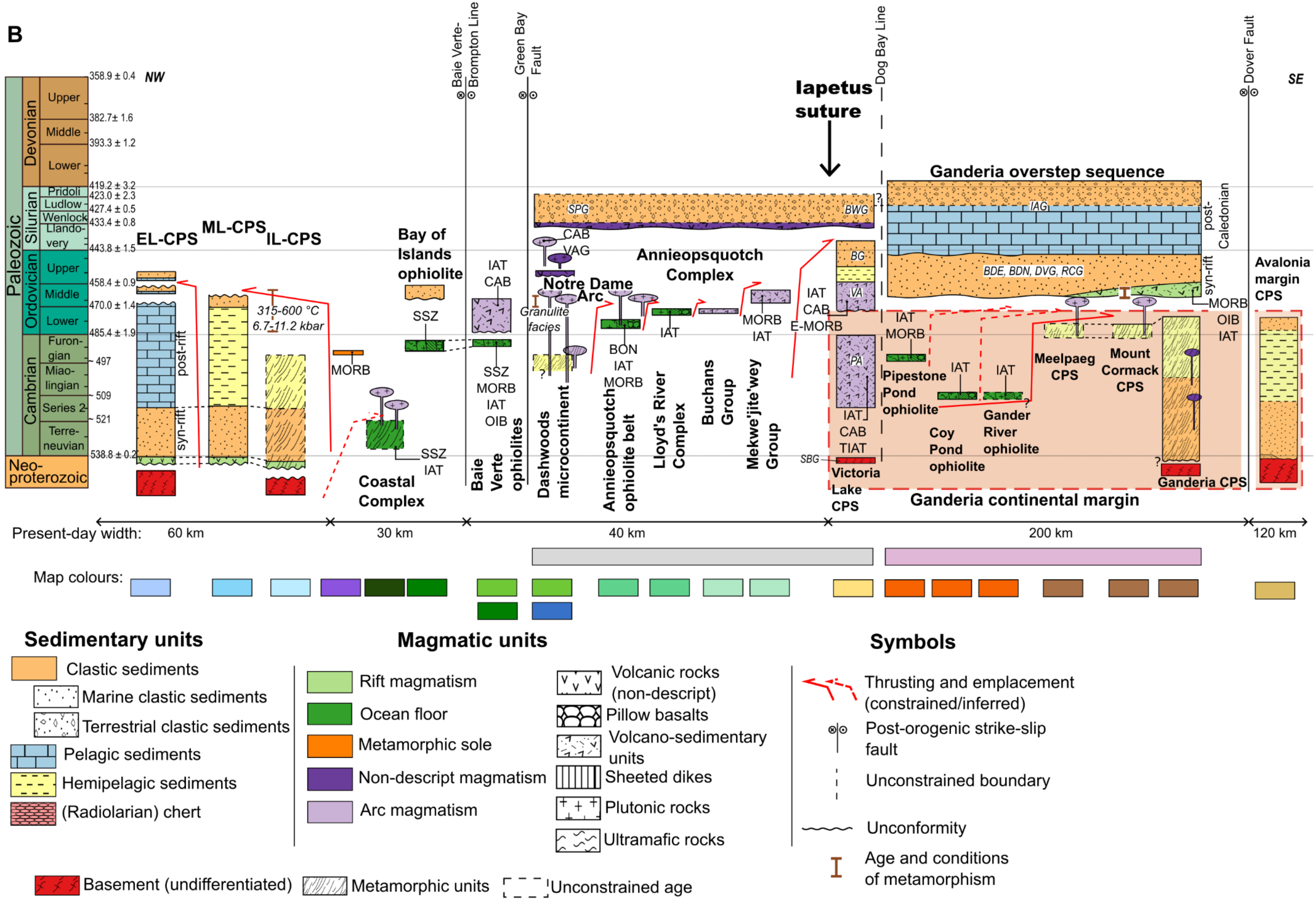
The Laurentian Margin Records a Full Wilson Cycle

The Laurentian continental margin records continental plate stratigraphy with a straightforward paleogeographic and tectonic history characterized by rifting of older continental lithosphere, passive margin sedimentation and seafloor spreading, followed by oceanic closure. A Grenvillian basement inherited from a previous orogeny underlies the rift-and-drift-related (volcano-) stratigraphy. Continental break-up occurred between ca. 615 and 550 Ma (Fig. 5a), as indicated by rift volcanic rocks intercalated with syn-rift clastic sedimentary rocks.

A passive margin phase followed the onset of 'oceanization' (i.e., the drift phase), recorded by post-rift sediments comprising limestones, mudstones and shales of late early Cambrian-Early Ordovician age atop the rift-related volcano-sedimentary sequence. Seafloor spreading occurred to the east of the Laurentian margin (Fig. 5b), indicated by the grading of more proximal post-rift facies in the structurally lower, western nappes to more distal post-rift facies in the structurally higher, eastern nappes. All units contain detritus that indicate the sedimentary rocks were derived from material shedding off the Laurentian continental margin. The ocean east of Laurentia was



1177 *Figure 4* - Orogenic architecture diagrams of A) northern Newfoundland and B) central-southern Newfoundland; the legend in (B) refers to both diagrams. The trace of the transects can be found in Fig. 3. The 'Map colours' at the bottom of each column are the colours with which each unit is depicted in the map in Fig. 3; in the case of units overlying one another, the colour boxes are in the same stratigraphic order and have the same width as the unit they represent. Abbreviations of the geochemical signatures: BON=boninite; CAB=calc-alkaline basalts; E-MORB=enriched mid-ocean ridge basalt; IAT=island-arc tholeiite; MORB=mid-ocean ridge basalt; OIB=ocean island basalt; PC= post-collisional; SSZ=suprasubduction zone; TIAT=transitional island-arc tholeiite; VAG=volcanic-arc granite; WPG=within-plate granite. Abbreviations of the lithological units (italics): BDE=Baie d'Espoir Group, BDN=Bay du Nord Group, BG=Badger Group, BWG=Botwood Group, DVG=Davidsville Group, IAG=Indian Islands Group, PA=Penobscot Arc, RCG=Red Cross Group, SBG=Sandy Brook Group, SPG=Springfield Group, VA=Victoria Arc.


B
NW
SE
Paleozoic
Devonian
Silurian
Ordovician
Cambrian
Neo-proterozoic
Upper
Middle
Lower
Pridoli
Ludlow
Wenlock
Llando-very
Furon-gian
Miao-lingian
Series 2
Terre-neuvian
358.9 ± 0.4
382.7± 1.6
393.3 ± 1.2
419.2 ± 3.2
423.0 ± 2.3
427.4 ± 0.5
433.4 ± 0.8
443.8 ± 1.5
458.4 ± 0.9
470.0 ± 1.4
485.4 ± 1.9
~ 497
~ 509
~ 521
538.8 ± 0.2
EL-CPS
ML-CPS
IL-CPS
post-rift
syn-rift
315-600 °C
6.7-11.2 kbar
MORB
Bay of Islands ophiolite
SSZ
Coastal Complex
SSZ
IAT
Baie Verte-Brompton Line
IAT
CAB
SSZ
MORB
IAT
OIB
Baie Verte ophiolites
Green Bay Fault
SPG
CAB
VAG
Notre Dame Arc
Granulite facies
Dashwoods microcontinent
BON
IAT
MORB
Annieopsquotch ophiolite belt
Annieopsquotch Complex
IAT
Lloyd's River Complex
Buchans Group
MORB
IAT
Mekwe'jite'wey Group
IAT
CAB
E-MORB
Iapetus suture
Dog Bay Line
BWG
BG
VA
PA
IAT
CAB
TIAT
SBG
Victoria Lake CPS
Ganderia overstep sequence
IAG
BDE, BDN, DVG, RCG
post-Caledonian
syn-rift
MORB
OIB
IAT
IAT
MORB
Pipestone Pond ophiolite
IAT
Coy Pond ophiolite
IAT
Gander River ophiolite
Meelpaeg CPS
Mount Cormack CPS
Ganderia CPS
Ganderia continental margin
Dover Fault
Avalonia margin CPS
Present-day width:
60 km
30 km
40 km
200 km
120 km
Map colours:
Sedimentary units
Clastic sediments
Marine clastic sediments
Terrestrial clastic sediments
Pelagic sediments
Hemipelagic sediments
(Radiolarian) chert
Magmatic units
Rift magmatism
Ocean floor
Metamorphic sole
Non-descript magmatism
Arc magmatism
Volcanic rocks (non-descript)
Pillow basalts
Volcano-sedimentary units
Sheeted dikes
Plutonic rocks
Ultramafic rocks
Symbols
Thrusting and emplacement (constrained/inferred)
Post-orogenic strike-slip fault
Unconstrained boundary
Unconformity
Age and conditions of metamorphism
Basement (undifferentiated)
Metamorphic units
Unconstrained age

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subsequently consumed in an orogenic phase characterized by east-directed subduction and west-directed thrusting. This step is indicated by east-dipping flysch sequences that young structurally downward, indicating that foreland thrusts propagated in the continental units from east to west between ca. 470 to 460 Ma (Fig. 5e, f).

Following the sequence of events proposed so far, we hypothesize that to the east we will either find the eastern continuation of the lower plate, i.e., a CPS or OPS with older flysch, and older metamorphism (if burial was deep enough), or geological remnants of an overriding plate. Our diagram shows that the Coastal Complex and Bay of Islands ophiolite are east of the Laurentian CPS, therefore supporting the latter hypothesis.

The Coastal Complex currently sits structurally above the most distal and stratigraphically highest (youngest) CPS units. It comprises ocean floor lithologies which were highly deformed and metamorphosed prior to intrusion of supra-subduction zone trondhjemites at ~515 Ma and possibly also by magmatic rocks of the Bay of Islands ophiolite. This implies that by 515 Ma, the Coastal Complex occupied an upper plate position, and a subduction zone was active and located between the Laurentian margin (i.e., the lower plate) and the Coastal Complex (Fig. 5c). The composition and deformation of the Coastal Complex – which resemble that of a small segment of an OPS-derived accretionary prism – imply that the Coastal Complex record the existence of older subduction that led to accretion of oceanic floor: the Coastal Complex represents an accretionary prism that developed above a subduction zone before 515 Ma (Fig. 5a). The age of this prism is unknown, but it is possible that it formed by subduction below the Laurentian margin prior to opening of a back-arc basin within that margin (Fig. 5b). Opening of the basin then separated the Laurentian margin from its accretionary prism. Note that the Coastal Complex then provides the sole evidence on Newfoundland of such a west-dipping subduction zone. By 515 Ma, eastward subduction initiated within the back-arc basin, i.e. a subduction polarity switch, leaving the Coastal Complex 'fossil' prism in an upper plate position (Fig. 5c).

The Bay of Islands Ophiolite, east of the Coastal Complex, yields a supra-subduction zone (SSZ) signature (Elthon 1991) and is floored by a metamorphic sole that testifies that such east-dipping subduction must have been ongoing by 490-485 Ma (Fig 4b, 5c) (Fournier-Roy *et al.* 2024; Yan and Casey 2023). Other soles in the region, for example the one beneath the St. Anthony ophiolite in northern Newfoundland (Fig. 3), exhibit similar cooling ages which may suggest it is a northern continuation of the Bay of Islands system. Ages of the mafic crust (i.e., from plagiogranites) of the Bay of Islands Ophiolite indicate that upper plate extension was underway by 488 Ma (Yan and Casey 2020), which may constrain the timing of slab roll-back of a mature subduction setting (Guilmette *et al.* 2018; 2023). As the Bay of Islands ophiolite intrudes into the Coastal Complex, forearc spreading must have been located within the 'fossil' accretionary prism (Fig. 5c).

We identified the location of an ancient subduction zone in our orogenic architecture diagrams and inferred that units on either side of this structure are lower plates (west) and upper plates (east). 'Finding' the subduction zone is the final ingredient required to reconstruct a complete Wilson cycle, beginning with continental break-up, drifting, subduction initiation, and westward thrusting and crustal accretion. Our architecture diagram successfully captures this complete tectonic cycle for the western side of the orogen.

Moving farther east, the simplest hypothesis would be to find a geologic history that corresponds with other units in the same upper plate setting. Alternatively, we could identify a change from upper to lower plate setting, which would indicate either that we crossed a suture, or that the 'Bay of Islands' upper plate acts as a lower plate in another, younger subduction system.

Lateral Paleogeographic Complexity and Records of Subduction in Upper Plate Units

Supra-subduction zone ophiolites (i.e., Baie Verte ophiolites) to the east record similar upper Cambrian ages (ca. 490 Ma) as the Bay of Islands complex, are not metamorphosed, and are overlain by volcano-sedimentary magmatic arc sequences, indicating that they occupied the same upper plate setting. The Notre Dame arc appears to have been the surface expression of the Bay of Islands subduction zone, because it exhibits ages spanning the time window between mature subduction as inferred from metamorphic ages of the Bay of Islands sole, and the end of subduction when the Laurentian continental margin arrived at the trench (Fig. 5). Moreover, the westernmost location of the Bay of Islands (proto)forearc ophiolites marks the easternmost possible location of the trench during subduction initiation; the Notre Dame arc is ~100 km east of this position, which is the minimum width of a typical forearc (Gill, 1981; Stern, 2002). Although it is possible that the forearc underwent shortening during accretion, the amount of shortening is unknown and we may assume that it was minimal, as subduction of ocean floor rarely result in thick-skinned deformation.

The ~490-460 Ma Notre Dame arc intrudes the > 504 Ma Lush's Bight ophiolites (see section 3.3) in northern Newfoundland (Szybinski 1995), and the Dashwoods 'microcontinent' crust (that recorded metamorphism around 466-460 Ma) in southern Newfoundland (Fig. 4a, b), which we infer to highlight paleogeographic complexity along-strike of this tectonic system. We note that the ophiolites, microcontinental crust, and cross-cutting arc units are all preserved in a ~40 km-wide, northeast-southwest striking band (Fig. 3), so indeed the simplest interpretation is that this entire complex comprises remnants of a narrow strip of genetically related composite continental-oceanic lithosphere. If not, then there must be sutures that accommodated long-lived subduction separating the map-scale units.

We prefer the simpler interpretation of a single, narrow strip of composite lithosphere. In this scenario, the Lush's Bight ophiolites represent remnants of the oceanic basin that opened east of the Laurentian margin in the late early Cambrian, and that occupied an upper plate position after subduction initiated within the basin, thus escaping subduction-related deformation and metamorphism (Fig. 5c). In southern Newfoundland, the same Notre Dame arc crosscuts very different (i.e., Dashwoods) micro-continental and/or meta-sedimentary basement rocks, but the underlying lithosphere exhibits zircon provenance indicative of a Laurentian source. These same meta-sediments do not overlie the Lush's Bight ophiolite to the north. This implies that these (meta-) sediments were initially deposited proximal to Laurentia but with a highly focused depocenter likely controlled by paleogeography and topographic divides. They then tectonically separated from Laurentia during the rift-to-drift phase described above and later became re-incorporated into the Laurentian margin during orogenesis. Therefore, the Dashwoods (meta-) sediments and Lush's Bight ophiolite may well have been part of the same strip of lithosphere that was separated from the continental Laurentian margin in the middle Cambrian. Furthermore, if the Coastal Complex represents a fossil accretionary prism that formed along the Laurentian margin, then the Dashwoods metasediments would be part of the same prism, rifting off Laurentia together upon opening of the Cambrian oceanic (back-arc) basin. Upper plate extension and formation of the Bay of Islands ophiolite then separated the Coastal Complex from Dashwoods (Fig. 5c).

The Annieopsquotch Complex outboard of Lush's Bight and Dashwoods is another ophiolitic-arc system that affirms the upper plate setting continues to the east. The ophiolitic units are younger than those of the Baie Verte and Bay of Islands, suggesting they formed after subduction initiation. An interesting inference from the relative positions and ages of the Annieopsquotch Complex is that it requires eastward ridge jump around ca. 481 Ma, with the spreading center relocating outboard of the crustal block represented by Dashwoods and Lush's Bight (Fig. 5e). This is justified because older (middle-Cambrian) oceanic (Lush's Bight) or microcontinental crust (Dashwoods) sits between portions of younger (upper Cambrian-Early Ordovician) oceanic lithosphere represented by Bay of Islands-Baie Verte ophiolites and the Annieopsquotch Complex.

Structurally, the Annieopsquotch Complex poses further complexity: the units occupy an east-verging thrust stack, which is the opposite sense of movement than recorded in the west, along the Laurentian margin. This could possibly indicate backthrusting when the Laurentian continental margin arrived at the subduction zone and was dragged beneath the BOIC forearc-Notre Dame arc-Annieopsquotch backarc upper plate system. Alternatively, it could reflect a west-dipping subduction zone to the east of the Annieopsquotch Complex. In fact, 'SSZ' signatures in the Coastal Complex OPS and Lush's Bight ophiolite may indicate that a subduction zone operated from the middle-Cambrian onwards. Moreover, the Notre Dame Arc units are intruded by Late Ordovician-early Silurian magmatic units, some of which yield arc signatures (Whalen *et al.* 2006). This magmatic age does not fit with the east-dipping subduction zone in the west, because that system ended by the Upper Ordovician (i.e., post-tectonic sedimentation), but it could support the presence of another west-dipping subduction zone to the east by the early Silurian.

Iapetus Ocean And Gondwana-Derived Units

The first units derived from Gondwana appear in the footwall of a top-east thrust stack across the Mekwe'jit Line that emplaces the Annieopsquotch Complex (Williams *et al.* 1988; 1995; White and Waldron 2022) above arc and continental units contain fossil fauna characteristic of the Gondwanan margin (e.g., Harper *et al.* 2009; Hibbard *et al.* 1977; van Staal *et al.* 1998). Therefore, we interpret the thrust between the Annieopsquotch Complex and underlying Gondwana-derived sedimentary and igneous units as a suture marking the disappearance of the Iapetus Ocean that separated the two continents. Remarkably, we did not identify any units interpretable as an accretionary prism containing OPS of the Iapetus Ocean anywhere in Newfoundland.

The structure of Gondwana-derived units is relatively poorly constrained compared to units derived from the Laurentian margin because they are overlain by the Ganderia Overstep Sequence. However, its structure and geological history appear to be a mirror image of the Laurentian margin, but slightly older. The westernmost Gondwana-derived units of the Victoria Lake CPS comprise a crystalline basement (the Sandy Brook Group) overlain by the Cambrian Penobscot arc magmatism (McNicoll *et al.* 2008). East of the arc, mid-late Cambrian ophiolites were thrust upon the Ganderia continental margin leading to metamorphism up to amphibolite grade in the Early-Middle Ordovician. Since the Penobscot arc was not obducted, the ophiolites were likely derived from an ocean basin that opened between the composite Sandy Brook Group-Penobscot arc unit and the Ganderia margin to the east. This could have been a back-arc basin above an east-dipping subduction system beneath Gondwana at the eastern extent (in present-day coordinates) of the Iapetus Ocean (e.g., van Staal *et al.* 1998; Zagorevski *et al.* 2010) (Fig. 5d). In turn, thrusting and metamorphism of the back-arc basin basalts over the Gondwanan margin might indicate the presence of a west-dipping subduction zone (present coordinates); alternatively, they could simply be a result of backthrusting of the back-arc basin above the continental margin. The ophiolites were thrust on top of the westernmost portion of the Gondwana margin (i.e., Ganderia) but did not reach the more inboard part (i.e., Avalonia), which explains why Ganderia records a stage of deformation-metamorphism that Avalonia does not (Fig. 5e, f).

Based on the orogenic architecture diagrams, we can draw the following correlations between the Laurentian and Gondwana sides of the margin: (1) the Sandy Brook Group is equivalent to the Dashwoods continent; (2) the Pipestone Pond, Coy Pond, and Gander River ophiolites are equivalent to the Bay of Islands ophiolite (if they formed as SSZ ophiolites above the subduction zone that formed within the back-arc basin) or the Lush's Bight ophiolite (if they represent the original back-arc basin crust); (3) the Ganderia (micro)continent is equivalent to the internal Laurentian CPS units; and (4) and the Avalonian crust is equivalent to the external Laurentian CPS units. There is no geologic evidence that Avalonia and Ganderia were once separated by an ocean, or by a subduction zone. According to the orogenic architecture, 'Avalonia' could be interpreted as an eastward, non-metamorphosed continuation of 'Ganderia' and was just another part of the train of continental fragments that rifted away from Gondwana and migrated westward on the same plate (Fig.4 and 5).

The volcano-sedimentary sequences, thrust imbrication, and deformation-metamorphism recorded in the Gondwanan margin units are diagnostic of an orogenic event that was completed by 470 Ma, constrained by the age of the Ganderia Overstep sedimentary (post-orogenic) Sequence. This is 30 million years *before* these units arrived at the Laurentian margin, as indicated by the Laurentian zircon signature in the flysches of the Upper Ordovician-lower Silurian Badger Group, overlying the Victoria Arc CPS units. The orogeny effectively created a composite 'CPS' basement for the younger sediments and magmatic rocks. For example, syn-rift clastics of the Ganderia Overstep Sequence indicate rifting of the Ganderia-Avalonia microcontinent(s) from Gondwana. Mid-Ordovician mafic volcanic rocks of the Ganderia Overstep Sequence (i.e., the basalts of the Red Cross and Baie d'Espoir Groups) further testify to this rifting and lithospheric thinning. In contrast with the Badger Group, there are no clear foreland basin deposits of Upper Ordovician-lower Silurian age in the Ganderia Overstep sequence; this may be due to distance from the foreland resulting in a different sedimentary setting. The Upper Ordovician-Silurian pelagic and clastic sediments (Indian Islands Group) of the Overstep Sequence indicate that this sedimentary setting was initially marine.

Arc magmatism of the 'Victoria Arc' units directly to the west is coeval with the Ganderia Overstep Sequence to the east, indicating that they occupied an upper plate setting and thus that east-dipping subduction was active below the Gondwana-derived microcontinent(s) in the Lower-Middle Ordovician and was coeval with rifting of the microcontinents (Fig. 5f).

The Victoria arc is located immediately east of the Iapetus suture (Mekwe'jit Line, Fig. 3), which implies that the forearc of this subduction zone, and possibly an accretionary prism preserving slivers of the Iapetus Ocean, was either removed by subduction erosion or buried beneath the Annieopsquotch complex. This east-dipping subduction zone below Ganderia/Avalonia consumed the intervening ocean basin until the Gondwana-derived units arrived at the Laurentian margin in the Upper Ordovician (Fig. 5g). The youngest arc ages are rapidly succeeded by foreland basin, Laurentian-derived siliciclastic deposits (Badger Group) of Upper Ordovician-lower Silurian age which capture the 'docking' phase.

After accretion of the Gondwanan-derived units, post-orogenic early-late Silurian volcanoclastic and terrestrial sediments deposited on both sides of the Iapetus suture (i.e., Springdale Group overlying

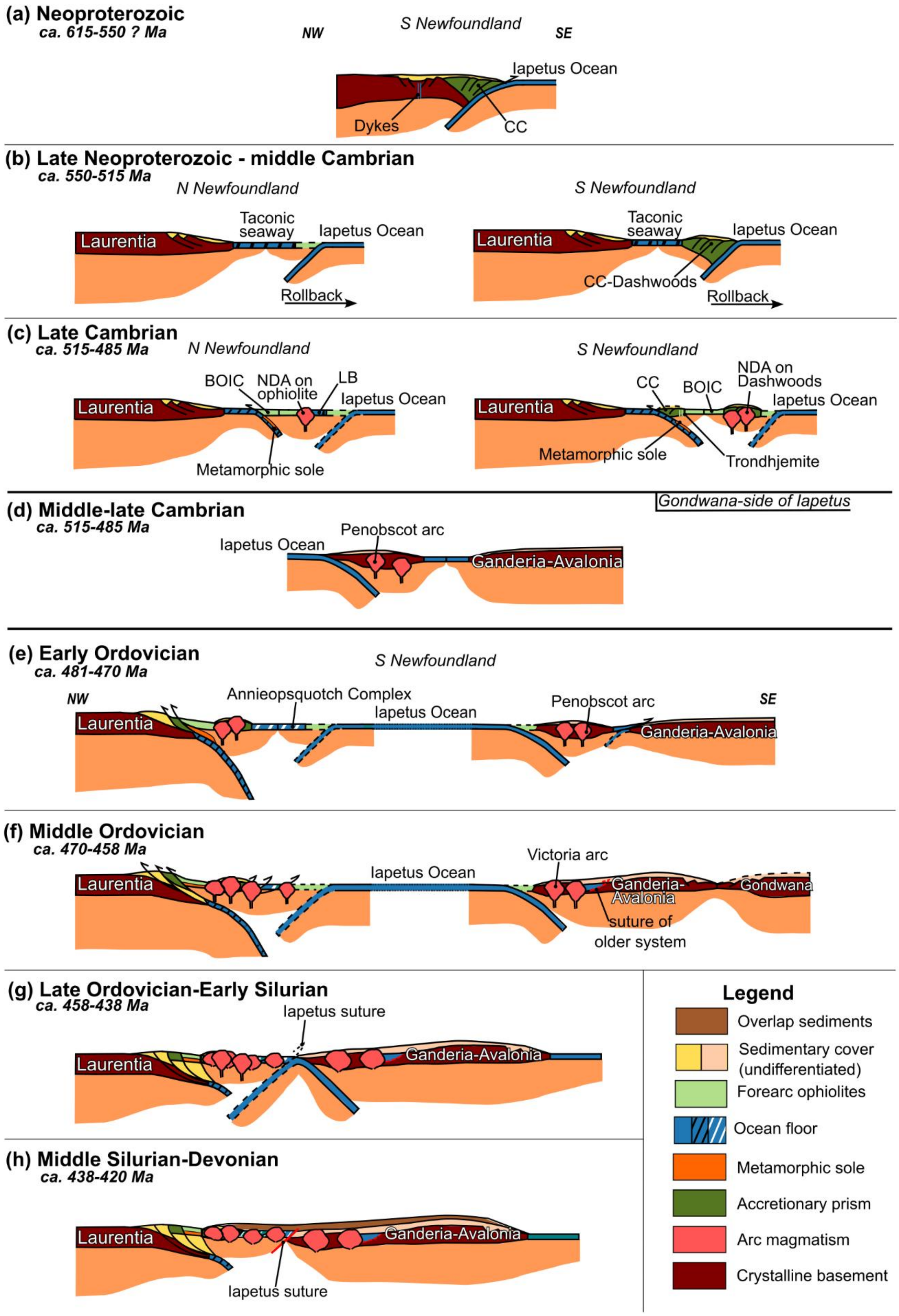

Figure 5 - Schematic cross-sections (NW-SE) of the evolution of the Newfoundland Appalachians during the Caledonian orogeny, from the Neoproterozoic (a) to the Devonian (h). Cross-sections (a) to (c) refer to the Laurentian side of the Iapetus Ocean only, and are subdivided in North and South following the two orogenic architecture diagrams in Fig. 4. Cross-section (d) refers to the Gondwanan side of the Iapetus Ocean only, is coeval with cross-sections (a)-(c) and is based on the orogenic architecture diagram of Fig. 4b. Cross-sections (e) to (h) refer to both sides of the Iapetus Ocean and are based on the orogenic architecture diagram of Fig. 4b. Abbreviations: BOIC=Bay of Islands Complex, CC=Coastal Complex, LB=Lush's Bight, NDA=Notre Dame Arc.

the Notre Dame Arc and Annieopsquotch units and Botwood Group overlying the Victoria Arc), testifying to the final closure of the Iapetus Ocean and to the end of accretion (Fig. 5h). Further to the east, sedimentation of Ganderia Overstep Sequence with post-orogenic sediments continued with a coarsening upward, marine to terrestrial sequence (Indian Islands Group) until the early Devonian.

DISCUSSION

In the previous section, we synthesized our 'orogenic architecture diagrams' and interpreted a first-order paleogeographic and tectonic reconstruction of the Newfoundland Appalachians based on compiled stratigraphy, magmatism, geochemistry, and metamorphism data. Our reconstruction shows that the Laurentian margin records a complete Wilson cycle, which agrees strongly with most previous interpretations (e.g., van Staal *et al.* 1998; van Staal and Barr 2012; White and Waldron 2022). This affirms that orogenic architecture diagrams provide a useful approach to reconstruct plate tectonic and paleogeographic history. Interestingly, our interpretation deviates in several ways from the most accepted models of Northern Appalachian orogenesis. Herein we discuss three discrepancies that illustrate how our method may provide a useful tool to (re)assess previous interpretations and identify the key observations that underlie contrasting views.

Did Dashwoods and Lush's Bight Occupy The Same Upper Plate?

In our reconstruction, Lush's Bight ophiolites make up part of the ocean between Laurentia and the Dashwoods microcontinent (i.e., the Taconic Seaway; e.g., Hibbard *et al.* 2007; van Staal *et al.* 2007); in most previous reconstructions, Lush's Bight formed in the forearc above a middle-late Cambrian, west-dipping subduction zone within the Taconic Seaway and was thrust eastward over the Dashwoods terrane (e.g., Szybinski 1995; Swinden *et al.* 1997; Zagorevski and van Staal 2011). However, we did not identify any evidence of Lush's Bight obduction in northern Newfoundland. The contacts of the Lush's Bight units are mostly obscured by Notre Dame Arc intrusions; no metasediments of the Dashwoods continent are exposed; and Dashwoods is approximately 40 km wide (less than half of a typical lithospheric thickness) which is small even for microcontinents (Péron-Pinvidic and Manatschal 2010).

The argument for obduction is mostly based on correlations with other ophiolitic complexes such as the St. Anthony ophiolite and Long Range mafic-ultramafic complex (van Staal *et al.* 2009; van Staal and Barr 2012). The St. Anthony ophiolite, for example, has a sole with a metamorphic age of 495 Ma, which has been interpreted as the age of emplacement atop the Laurentian margin (Jamieson, 1988; van Staal *et al.* 2009; van Staal and Barr 2012). However, recent studies suggest that the age of metamorphic soles record subduction initiation, rather than the age of thrusting over a continental margin (e.g., Guilmette *et al.* 2018). The St. Anthony Complex may therefore be a northern equivalent of the Bay of Islands Ophiolite, since it has similar metamorphic sole ages and a similar structural position above allochthonous units of the Laurentian margin (Fig. 3).

Another argument for Lush's Bight ophiolite obduction is a proposed correlation with the Long Range mafic-ultramafic Complex in southern Newfoundland (Dubé *et al.* 1996). However, these complex lacks age or geochemical constraints except for being intruded by late Cambrian plutons of the Notre Dame Arc, so correlations with Lush's Bight are inferred from the geographic locations of the two ophiolitic complexes within the same 40-km wide zone. Both may well be part of the same lithosphere.

Finally, calc-alkaline dykes of 504-495 Ma age that are apparently contaminated by continental crust crosscut lithologies of the Lush's Bight ophiolite, which is taken as evidence that Lush's Bight was thrust atop continental material of the Dashwoods terrane (Szybinski 1995; Swinden *et al.* 1997; van Staal *et al.* 2009). However, a 'continental' fingerprint is not necessarily diagnostic of Dashwoods per se but could also derive from the continental crust of Laurentia *sensu stricto*, or subducted Laurentian-derived sediments.

We argue that the geology of Newfoundland does not contain unequivocal evidence for a west-dipping subduction zone within the Taconic Seaway in the middle-late Cambrian. Contrary to this, evidence from the trondhjemitic intrusions of the Coastal Complex suggest that east-dipping subduction was ongoing within the Taconic basin at that time (Yan and Casey 2020, 2022). Therefore, we prefer the interpretation that the (back-arc) basin separated lithosphere that contained both the Dashwoods microcontinental fragment and the Lush's Bight sequence from the Laurentian margin, capturing lateral heterogeneity along-strike of the paleo-margin, for instance in a fashion similar to modern (hyperextended) continental margins (cf. Péron-Pinvidic and Manatschal 2010). Dashwoods may have represented one of such klippen that separated from the hyperextended margin of Laurentia during the opening of the Taconic Seaway (see Waldron and van Staal 2001; Hibbard *et al.* 2007; van Staal *et al.* 2007, 2013).

What Was the Subduction Polarity of The Iapetus Ocean?

Our reconstruction highlights the lack of conclusive evidence for westward subduction of the Iapetus Ocean, except from evidence from the Coastal Complex accretionary prism, and from Late Ordovician-early Silurian arc magmatism; however, west-dipping subduction of the Iapetus Ocean below Laurentia is commonly envisioned from the Lower Ordovician onwards, and as being coeval to east-dipping subduction of the Taconic Seaway (van Staal *et al.* 2007, 2009; Zagorevski *et al.* 2008; Zagorevski and van Staal 2011; van Staal and Barr 2012).

The Coastal Complex may represent the only exposed accretionary record of the Iapetus Ocean. It has previously been interpreted as representing juvenile forearc lithosphere of the east-dipping subduction of the Taconian Seaway (e.g., Yan and Casey 2020, 2022), and its deformation as the result of e.g. obduction processes (e.g., Karson and Dewey 1978; Karson 1984; Yan and Casey 2022). However, the deformation and metamorphism of the Coastal Complex predates the formation of the Bay of Islands Ophiolite and thus requires an older ocean floor formation and destruction phase before 514-503 Ma (Yan and Casey 2022). Our alternative interpretation is that the Coastal Complex is an OPS-derived accretionary prism derived from westward subduction of Iapetus Ocean below the Laurentian margin. Such westward subduction of the Iapetus Ocean may then explain the opening of the Taconic Seaway due to rollback, and the separation of the Coastal Complex and Dashwoods accretionary prism as a 'microcontinent' from the Laurentian margin. This may be comparable to the separation of the Palawan 'continental terrane' - a Mesozoic accretionary prism that formed along the South China margin, during the Cenozoic opening of the South China Sea (e.g., Shao *et al.* 2017; van de Lagemaat *et al.* 2024), or the Japan accretionary prism from Eurasia during the Cenozoic opening of the Sea of Japan back-arc basin (Isozaki *et al.* 1990). Despite this, no arc units or forearc ophiolites of this age are preserved on the margin of Laurentia, thus the polarity and extent of Iapetus subduction in the early Cambrian remain mostly unconstrained.

Following initiation of subduction within the Taconian Seaway, with a polarity switch, there is no conclusive evidence for continued west-dipping subduction of the Iapetus Ocean east of Dashwoods.

In most interpretations, the arc associated with the west-dipping subduction zone is the narrow, Early-Middle Ordovician Notre Dame - Annieopsquotch sequence. These arc magmatic sequences are typically interpreted as two different arcs (Swinden *et al.* 1997; Lissenberg *et al.* 2005a, b; Zagorevski *et al.* 2006; van Staal and Barr 2012). However, they are only separated by a short distance of ca. 40 km, which is less than the diameter of a typical arc volcano, making it more likely that the two time-equivalent arc sequences formed above the same subduction zone. Most of the arc magmatic units developed during subduction of the Taconic Seaway and the Laurentian margin and is temporally equivalent to the accretionary complex between the Bay of Islands ophiolite and the Laurentian foreland. The distance between the western margin of the Bay of Islands ophiolites and the Notre Dame-Annieopsquotch arc sequences is ~100 km, within the range of typical arc-trench distances (Stern 2002). Therefore, the arc complex fits well with the east-dipping 'Taconic' subduction zone. If, however, the Annieopsquotch Complex represents an arc related to west-dipping Iapetus subduction (Swinden *et al.* 1997; Zagorevski *et al.* 2006; van Staal and Barr 2012), this poses a geodynamic difficulty; the two simultaneously operating, opposite polarity subducting slabs would collide at depth. In this case, the two arcs would have had to be separated by lithosphere that would since have subducted, but there is no record (i.e., accreted OPS) of this hypothetical subduction zone. Thus, a west-dipping slab of Iapetus in the late Cambrian to Middle Ordovician is hard to reconcile with the geological record in Newfoundland.

Small-volume arc units of Late Ordovician-early Silurian age are locally preserved in the same narrow upper plate strip, which post-date the subduction of the Laurentian margin, and predate the final deposition of foreland basin deposits on the Victoria arc (Fig. 4) (Waldron *et al.* 2012). These units may indicate a west-dipping subduction zone beneath Laurentia at this time. The foreland basin sequences imply that the Victoria arc and Ganderia-Avalonia occupied a downgoing plate position. Their lower plate setting may explain why the original forearc of the peri-Gondwana system, that must have separated the Victoria arc from its associated trench, is not preserved, as it could have been fully subducted in the west-dipping subduction below composite-Laurentia. A similar forearc would also have existed on the Laurentian side, adjacent to where the arc – i.e., the Buchans and Mekwe'jite'wey Groups of the Annieopsquotch Complex – is located next to the Mekwe'jit Line; this forearc could have been shortened due to accretion of the lower plate units and then eroded.

Were Ganderia and Avalonia part of the same microplate?

Plate reconstructions commonly depict the Caledonian orogeny resulting from the collision of several Gondwana-derived microcontinents with the margin of Laurentia, including Ganderia and Avalonia (e.g., Torsvik 1998; Domeier 2016; Merdith *et al.* 2021; Scotese 2023). However, our orogenic architecture diagrams suggest that differentiating Ganderia and Avalonia as two separate continents is neither required nor justified, because there is no evidence for a relict ocean basin or a subduction zone between them.

The interpretation that Ganderia and Avalonia are two separate microcontinents is largely based on lithological differences between the basement and the Cambrian sedimentary succession at the scale of the Caledonian orogenic belt (e.g., van Staal and Barr 2012; van Staal *et al.* 2021a). These differences mostly stem from Neoproterozoic basement ages and compositions, where rocks of the Ganderian basement are isotopically more evolved than Avalonia (Rogers *et al.* 2006; van Staal *et al.* 2012, 2021a; Waldron *et al.* 2022), and these may well suggest that the blocks have once been microcontinents with separate histories (although also that is debated, e.g., Landing *et al.* 2022).

Since there is no evidence for Cambrian seafloor between Ganderia and Avalonia, it is more likely that differences in the Neoproterozoic-lower Paleozoic lithological records of Ganderia and Avalonia relate to accretionary orogenesis along the Gondwana margin and are unrelated to the Caledonian accretionary history. Therefore, if an oceanic basin existed between the Gondwanan blocks, it could have already been closed and welded before traveling to the Laurentian margin as a coherent Gondwana-margin-derived continental fragment.

Furthermore, in our reconstruction we have hypothesised that the lithological differences between the sedimentary sequence overlying the Victoria Arc (i.e., the flysches of the Badger Group) and the Ganderia Overstep Sequence (which lacks Upper Ordovician flysch deposit), may be the result of distance from the foreland and thus a different sedimentary setting; in the literature, this difference is attributed to a backarc basin located between the Victoria Arc and the Overstep Sequence which then closed along the Dog Bay Line in the Silurian (e.g., Currie 1995; Williams *et al.* 1993; Valverde-Vaquero *et al.* 2006a). According to these studies, the 'Victoria Arc' and 'Ganderia Overstep Sequence' represented two different microcontinental blocks which accreted to composite Laurentia separately, in the Late Ordovician and late Silurian, respectively (e.g., van Staal *et al.* 2012). This inference may be supported by the lack of Victoria Arc detrital signature within the Overstep Sequence (e.g., Pollock *et al.* 2007), which requires that a sedimentary divide existed between the two sedimentary sequences. However, no OPS or ophiolites are preserved along the Dog Bay Line, thus its nature as a suture, and the nature and timing of the accretion of the Ganderian block(s) cannot be fully confirmed. If such an oceanic basin did not exist, or if it did not reach an 'oceanization phase', then the Ganderia Overstep Sequence and Victoria Arc block represented two edges of the same microplate, which accreted to the composite Laurentian margin by the early Silurian (i.e., the age of the Badger Group flysches); in this case the middle Silurian-Early Devonian sediments of the Overstep Sequence can thus be considered 'post-Caledonian'.

Finally, after this whole orogen had become part of Laurentia in the early Silurian, it became 'upper plate' during the closure of the Rheic ocean towards the formation of Pangea (e.g., Domeier 2016), and subsequently the "basement" of the next syn-rift sediments, in the next 'Wilson' cycle (Wilson 1966), that started with the Jurassic opening of the Central Atlantic Ocean (e.g., Tucholke *et al.* 2007), and that still awaits its subduction and closure phase.

These interpretations are based on geologic records from Newfoundland only, so applying the orogenic architecture concept to other areas of the Caledonian orogenic belt (i.e., the British Isles or mainland Canada), or paleomagnetic constraints, may justify a more complex Caledonian history.

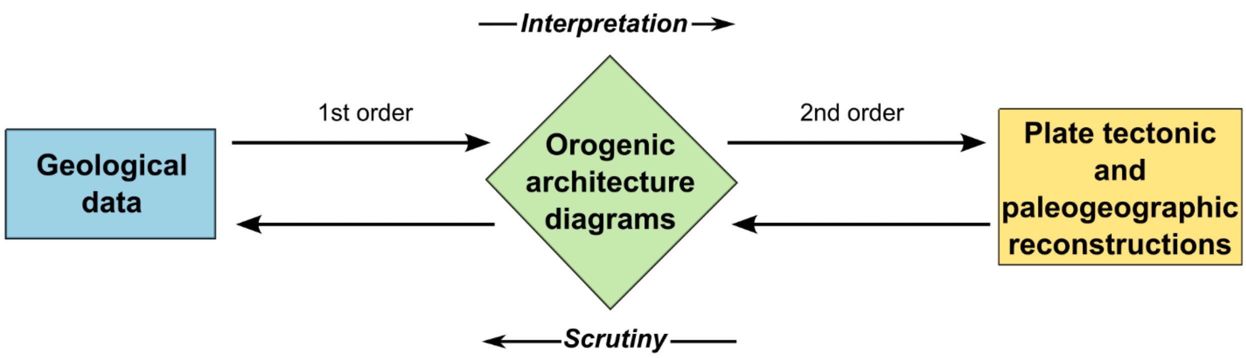

Figure 6 - Flow chart showing where the orogenic architecture diagrams are positioned in the logic sequence from geological data to large scale reconstructions.

Benefits Of Orogenic Architecture Diagrams

The orogenic architecture approach provides a useful tool to systematically synthesize geological data into reproducible framework for paleogeographic and tectonic reconstructions. We applied this methodology to the Caledonian orogeny in Newfoundland and demonstrated that it provides a basis for data-driven reconstructions of complex tectonic histories, and that it facilitates logical orogen-scale interpretations (Fig. 6). Having all available geologic data in one digestible diagram encourages scrutiny of our own interpretations and past interpretations, rooted in plate tectonic theory.

The concept of orogenic architecture diagrams was first developed for Mesozoic-Cenozoic orogens in the Tethyan and Pacific regions (Isozaki *et al.* 1990; Handy *et al.* 2010; van Hinsbergen *et al.* 2020; Boschman *et al.* 2021; van Hinsbergen and Schouten 2021; Advokaat and van Hinsbergen 2024). For Neoproterozoic-Paleozoic Newfoundland, we applied the same general classification scheme of continental plate, oceanic plate, and ophiolite units (CPS/OPS/ophiolites); used the same strategies for identifying upper and lower plate units; and similarly distinguished geological expressions of rifting and oceanic and continental subduction. This demonstrates that orogenic architecture diagrams as we outlined above apply well to early Paleozoic orogens. If we apply these concepts to increasingly older orogens, this may provide a method to evaluate different geological expressions of plate tectonics in a hotter, more juvenile Earth, and when and where assumptions rooted in the theory of modern plate tectonics – i.e., the basic hypothesis our methodology is based on – start to break down. This may shed a new light on debates on the origin, evolution, and expression of plate tectonics throughout Earth's history.

A particular advantage of our approach is that it highlights the underlying geologic observation or data that sources discrepancies in interpretations. Therefore, data-based interpretations naturally emerge that comply with the current paradigm of plate tectonics and plate boundary deformation. As such, it provides a means to identify targets for future research. Reconstructions can be further tested against paleomagnetic data that constrain convergence and divergence unaccounted for in the accretionary record.

An interesting finding that emerges from our reconstruction of Newfoundland is that the structure and metamorphism preserved in the orogen mostly reflect accretion and ophiolite emplacement, rather than continent-continent collision. ‘Collision’ between Laurentia and Ganderia/Avalonia – the final Gondwana-derived block to arrive – at the end of orogenesis did not impart any diagnostic regional metamorphic or structural features.

Our example of the Caledonian orogen merely serves to illustrate that a complete tectonic history based on all available information is objectively possible, and that a more-complete understanding of the orogen benefits from multiple orogen-scale cross section lines to characterize lateral complexities relevant for geodynamic and kinematic plate reconstructions. In the case of the Caledonian orogeny, the most recent Paleozoic plate model (Domeier 2016) mainly based their reconstruction on paleomagnetic data, and only briefly reviews the architecture of the Caledonian orogen. The architecture that was considered was based on the most widely accepted interpretations, which we demonstrated are not always justified by the synthesized geologic record. Our new geological review can be the basis for further integration throughout the entire Caledonian orogenic belt, and with paleomagnetic data, can pave a way forward for improving the plate model. Ultimately, this approach of integrating interpretation-free records of stratigraphy, composition, geochemistry, structure, and metamorphism can form the basis for geodynamic and kinematic plate reconstructions on a global scale.

CONCLUSIONS

Accretionary orogenic complexes comprise remnants of lithosphere that was consumed by subduction in the geological past and typically record protracted histories and tectonic stages spanning tens of millions of years. Interpretations of geological records are a prerequisite for paleogeographic and plate tectonic reconstructions but can be complicated by the multidisciplinary nature of available geologic information, including paleontology and sedimentology, stratigraphy, paleomagnetism, geochemistry, deformation, and metamorphism. Many famous orogens worldwide are explained by a variety of contradicting interpretations that arise from efforts to reconcile disparate datasets. In an effort to objectify data syntheses and paleogeographic and tectonic interpretations, we outlined the working principles of a method that compiles data across disciplines at the scale of individual nappes, which form the building blocks of accretionary orogens. This serves as a mesoscale step between detailed field and laboratory analyses and large-scale plate reconstructions. We developed a template and protocol for creating so-called 'orogenic architecture diagrams' and apply the method to the Newfoundland Caledonides as a case study. Our findings are the following.

- For each ‘nappe’, we compile (where relevant) lithological, stratigraphic, structural, geochronological, geochemical, and metamorphic data, and plot the data with simple symbology against geological time. We distinguish ‘lower plate’ Continental Plate Stratigraphy (CPS) or Ocean Plate Stratigraphy (OPS) from ‘upper plate’ ophiolites; upper plate ophiolites are locally associated with lower-plate slices (i.e., metamorphic soles) formed during subduction initiation. Upper plate units can consist of accreted CPS or OPS, and/or magmatic rocks of earlier tectonic phases.
- By recognising key structural features such as thrusts, stratigraphic repetitions and lithological correlations, orogenic architecture diagrams further reveal when and in what order these building blocks were structurally juxtaposed along faults. Post-orogenic strike-slip structures also represent an important marker to account for lateral movements and restore the location and geometry of accretion of the building blocks.
- We apply this method to the Newfoundland Caledonides, Canada, which has long been interpreted as an orogenic belt resulting from accretion of Gondwana-derived continental rocks to the Laurentian margin via closure of the Iapetus Ocean and other marginal ocean basins. The diagrams clearly identify phases of rifting and ocean basin opening; the subsequent closure of oceans associated with ophiolite emplacement and margin thrusting; and metamorphic signatures indicative of a complete 'Wilson-cycle'-style along both the Laurentian margin (Cambrian to Middle Ordovician) and the Gondwana margin (Cambrian to Early Ordovician). Subsequent rifting of the Gondwanan margin and subduction carried fragments of the Gondwanan orogen to the Newfoundland margin, where they arrived in the Late Ordovician-early Silurian according to the youngest foreland basin sequences in the orogen.
- The geological record of Newfoundland is 'marginal', i.e., it records accreted units associated with back-arc opening and closure. Remarkably, there is no definite geological record of the vast Iapetus Ocean, but its presence is required due to differences in fossil fauna provenance and basement characteristics. The subduction polarity of the Iapetus Ocean is inferred based on geochemical and stratigraphic arguments from the marginal geology.

- Most deformation and metamorphism recorded in Newfoundland resulted from subduction and ophiolite emplacement. Continent-continent collision is not preserved in the metamorphic record and represents only the final event in the orogenic process in a 'soft docking' manner.
- We illustrate that orogenic architecture diagrams are useful tools to comprehensively synthesize data and support data-driven interpretations at the orogen scale. This provides a base for larger scale paleogeographic, tectonic plate kinematic reconstructions. We highlight differences between our interpretations (based solely on the diagrams, purposefully ignoring past interpretations) and previously published models to illustrate how the orogenic architecture diagram approach illuminates the source of interpretation discrepancies. This in turn aids in identifying objectives for future research.
- Our methodology expands upon similar efforts applied to Mesozoic-Cenozoic orogens. We find that the paradigm of plate tectonics applies well to the early Paleozoic orogens studied here. Applying the same methods and theories to increasingly older orogens may unveil time frames in which the modern-day paradigm of plate tectonics can still be applied through Earth's history, and to probe the emergence of (modern style) plate tectonics on a cooling planet.

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