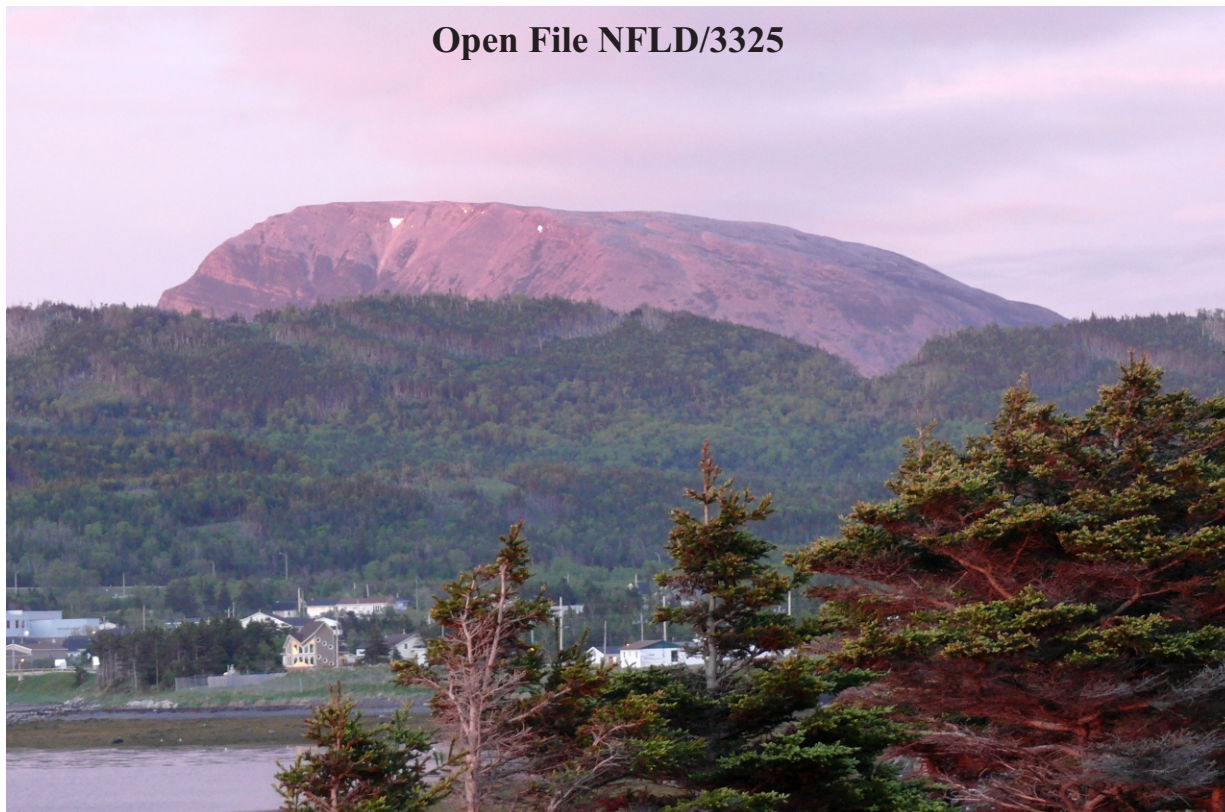


Cambrian – Middle Ordovician Platform-Slope Stratigraphy, Palaeontology and Geochemistry of Western Newfoundland

Open File NFLD/3325



Led by:

Svend Stouge, Gabriella Bagnoli and Duncan McIlroy

FIELD TRIP 2



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St. John's, Newfoundland, June 2017

For:

The International Subcommittee on Ediacaran Stratigraphy (ICES)

The International Subcommittee on Cambrian Stratigraphy (ISCS)

Cover picture – Gros Morne seen from Rocky Harbour; the mountain is capped by lower Cambrian quartzarenite (Bradore Formation). (photo: Svend Stouge)

Cambrian – Middle Ordovician platform-slope stratigraphy, palaeontology and geochemistry of western Newfoundland, Canada

By

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SAFETY INFORMATION

The Memorial University of Newfoundland, and the field trip leaders, recognize that field trips may involve hazards to the leaders and participants. The trip leaders are committed to taking every precaution, reasonable in the circumstances, to ensure that field trips are run with due regard for the safety of leaders and participants.

The weather in Newfoundland in June is unpredictable, and participants should be prepared for a wide range of temperatures and conditions. Always take suitable clothing into the field each day. A rain jacket, waterproof trousers, sweater, and sturdy footwear are essential. Gloves and a warm hat could prove invaluable if it is cold and wet, and a sunhat and sunscreen might also be required even on the same day.

Above all, field trip participants are responsible for acting in a manner that is safe for themselves and their co-participants. This responsibility includes using personal protective equipment (PPE) when necessary (when recommended by the field trip leader or upon personal identification of a hazard requiring PPE use). It also includes informing the field trip leaders of any matters of which they have knowledge that may affect their health and safety or that of co-participants. Field trip participants should pay close attention to instructions from the trip leaders at all field trip stops.

All of the sites we will visit require walking across uneven and often wet terrain. Sturdy hiking boots, preferably with some ankle support, are therefore recommended for all stops. A walking pole may be useful for some participants. Since many localities are on or near the coast, please keep away from cliff edges, and stay on the trails. This is especially important if fog descends on Mistaken Point. Participants should be aware of slippery rock surfaces, especially those coated in black or green algae: do not walk on such algal coverings. Large waves are common all along the Newfoundland coastline, so please be alert to these when examining outcrops close to the water's edge. Take care when descending to localities down rubble-covered slopes. Follow the instructions of trip leaders at all times, and stay with the group.

You have a responsibility to your fellow participants to behave in a safe manner. **HAMMERS ARE NOT PERMITTED AT SOME SITES. ASK FIRST!!!!**

More specific guidance about the hazards associated with particular stops will be provided later in the guidebook, under each stop description. These points will be reiterated by the field trip leaders upon arrival at each locality. Field trip participants are advised to read these sections carefully, and to take necessary precautions to maintain both their own safety, and the safety of fellow participants. If you have any concerns regarding your or your fellow participants safety during the course of the trip, please inform the trip leaders straight away.

INTRODUCTION

Newfoundland and Labrador is located on the eastern edge of North America (Figure 1). The island of Newfoundland, known to its friends as “The Rock”, lies off the east coast of the North American mainland, and is the most populous part of the Canadian province of Newfoundland and Labrador. The island is only 29% of the total province's land area (111,390 km²), but is still comparable to the size of the three maritime provinces of Nova Scotia, New Brunswick, and Prince Edward Island combined.

The island is separated from Labrador by the Strait of Belle Isle and the Gulf of St. Lawrence. Newfoundland's nearest neighbour is the French colony of Saint-Pierre and Miquelon, which lies opposite the GSSP for the Ediacaran–Cambrian boundary at Fortune on the Burin Peninsula (where one of the post-conference field excursions associated with ISECT 2017 will go).

Though Newfoundland and Labrador is larger than some countries, it has a small population of 510,000, around half of whom live in the greater St. John's area. The Communities of Rocky Harbour and Norris Point are enclaves within Gros Morne National Park, and form a rich local scientific and artistic hub on the west coast of Newfoundland. Many of the localities we visit will be within Gros Morne National Park (a UNESCO World Heritage Site). Collecting and hammering is not permitted at these localities. Your guides will be explicit about when you are within Gros Morne National Park.

The terrain of Newfoundland and Labrador varies from arctic tundra, ancient mountain ranges, lush boreal forest to rugged coastline.

In Gros Morne National Park you will see the direct evidence for plate tectonics, and get a chance to step on rocks from the earth's mantle. The presence of the ophiolite is one of the

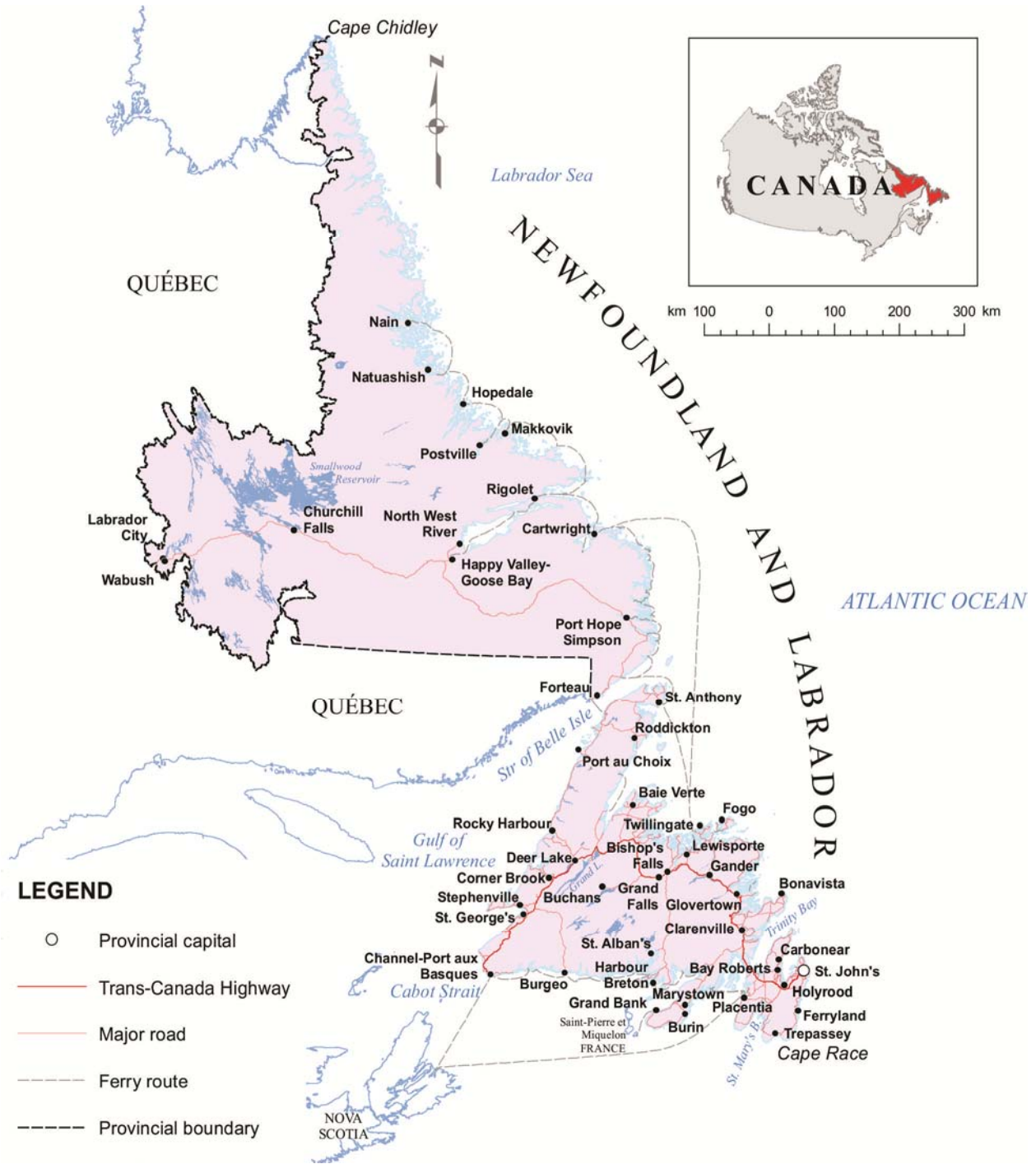


Figure 1. Geographical map of Newfoundland and Labrador.

reasons for Gros Morne National Park's existence, as it was the first place that field evidence for plate tectonics was demonstrated.

On the east coast of Newfoundland, where many of us will go for the formal meetings of the Ediacaran and Cambrian commissions, there are other sites of enormous scientific importance. The spectacularly preserved Ediacaran fossils found at Mistaken Point provide important evidence for the earliest evolution of macroscopic animal life. The importance of those fossils to the understanding of animal evolution has very recently led to the site being designated as the province of Newfoundland and Labrador's second UNESCO world heritage site (in 2016).

Geological Setting

Newfoundland is the most north-easterly part of the Appalachian Orogen in North America. The rocks of the Appalachian Orogeny extend along the whole eastern margin of Laurentia. The Appalachian fold-belt is subdivided into three lithotectonic subdivisions (Hibbard *et al.* 2006, 2007) named the Laurentian, Iapetan, and the peri-Gondwana realms. The three realms can be traced throughout the entire orogen, extending from Newfoundland in the northwest to Alabama, USA in the south (Figure 2).

The Laurentian realm comprises the sedimentary rocks that deposited either on or adjacent to ancient North America. It records the Neoproterozoic–early Palaeozoic rift-drift history of the Appalachian passive margin, the formation of a 'Taconic Seaway' (van Staal and Barr 2012) and the collision of island arcs complexes in the Middle Ordovician (classic 'Taconian' *sensu* Stockmal *et al.* 1998).

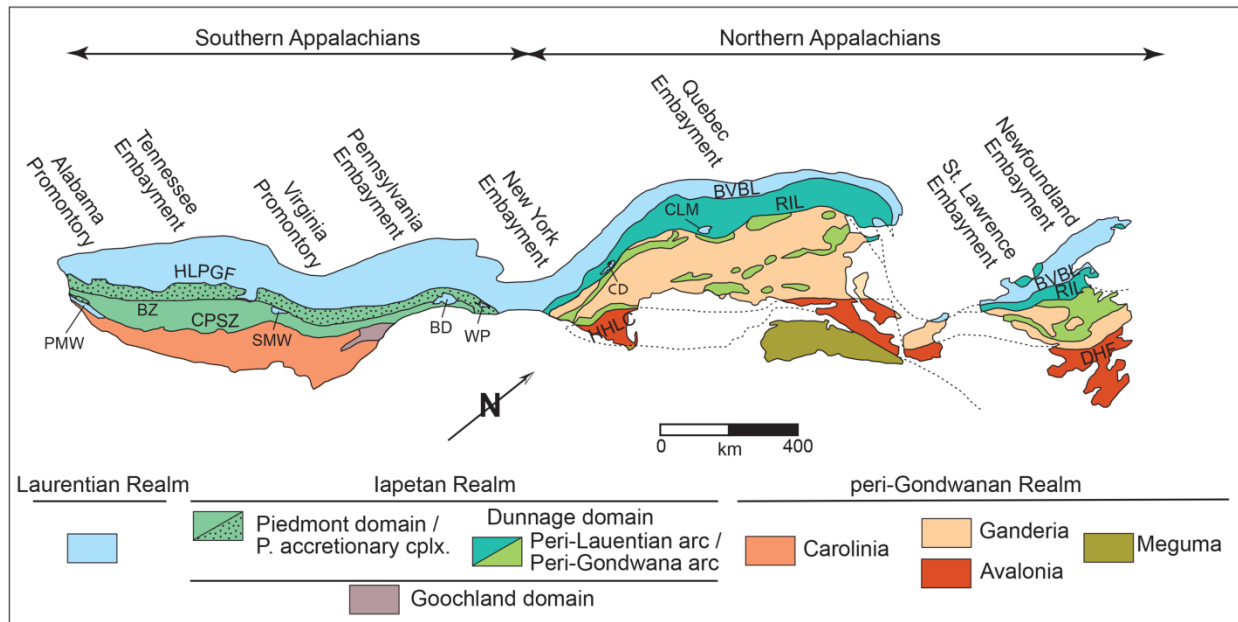


Figure 1. Lithotectonic divisions of the Appalachian orogeny (modified from Hibbard *et al.*, 2007 with permission).

- | | |
|------------------------------------|--|
| BVBL – Baie Verte – Brompton Line | HHLC – Honey Hill – Lake Char fault system |
| BD – Baltimore domes | HLPGF – Hollins Line – Pleasant Grove fault system |
| BZ – Brevard zone | PMW – Pine Mountain window |
| CD – Chester dome | RIL – Red Indian Line |
| CLM – Chain Lakes massif | SMW – Sauratown Mountains window |
| CPSZ – central Piedmont shear zone | WP – Westchester prong |
| DHF – Dover-Hermitage Bay faults | |

The Iapetan realm is composed of domains and terranes of oceanic crust and magmatic arc, and also preserves the remnants of the Iapetus Ocean including several coeval arc–back-arc complexes that existed outboard of the Ordovician Laurentian margin, situated between the Laurentian and peri-Gondwanan realms. The Iapetan realm is subdivided into peri-Laurentian and peri-Gondwanan domains separated by the Red Indian Line, the main Iapetus suture zone (Figures 2, 3; Williams 1995; Hibbard *et al.* 2005, 2007). The elements of the peri-Gondwana realm were rifted away from Gondwana. These are the Ganderia and Avalonia terranes (Hibbard 2007; Zagorevski *et al.* 2008).

Laurentia rifted, apparently from Amazonia, in several stages (e.g. Cawood *et al.* 1991; Hibbard *et al.* 2007; van Staal *et al.* 2009; van Staal and Barr 2012). The initial breakup of Rodinia, prior to 600 Ma, opened the relatively narrow ‘Taconic Seaway’ (*sensu* van Staal and Barr 2012) between Laurentian and an outboard terrane or micro-continent (the Dashwoods micro-continent of Waldron and van Staal 2001). The Iapetus Ocean finally opened along the Laurentian margin between 570 and 540 Ma according to Waldron and van Staal (2001) and Cawood *et al.* (2001), developing a passive margin. The opening of Iapetus formed major salients and recesses, creating coastal irregularities in the Laurentian margin (Thomson 1977, 1991). The passive margin of Laurentia in western Newfoundland lies on the St. Lawrence promontory that connects to the Quebec re-entrant to south (James *et al.* 1989; Lavoie *et al.* 2003). The Quebec re-entrant extends from Anticosti Island south to the border with the U.S. (Figure 2).

The margin of Laurentia experienced three orogenic episodes between Ordovician and Early Devonian times, namely the Taconic, Salinic, and Acadian orogenies. These episodes occurred as a result of the successive accretion of the Dashwoods, Gander, and Avalon micro-continents (van Staal 2005). The passive margin existed from the mid Cambrian until the early Middle Ordovician, when the closure of the Taconic Seaway—caused by subduction of Laurentia—occurred during the ‘classic Taconic’ event (*sensu* Stockmal *et al.* 1998).

The complexity of the closure of the Iapetus Ocean is reflected in the zonal division of the northern Appalachians, where five tectonostratigraphic zones have been defined: Humber, Dunnage, Gander, Avalon, and Meguma (Williams 1995). The first four of which are determined in Newfoundland (Figure 3). The northern Appalachian accretion of Ganderia to Laurentia occurred in the Late Ordovician (the Salinic Orogeny; van Staal *et al.* 2009). This

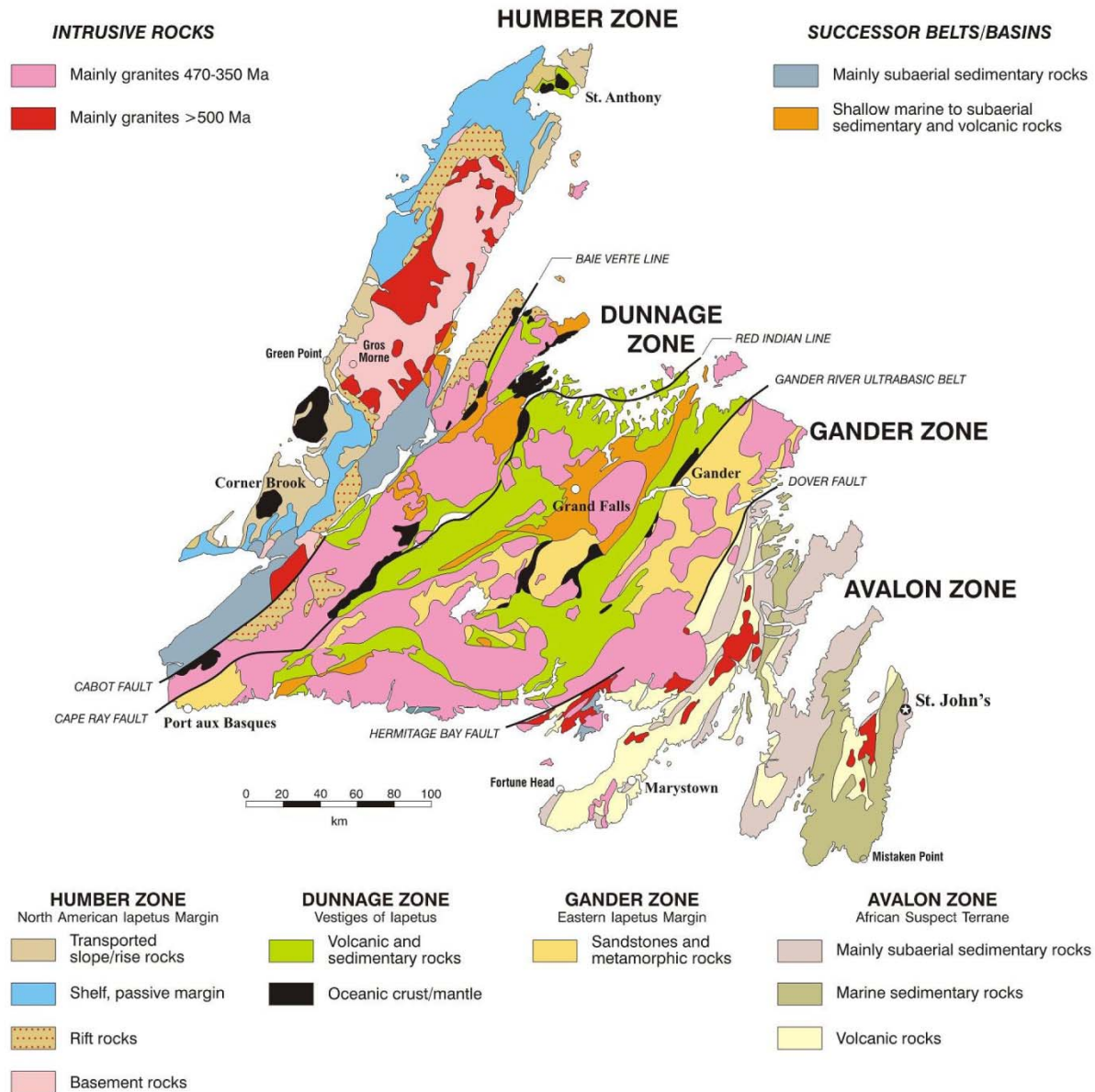


Figure 3. Geology of Newfoundland with tectonostratigraphic zones. The Red Indian Line is the Iapetus suture line (from Hayes 1987; modified by H. Williams 2004).

event was followed by the Acadian accretion of Avalonia, which was in turn immediately followed by the Middle Devonian – Early Carboniferous accretion of the Meguma and possibly Suwannee terranes, and then the Fammenian Orogeny. This sequence of orogenesis suggests that the current spatial distribution of these domains reflects their order of accretion. The eventual

rifting of Pangea during the Mesozoic opening of the Atlantic occurred outboard of the Palaeozoic collision zones that accreted Carolina, Ganderia, Avalonia, Meguma, and Suwannee to Laurentia, leaving these terranes attached to North America.

Regional Geological Setting

Western Newfoundland lies within the Humber Zone of the Appalachian Orogen, the westernmost of the five main Appalachian tectono-stratigraphic zones distinguished across the island (Figure 3; Williams 1979; Williams *et al.* 1988). The eastern boundary between the Humber Zone and the Dunnage Zone is delineated by the Baie Verte line (Figures 3, 4), which preserves the initiation and development of the Laurentian Margin in association with the opening of the Iapetus Ocean (Cawood *et al.* 2001; Cawood and Nemchin 2001).

The Humber Zone is characterized by a Cambro–Ordovician passive margin succession, deposited on rifted, Grenvillian (ca. 1.5 Ga) crystalline basement (Figure 4). The crystalline basement of the Humber zone is composed of granitic gneisses (~ 1.5 Ga) intruded by ~1.05 Ga plutons. The basement is unconformably overlain by a platformal succession composed of Neoproterozoic–lower Cambrian rift-related deposits. This is overlain by a lower Palaeozoic sequence deposited during the post-rift period (i.e. drift) that accumulated on the passive margin of Laurentia and foreland basin sedimentary succession. The platformal sedimentary rocks are well preserved in the weakly deformed external zone of the Humber Zone of Newfoundland (Figure 4).

The age of the rifting of the Laurentian passive margin ranges from 620 to 550 Ma in Newfoundland, though it may have occurred as multiple rift events. The first recorded event associated with the opening of the Iapetus Ocean is the late Neoproterozoic and early Cambrian

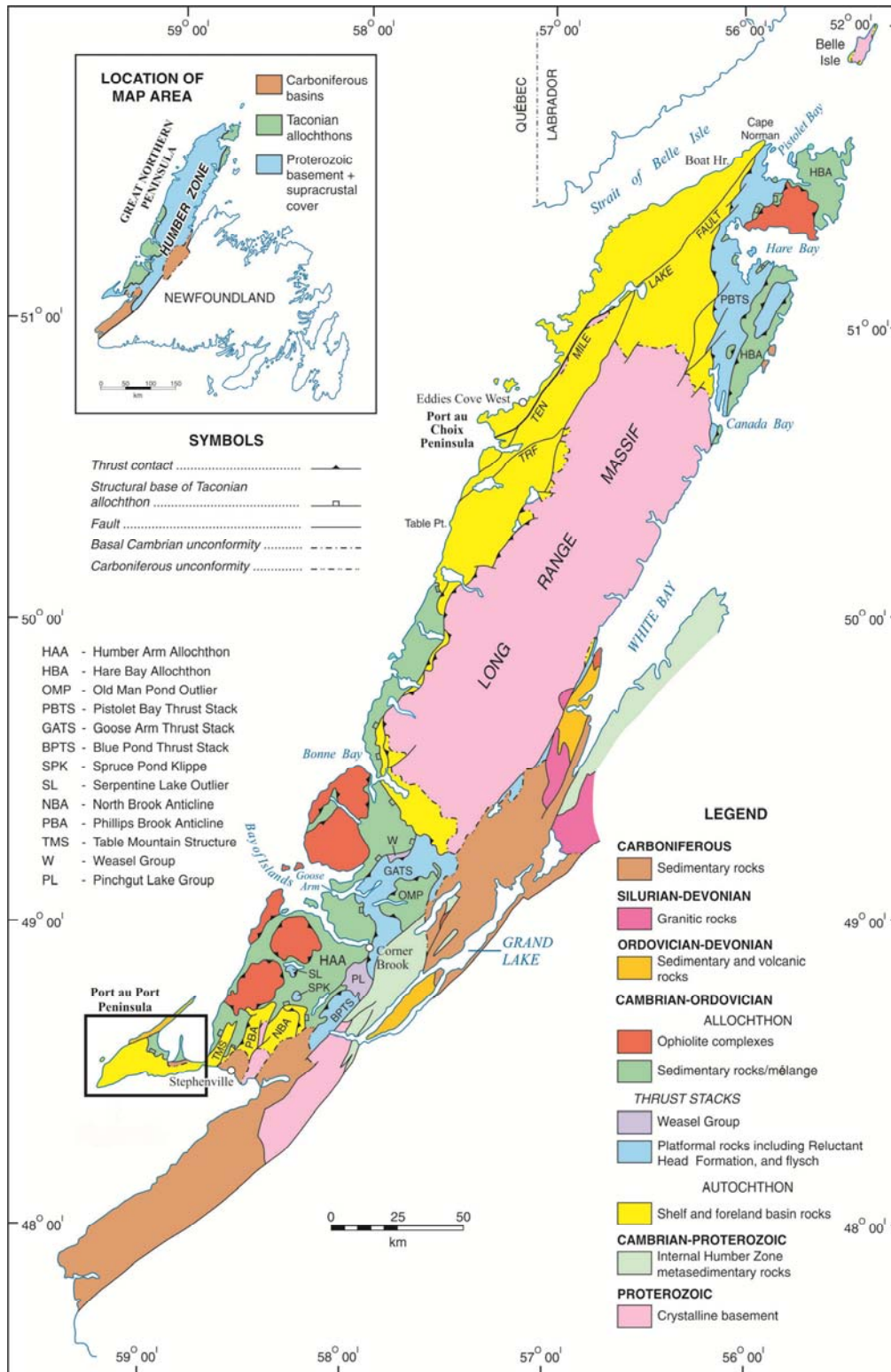


Figure 4. Regional geological map of western Newfoundland (from Knight 2007). The frame around Port au Port Peninsula is reference to Figure 12.

rifting. The synrift succession includes upper Ediacaran to lower Cambrian fault-bounded basins with siliciclastic sedimentary rocks dominated by conglomerates, quartzites, arkoses, siltstones and shaly mudstones, along with volcanic rocks of the lower Labrador Group.

The unconformably overlying lower and mid Cambrian, mainly siliciclastic, sedimentary succession is more than 1000 m thick (Bradore, Forteau and Hawkes Bay formations), are referred to the upper Labrador Group (Figure 5). The final rifting stage and the opening of the Iapetus Ocean is considered to be related to the early Cambrian Hawkes Bay event (James *et al.* 1989; Palmer and James 1979; Knight *in Lavoie et al.* 2012). The subsequent drift-related passive-margin type sedimentary succession spans the late early Cambrian to Early Ordovician (Knight *et al.* 1995; Lavoie *et al.* 2003, 2012). The stratigraphic succession includes intertidal to marine shallow-water carbonates of the Port au Port Group (upper lower Cambrian – lowermost Ordovician), and the St. George Group (Lower – lower Middle Ordovician) (Chow and James 1987; Cowan and James 1989; Knight and James 1987; James *et al.* 1989; Cooper *et al.* 2001; Lavoie *et al.* 2003; Knight *et al.* 2008; Knight *in Lavoie et al.* 2012). This tectonically stable period from the Cambrian to the early Middle Ordovician, with its carbonate-dominated sedimentary successions, is termed ‘the Great American Carbonate Bank’ (Derby *et al.* 2012; Lavoie *et al.* 2012).

The stable carbonate accumulation on the platform ended in latest Early to earliest Middle Ordovician, when an unconformity developed on top of the St. George Group on the Port au Port Peninsula (Knight *et al.* 1991). The regional St. George Unconformity largely defines the boundary between the St. George Group and the overlying Table Head Group. Jacobi (1981) and Knight *et al.* (1991) interpreted this unconformity as being due to the passage of a lithospheric

flexural bulge produced by encroachment of a trench system during the early stages of the Taconian Orogeny.

Rapid subsidence during the deposition of the Table Head Group is interpreted to reflect tectonic loading of the Laurentian Margin by the converging Taconian allochthons (Stockmal *et al.* 1995, 1998). Carbonate accumulation persisted during the early drowning stage of the Laurentian passive margin, and through the formation of the foreland basin. The Middle Ordovician Table Head Group overlies the St. George Unconformity, and records the early stages of Taconian foreland basin subsidence prior to the arrival of material derived from the allochthons to the east.

The lowest unit of the Table Head Group, the Table Point Formation, is a shallow-water shelfal marine carbonate that varies markedly in thickness along strike, suggesting the presence of active faulting of the platform during foreland subsidence (Stouge 1984; Stenzel *et al.* 1990; Palmer *et al.* 2001). The overlying Table Cove Formation comprises deeper water sediments that include graptolitic shaly mudstones. The increased rate of subsidence resulted in the cessation of carbonate accumulation and diachronous migration of deep-water deposition as the Table Cove and Goose Tickle facies became more widespread across western Newfoundland (Stevens 1970; Stouge 1984; Quinn 1988, 1996; Stockmal *et al.* 1995). The overlying, Darriwilian, Cape Cormorant Formation contains clasts and blocks of limestones, some up to 65 m long, derived from the upper 1000 m or more of the underlying platform succession (Stenzel *et al.* 1990). On the Port au Port Peninsula, this unit is restricted to a small area, and lies in the immediate hanging wall of the Round Head Thrust (Waldron and Stockmal 1991; Stockmal *et al.* 1998).

Overlying the Table Head Group are turbiditic siliciclastics of the Goose Tickle Group, which are derived from the allochthon (Stevens 1970; Quinn 1996). On the Port au Port

Peninsula the Goose Tickle Group is represented by the Mainland Sandstone (Stenzel *et al.* 1990), which is approximately 1.5 km in maximum thickness, but is locally structurally thickened (Waldron and Stockmal 1991; Waldron *et al.* 1993). Within the Goose Tickle Group are discontinuous bodies of massive limestone conglomerate, dominated by clasts of the Table Point Formation, which constitute the Daniel's Harbour Member (Figure 5) (Stenzel *et al.* 1990; Quinn 1996). The Daniel's Harbour Member may — like the Cape Cormorant Formation — have been derived from the scarps of normal faults active in the Taconian foreland.

The diachronous Goose Tickle Group (upper Lower – Middle Ordovician) sediments were sourced from the Taconian allochthons to the east, and accumulated in the foreland basin. The Goose Tickle Group itself is partly contemporaneous with, and partly younger than, the Table Head Group (Quinn 1996; Maletz *et al.* 2011). The foreland basin persisted during the Taconic and Salinic orogenic episodes into the early Silurian (Waldron *et al.* 1998; Cooper, M. *et al.* 2001). Upper Ordovician to lower Silurian strata overlie the older foreland sedimentary rocks, and include shallow-marine carbonates, deeper water siliciclastic facies, and red-bed successions of the Long Point Group (Schuchert and Dunbar 1934; Stevens 1970; Williams *et al.* 1996; Quinn *et al.* 1999; Reynolds and McIlroy 2017). The poorly-exposed Long Point Group is, in turn, disconformably overlain by upper Silurian red siliciclastic sedimentary rocks of the Clam Bank Formation.

The next youngest unit within the foreland succession is the Upper Ordovician Lourdes Limestone of the Long Point Group. On the Port au Port Peninsula, the Lourdes Limestone structurally overlies the Humber Arm Allochthon (Waldron and Stockmal 1991). The overlying siliciclastic units of the Long Point Group are the Winterhouse and Misty Point formations (Quinn *et al.* 1999; Reynolds and McIlroy 2017). Overlying the Long Point Group is the

dominantly non-marine Clam Bank Formation, which is dated as Lochkovian (lower Lower Devonian; *vide* Burden *et al.* 2002). The youngest unit known in this portion of the Anticosti Basin is the Red Island Road Formation, characterized by a clast-supported rhyolite pebble to cobble conglomerate. Williams *et al.* (1996) suggest the Red Island Road Formation is Emsian (upper Lower Devonian) on the basis of palynology.

Humber Arm Allochthon

The basement and the cover sequence are structurally overlain by the Taconic allochthons or the Humber Arm allochthon, in western Newfoundland (Williams and Stevens 1974). The allochthonous comprises sedimentary rocks equivalent to the platform cover succession (James & Stevens 1986; James *et al.* 1989; Boyce *et al.* 1992; Knight 2003, Knight and Boyce 2000, 2001, 2002, 2009). The Humber Arm Allochthon succession is referred to the late Neoproterozoic to Middle Ordovician Humber Arm Supergroup, and is composed of the Stirling Group, Cow Head Group and the Northern Head Group, preserved in a series of imbricate thrust sheets. The base of the Humber Arm Allochthon is marked by the early Cambrian Curling Group, which is a succession of deep-water siliciclastic turbidites that are considered equivalent to the Labrador Group (Palmer *et al.* 2001). The Cow Head Group is overlain by the Lower Head Formation, which was deposited during the early stages of a foreland basin development and Taconic deformation in the Middle Ordovician (Quinn 1995; Blamey *et al.* 2016).

The highest allochthon slices of the Humber Arm Allochthon include the Bay of Islands ophiolite that represents the oceanic lithosphere of Iapetus (Williams and Cawood 1989; Jenner *et al.* 1991). The basinal sediments were thrust westwards by up to 100 km over the autochthonous strata during the Taconic Orogeny (Stockmal *et al.* 1995).

STRATIGRAPHIC TERMINOLOGY OF WESTERN NEWFOUNDLAND

The shelfal succession of the Labrador, Port au Port and St. George groups is overlain by the carbonate-dominated Table Head Group (James *et al.* 1989; Figure 5). The deeper water successions come from the eastern thrust packages and the Taconic Humber Arm allochthon, and include the Weasel Group, Reluctant Head Formation, Cow Head Group, Curling Group and the Northern Head Group (Knight and Boyce 2000, 2001, 2002; Boyce *et al.* 1992; Figure 5).

Labrador Group

The rifting of Rodinia created accommodation space that was filled with siliciclastic and minor carbonate sediments of the lower Labrador Group during the uppermost Neoproterozoic to lower part of the middle Cambrian.

The more than 1000 m thick upper Labrador Group is mainly siliciclastic, with minor carbonate units (Schuchert and Dunbar 1934; Knight and Boyce 1987). In ascending order, the Labrador Group is subdivided into the Bradore, Forteau and Hawkes Bay formations.

Bradore Formation – The Bradore Formation is a sandstone unit with some conglomerates. The basal sediments consist of red pebbly subarkosic sandstone, succeeded by cross-bedded sandstone and pebble conglomerate. The sediments were deposited in a fluvial shallow marine depositional setting.

Forteau Formation – The overlying Forteau Formation is composed of limestone, shaly mudstone, siltstone and minor sandstone. Towards the south and east of the outcrop belt dark shaly mudstone along with minor ribbon limestones, intraclastic lime breccias and oolitic-oncolitic lime grainstones prevail. Mud-rich, nodular, red to white fossiliferous wackestones with solitary archeocyathans and archaeocyathan biostromes grade westward and northward into

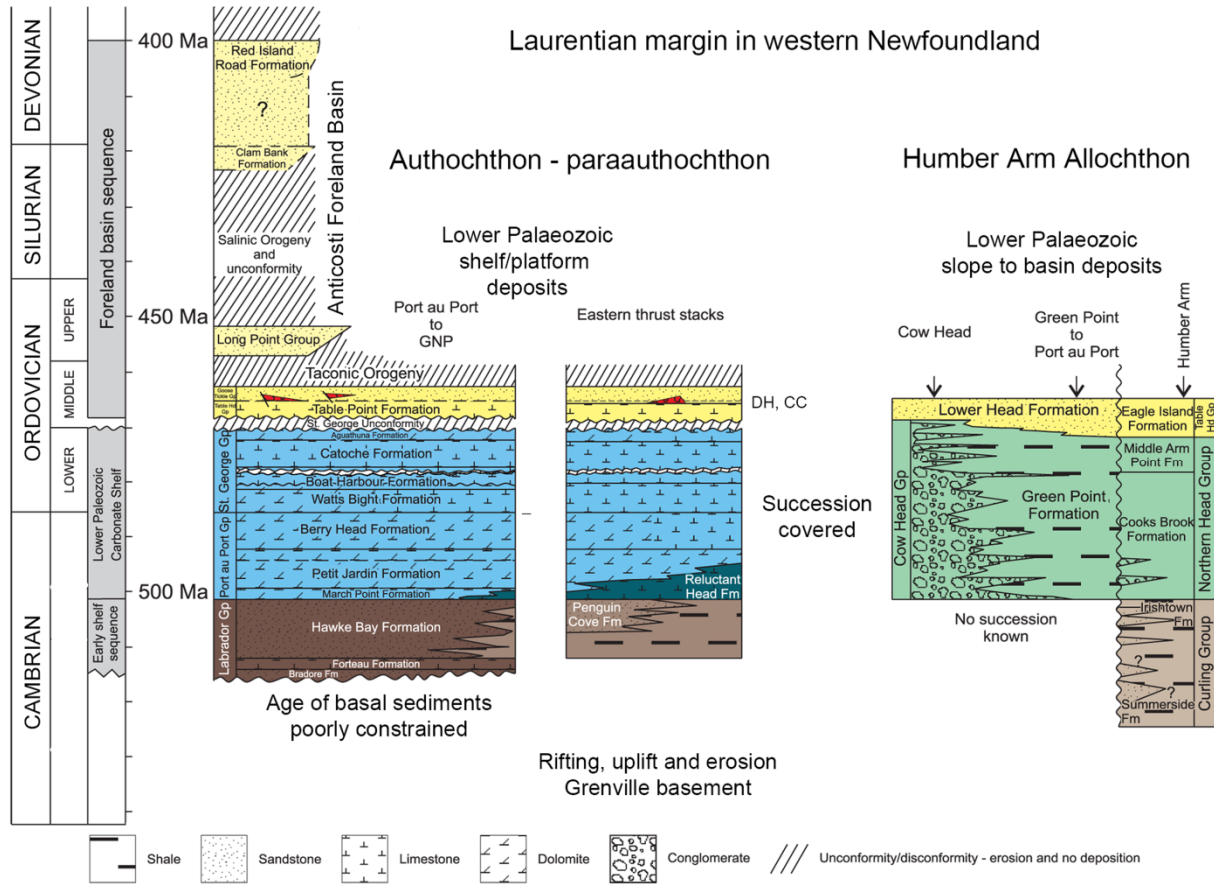


Figure 5. Lithostratigraphy of the Lower Palaeozoic succession in western Newfoundland (based on Cooper, M. *et al.* 2001; modified from Hinchey *et al.* 2015). DH = Daniels Harbour Member; CC = Cape Cormorant Formation.

archaeocyathan bioherm complexes in Labrador (James and Kobluk 1978; Knight and Boyce 1984). The trilobites, archaeocyathans and layers of *Salterella* indicate deposition entirely within the *Bonnia-Olenellus* Zone (lower Cambrian).

Hawke Bay Formation – The Hawke Bay Formation consists of siliciclastic sedimentary rocks and minor carbonates, and overlies the Forteau Formation. The unit is a package of mainly mineralogically and texturally mature, massive cross-bedded quartz-arenites (Knight and Boyce 1987). Trilobites range in age from the upper part of the *Bonnia-Olenellus* Zone of the lower Cambrian to the *Bathyriscus-Elrathina* and *Ehmaniella* Zones of the mid Cambrian (Boyce

1977; Knight 1977; Knight and Boyce 1987). The sandstone of the Hawkes Bay Formation was deposited in a major, probably highstand, phase of progradation (cf. James *et al.* 1989).

The Hawke Bay Formation in the west of the outcrop belt is coeval to the mixed shallow-water siliciclastics and carbonates of Bridge Cove Member and Penguin Cove Formation as are preserved in the eastern thrust stacks (Knight and Boyce 1987, 1991; Knight 2006; Figure 5). The distal and lateral equivalent of the Labrador Group deposits on the shelf is the Curling Group from the Humber Arm Allochthon (Figure 5).

The Labrador Group is overlain by a thick succession of shallow water carbonate platform sediments (the Port au Port Group and St. George Group) that accumulated during the drift stage, representing an Atlantic type of passive margin development.

Port au Port Group

The Port au Port Group is 450 – 500 m thick, and ranges from the upper mid Cambrian *Ehmaniella* Zone to the uppermost Cambrian *Symphysurina brevispicata* Zone (Boyce 1977; Westrop 1992; Boyce *et al.* 1992; Boyce and Knight 2005; Figure 5), spanning the upper Sauk II to lower Sauk III interval (James *et al.* 1989; Lavoie *et al.* 2012) and includes the SPICE excursion (Salzman *et al.* 2004). The Port au Port Group is subdivided into the March Point, Petit Jardin, and Berry Head formations (Figure 5).

March Point Formation – The March Point Formation is 40–100 m thick, and consists of shale, siltstone, limestone, and sandstone with some glauconite and phosphate. The upper part consists of dolomitic ribbon limestones, bioturbated limestones, oolitic and oncolitic grainstones, and minor stromatolitic limestones. The formation is referred to the *Ehmaniella* and *Bolaspidella* zones (upper Delamarian; Boyce 1977; Westrop 1992; Boyce and Knight 2005).

Petit Jardin Formation – The 300–360 m thick Petit Jardin Formation conformably overlies the March Point Formation and is divided into the Cape Ann, Campbells, Big Cove, Felix, and Man o’ War members (Chow and James 1987a; Cowan and James 1993). The formation consists of shaly mudstone; nodular, parted, and ribbon limestones and dolostones, and both stromatolitic and thrombolitic boundstones. Quartz-arenites, thin siltstones and litharenites occur at the top of the Felix Member. The Cape Ann Member includes a spectacular thrombolite/stromatolite mound complex (Kennard and James 1986). Trilobites indicate that the Petit Jardin Formation is of Marjuman age, and the thin sandstone beds at the top of the Felix Member separates the lower trilobite *Aphelaspis* Zone from the *Dundenbergia* Zone (Boyce 1977; Chow and James 1987; Westrop 1992; Cowan and James 1993; Boyce and Knight 2005) and coincides with the Sauk II and Sauk III boundary associated with the prominent the Steptoean positive $\delta^{13}\text{C}$ isotope excursion (SPICE; Salzman *et al.* 2004).

In the eastern thrust stacks, the dolostones of the Petit Jardin Formation are separated by a unit of interbedded, heterolithic, limestone, dolostone and shale. The heterolithic unit and the upper dolostone unit yield trilobite faunas of the *Cedaria* Zone and *Crepicephalus* Zone respectively (Knight and Boyce 1991; Boyce and Knight 2005).

Berry Head Formation – The overlying 200 m thick Berry Head Formation is composed of two members. The lower member is thick-bedded with a cherty basal mound and oolites, whereas the upper member is composed of interbedded peritidal burrowed limestones and parted dolomitic limestones. The fauna in the upper member correlates with the Sunwaptan to lower Skullrockian (Knight and Boyce 1991; Boyce and Knight 2005), but the top of the formation may be referred to the earliest Ordovician (Ji and Barnes 1994; S. Scorrer in prep.). The $\delta^{13}\text{C}$ isotope pattern from the Berry Head Formation is shown at **Stop 6**.

Reluctant Head Formation – The March Point Formation and much of the Petit Jardin Formation pass laterally into the Reluctant Head Formation in the east and southeast. The Reluctant Head Formation consists of shaly mudstones interbedded with siltstones along with nodular, ribbon and parted limestones. This lithofacies association is similar to off-shelf rocks of the allochthonous Weasel and Pinchgut Lake groups (Knight and Boyce 1991, 2009; Knight 1997). The Weasel Group is biostratigraphically dated to the Cambrian *Bolapsidella*–*Dundenbergia* Zone and ranges up to the lower Tremadocian (Boyce *et al.* 2000; Knight and Boyce 2009).

St. George Group

St. George Group is a succession of about 500 m marine subtidal and peritidal carbonates (Knight and James 1987) that conformably overlies the Port au Port Group. The St. George Group is subdivided into the Watts Bight, Boat Harbour, Catoche, and Aguathuna formations (Knight and James 1987; Boyce *et al.* 2000; Knight *in* Lavoie *et al.* 2012) and conformably overlies the Berry Head Formation of the Port au Port Group.

Biostratigraphically, the St. George Group is dated by trilobites and conodonts (Boyce 1978, 1979, 1989; Fortey 1979; Stouge 1982; Boyce and Stouge 1997; Boyce *et al.* 2000; Ji and Barnes 1994; Figure 6).

Many papers have been published on various abundant fossils of the St. George Group (extensive bibliography *in* Boyce and Williams 1995).

Watts Bight Formation – The Watts Bight Formation is 70 to 100 m thick, and is composed mainly of subtidal bioturbated carbonate-rich and microbial-metazoan thrombolitic mounds (the Green Head mound complex of Pratt and James 1982). The formation is commonly dolomitized

Chronostratigraphy				Trilobite Biozonation	Conodont Biozonation				Lithostratigraphy
O R D O V I C I A N	Series/Stages			Boyce and Stouge 1997 Boyce and Knight 2009	Ji and Barnes 1994				St. George Group
	Middle	Dapingian	Whiterockian	<i>Bathyurus perplexus</i> (Barren?)	(not zoned)	<i>Parapanderodus retractus</i>	<i>Pteracantiodus cryptodens</i>	Aguathuna Formation	
	Lower	Floian	Cassinian	<i>Benthamaaspis gibberrula</i>	<i>Oepikodus communis</i>	<i>P. carlae-Stultodontus ovatus</i>	<i>Oepikodus communis-P. simplicissimus</i>	Catoche Formation	
				<i>Strigigenalis caudata</i>					
		Jeffersonian	<i>Strigigenalis brevicaudata</i>	<i>Drepanoistodus concavus</i>	<i>P. inconstans-S. subrex</i>	<i>Acodus deltatus-A.? primus</i>			
	Tremadoc	Ibexian/Canadian	Demingian	<i>Randaynia saundersi</i> <i>Leiostegium proprium</i> <i>Hystricurus oculilunatus</i>	<i>Macerodus diana</i> <i>Striatodontus prolificus</i>	<i>S. prolificus-S. lanceolatus</i> <i>G. floweri-G. bolites</i>	<i>Drepanoistodus nowlani</i> --- <i>Macerodus diana</i>	Boat Harbour Formation	
			Gasconadian	<i>Parahystricurus</i> sp. 1	(not revised)	<i>R. manitouensis</i> --- <i>P. sulcatus</i> <i>Polycostatus falsioneotensis</i> --- <i>Rossodus tenuis</i>	<i>Cordylodus angulatus</i>	Watts Bight Formation	

Figure 6. Lithostratigraphy and trilobite and conodont zones of the St. George Group.

giving a sucrose surface. The Watts Bight Formation is referred to the *Cordylodus lindstromi* and *C. angulatus* conodont zones.

Boat Harbour Formation – The Boat Harbour Formation is a succession of peritidal limestone, with several horizons of thrombolite mounds (Pratt and James 1982). The middle part of the formation is bounded by two unconformities. The lower member of the Boat Harbour Formation is assigned to the *Rossodus manitouensis* – *Polycostatus sulcatus* conodont Zone (Tremadocian; Ji and Barnes 1994). The middle Boat Harbour Formation is referred to the *Drepanoistodus nowlani* - *Macerodus diana* conodont Zone (upper Tremadocian; Ji and Barnes 1994). The upper Boat Harbour Formation (Barbace Cove Member) i.e. the strata above the upper unconformity are assigned to the *Acodus delicatus* – *Acodus? primus* conodont Zone

(Floian Stage; Ji and Barnes 1994) corresponding to the *Protopliomerella contracta* trilobite Zone (see Figure 6).

Catoche Formation – This 160 m thick succession composed of fossiliferous shallow, subtidal limestone conformably overlies the Boat Harbour Formation. The rocks are well-bedded, fossiliferous, bioturbated, grey limestones with a mudstone to packstone texture, and intercalated lenses or thin beds of rippled bioclastic to intraclastic grainstone. This formation is contained in the general and widespread *Oepikodus communis* conodont Zone (Ibexian; Floian Stage). The upper Costa Bay Member, 20 to 40 m thick (Boyce *et al.* 2000; Knight 2007), is highly fossiliferous (see Boyce and Williams 1992; Boyce and Stouge 1997; Ji and Barnes 1994).

Aguathuna Formation – The Aguathuna Formation is composed of peritidal carbonates, mostly dolostone. The St. George Unconformity either cuts the surface or is locally a disconformity within the formation. The higher beds of the Aguathuna Formation are much less fossiliferous or barren relative to the lower Aguathuna Formation, which contains the Whiterockian conodont species *Pteracontiodus cryptodens*. The macrofaunal assemblage consists of shallow marine, shelly fossils (Boyce *et al.* 2000), and rare graptolitic horizons yield sparse, monospecific faunas (Williams *et al.* 1987).

Table Head Group

Following Stenzel *et al.* (1990) the Table Head Group comprises the Table Point, Table Cove and Cape Cormorant formations (Figure 7). It overlies the St. George Group, some places disconformably, and is overlain by the Lower Head Formation and Mainland Sandstone Formation (Klappa *et al.* 1980; Stouge 1984; Stenzel *et al.* 1990). The rich fauna of the Table

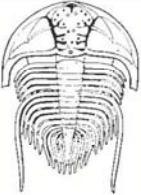


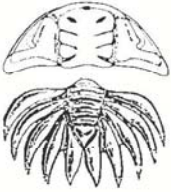



LITHOSTRATIGRAPHY		TRILOBITE ZONES		CONODONT ZONES	
TABLE HEAD GROUP	Table Cove Formation		<i>Cybelurus mirus</i>		<i>Histiodella bellburnensis</i>
					<i>Histiodella kristinae</i>
	Table Point Formation	▲ 	<i>Pseudomera barrandei</i>		<i>Histiodella holodentata</i>
		▲			
		▲ 	<i>Uromystrum validum</i>	<i>Paraprioniodus neocostatus</i>	
ST. GEORGE GROUP	Aguathuna Formation		<i>Bathyrurus perplexus</i>		

Figure 7. Lithostratigraphy and trilobite and conodont zones of the Table Head Group (from Boyce and Knight 2009, slightly modified).

Head Group is biostratigraphically divided into several trilobite zones (Whittington and Kindle 1963; Boyce and Knight 2009), conodont zones (Stouge 1984) and graptolite zones (Maletz *et al.* 2011) (Figure 7) (**Stops 3 and 4**). The Table Head Group is overlain by the Goose Tickle Group.

Table Point Formation – The unit comprises well-bedded, fossiliferous, bioturbated, grey lime-mudstones and packstones. The lower part is a succession of peritidal carbonates (Units A1 and A2 of Stouge 1984; Springs Inlet Member of Ross and James 1986) that grade upwards into subtidal carbonates with thin bedded, nodular, fossiliferous limestones, and capped by sponge

bioherms (Klappa and James 1980). The subtidal carbonates of the Table Point Formation are locally overlain by either the Table Cove Formation, or the Goose Tickle Group.

Table Cove Formation – This unit ranges from bioturbated, highly fossiliferous nodular limestone at the base through flat bedded parted to ribbon limestone. Trilobites, graptolites, chitinozoans, conodonts, sponge spicules and radiolarians are present to common in the parted to ribbon limestone and shale.

Cape Cormorant Formation. – At the type section at Cape Cormorant the formation consists of 200 m of interbedded limestone conglomerates, turbiditic grainstones and graptolitic shales (Stenzel *et al.* 1990; Albani *et al.* 2001; **Stop 4**). At Round Head the formation consists of very thick to massive bedded conglomerate - some blocks are up to 65 m wide (Waldron and Stockmal 1991).

Exposure and erosion of the underlying Middle Ordovician carbonates is reflected by the presence of spectacular conglomeratic horizons, composed almost exclusively of the underlying carbonates. The background sediments are black shale with graptolites.

Goose Tickle Group

The Table Head Group is overlain by the Black Cove Member of the Goose Tickle Group (Stenzel *et al.* 1990).

Black Cove Formation – This is a black shaly mudstone unit, varies from few meters to 10 m in thickness. It is rich in graptolites, and—conformably to unconformably—overlies the Table Cove and Table Point formations.

Daniels Harbour Member – This conglomeratic unit is composed mainly of carbonate block derived from the Table Head Group.

Humber Arm Supergroup

The Humber Arm Supergroup consists of the Curling Group, the Northern Head Group and the Cow Head Group.

Curling Group

The Curling Group consists of siliciclastic sedimentary rocks (shaly mudstones and sandstones) preserved in the Humber Allochthon (Stevens 1970; Botsford 1988) and is overlain by the Northern Head Group. The Curling Group itself is subdivided into the Blow Me Down Brook Formation, the Summerside Formation and the Irishtown Formation (Figure 5). The Blow Me Down Formation is dominated by very thickly bedded, normally graded, grey coloured, coarse-grained sandstones. The overlying Summerside Formation is a metasedimentary package, ca 700 m thick. The overlying Irishtown Formation is more than 1000 m thick, and is mainly composed of pelites with some siltstone and sandstone beds. The Curling Group is biostratigraphically dated as lower Cambrian and correlates with the Labrador Group (Palmer *et al.* 2001).

Cow Head Group

The allochthonous mid Cambrian to Middle Ordovician Cow Head Group (Kindle and Whittington 1958) comprises a 300–500 m thick succession of sedimentary rocks (James and Stevens 1986).

The Cow Head Group is characterized by conglomerate beds intercalated with deep-water carbonates, quartz-rich, coarse-grained limestones and minor siliciclastic facies. The succession

is exposed in a series of southeast dipping thrust slices, and is subdivided into two formations and seven members (James and Stevens 1986; Figure 8).

The coarse-grained facies in the northwest are termed the Shallow Bay Formation, and are contemporaneous with the fine-grained shaly mudstone facies exposed to the southeast as the Green Point Formation. Both are subdivided into several members (James and Stevens 1986; Figure 8). The Cow Head Group strata represent shelf margin to the lower slope depositional setting (Figure 9).

Shallow Bay Formation – The Shallow Bay Formation includes in ascending order the upper middle Cambrian to lower upper Cambrian Downes Point Member, a 100 m thick sequence of conglomerates, (beds 1–5 of Kindle and Whittington 1958). The overlying Tuckers

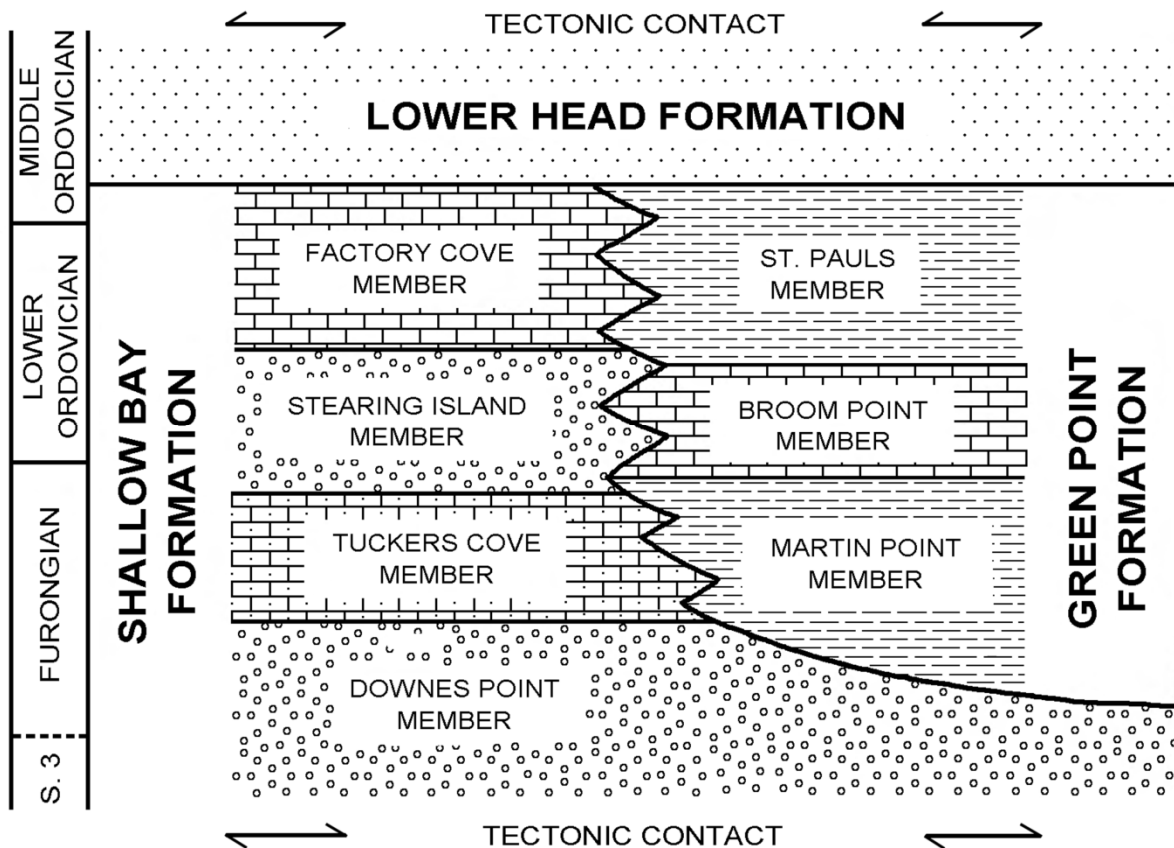


Figure 8. Lithostratigraphy of the Cow Head Group (modified from James and Stevens 1986).

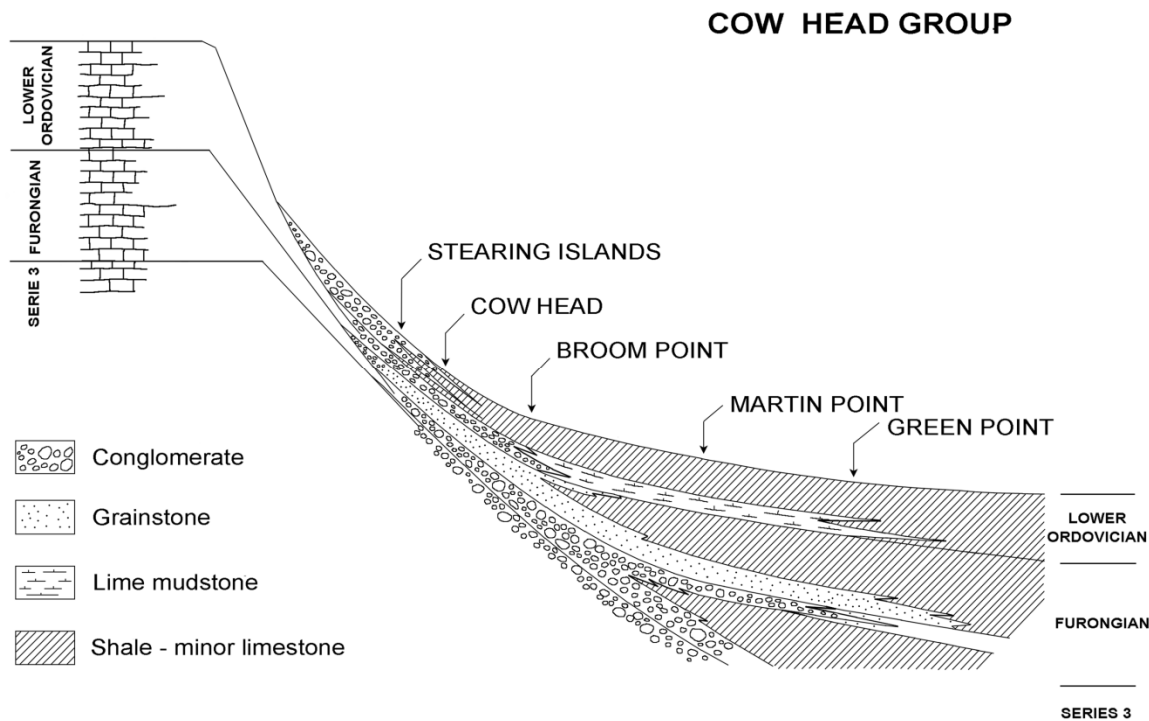


Figure 9. Depositional model for the Cow Head Group (modified from James and Stevens 1986).

Cove Member is a 60 m thick sequence of late Cambrian age comprising quartz-rich grainstone conglomerates and minor ribbon limestones, and the Stearing Island Member, which comprises a 80 m thick succession of mega-conglomerates with minor quartz-rich grainstones and shales ranging from upper Cambrian into the Lower Ordovician (Tremadocian, including beds 7, 8). The Factory Cove Member is a 100 m thick sequence of ribbon and parted limestone and minor shale intercalated with Lower to Middle Ordovician beds of boulder and mega-conglomerate (includes beds 9–15).

Green Point Formation – The Green Point Formation is subdivided into the Martin Point Member, the Stearing Island Member and Factory Cove Member. The Martin Point Member

(upper Cambrian) is 100 to 150 m thick and consists of green and black shaly mudstones with ribbon limestones, minor siltstones and calcareous sandstones. The Lower Ordovician Broom Point Member comprises an 80 m thick succession of ribbon to parted limestone. The St. Pauls Member is 130 to 150 m thick. It consists of red, green and black shaly mudstones, limestones and limestone conglomerates.

Lower Head Formation – Rocks of the Cow Head Group are overlain by over 1700 m of green sandstone of the Lower Head Formation, which include limestone rhythmites, shaly mudstones and siltstones (Blamey *et al.* 2016).

Northern Head Group

The Northern Head Group (Botsford 1988) comprises the Cooks Brook Formation, the Middle Arm Formation and Woods Island Formation. The Northern Head Group is considered a more distal equivalent of the Cow Head Group (Botsford 1988; Fåhræus and Roy 1994; Figure 5). The top of the formation is biostratigraphically dated to the *Loxodus bransoni* Interval, which is top Skullrockian (Fåhræus and Roy 1993). The Cooks Brook Formation is largely coeval with the upper Port au Port Group, up to the uppermost part of the Lower Ordovician Watts Bight Formation, and extending into the lowermost Boat Harbour Formation of the St. George Group of the platform (Ji and Barnes 1994). The same conodont succession as in the Cook Brook Formation has been recorded from the Martin Point and Broom Point members of the Cow Head Group.

EXCURSION OUTLINE

This field excursion will examine sedimentary rocks deposited along the Early Palaeozoic continental margin of Laurentia, referred to the Humber Zone of the Appalachian Orogen.

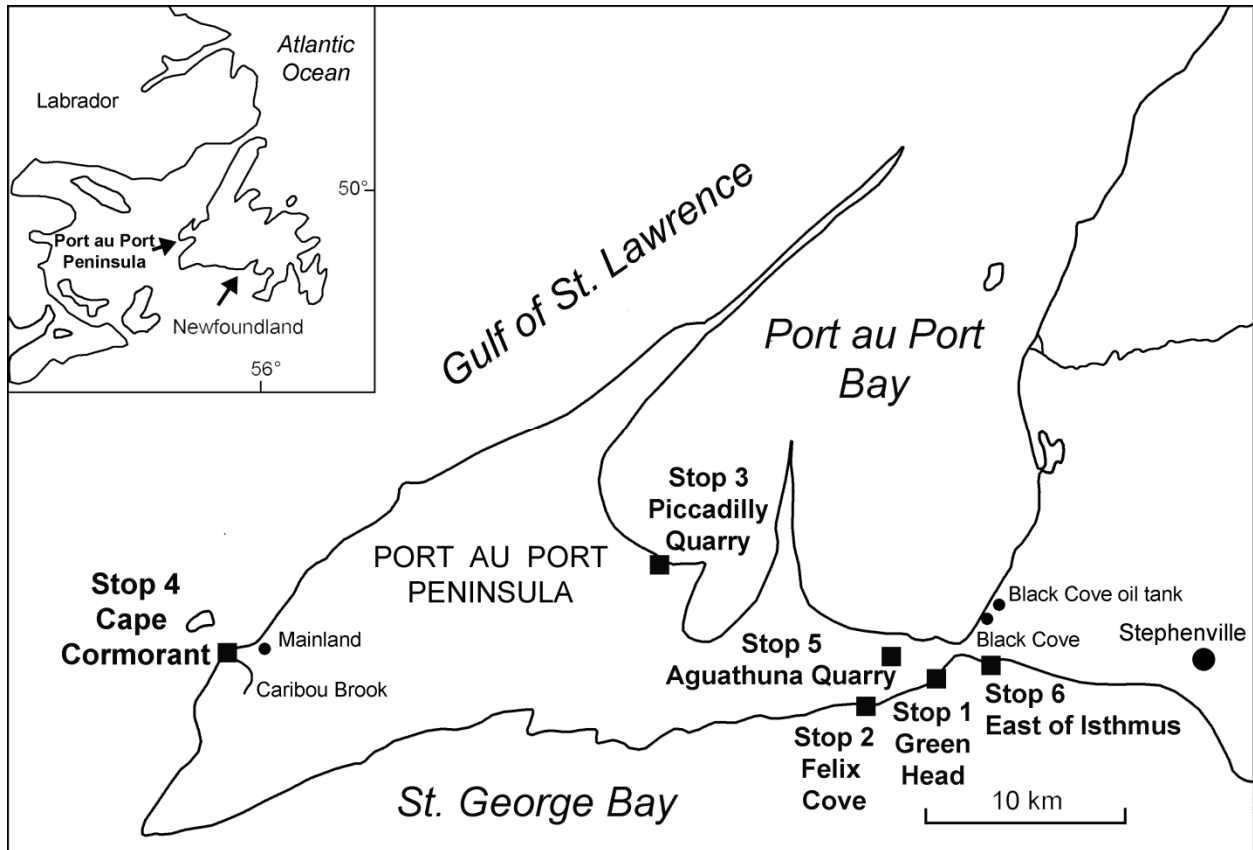


Figure 10. Map of Port au Port Peninsula showing excursion stops.

The plan is to start on Port au Port Peninsula in the south (Stops 1 to 6; Figure 10). We will then travel northward (Stops 7–9; Figure 11) to the Great Northern Peninsula (Stops 10–14; Figure 11).

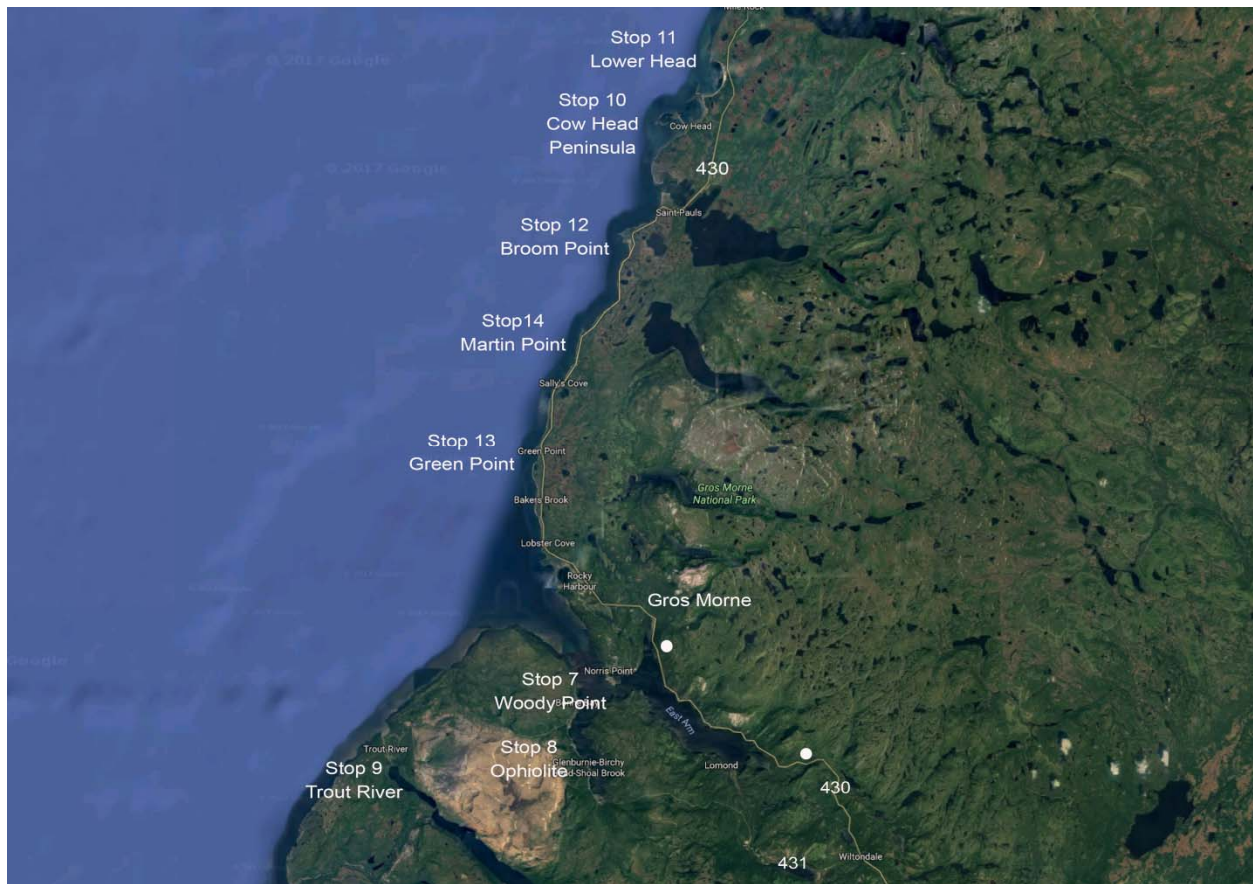


Figure 11. Google map of Gros Morne park showing excursion stops.

The first day will be spent looking at shallow water, platform sediments ranging in age from Cambrian (*Ehmaniella* Zone) to Middle Ordovician on the Port au Port Peninsula (Figures 10, 12). Carbonate sedimentation during the foundering of the platform and evidence for the formation of a foreland basin will also be studied along the northern part of the peninsula.

The following day we will drive northward (Figure 11) and stop and look the famous ophiolite sequence and then spend two days on the allochthonous slope to basin carbonates of the Cow Head Group, which are deep water equivalents of the platform deposits seen earlier, and include the GSSP section for the Cambrian–Ordovician boundary.

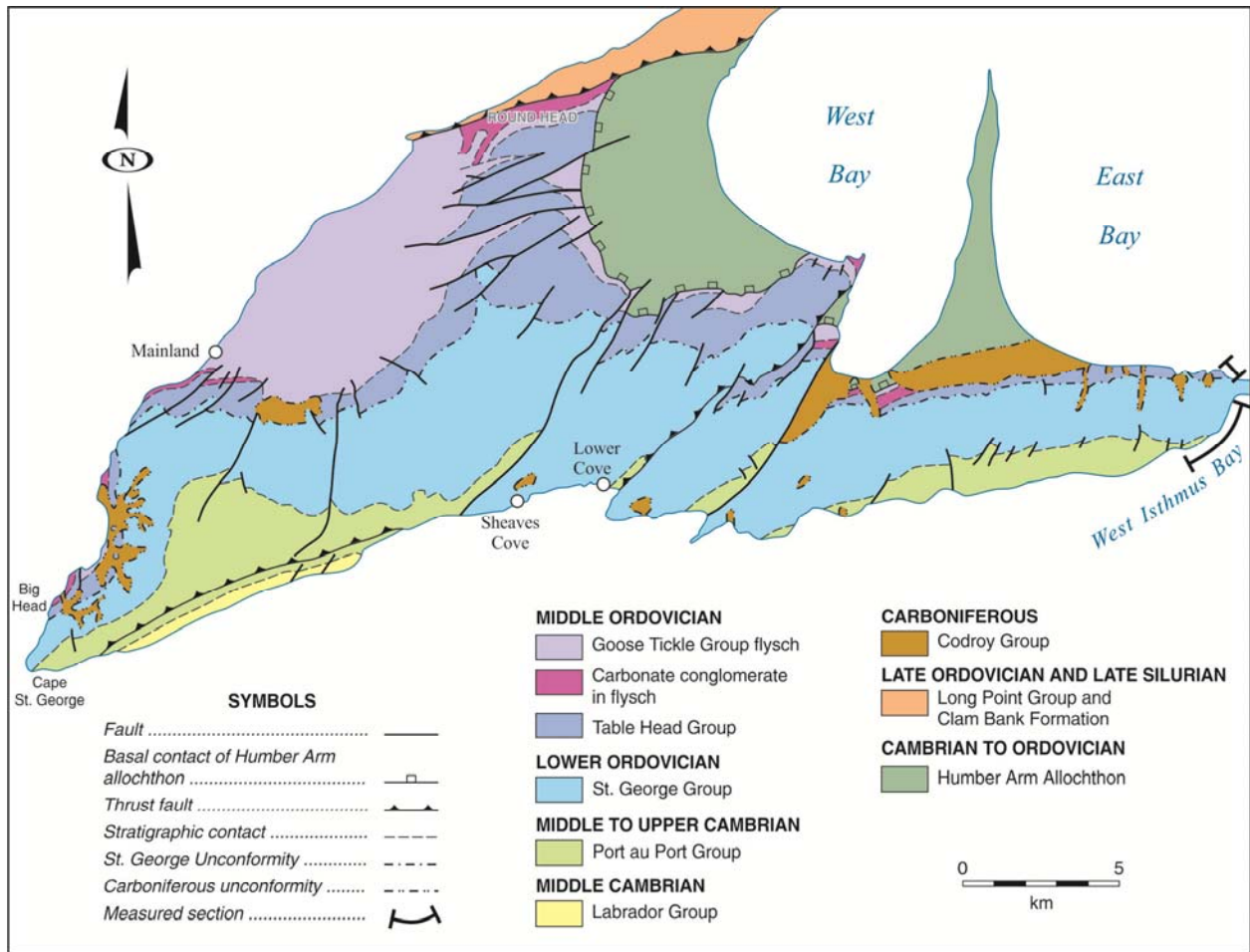


Figure 12. Geological map of the Port au Port Peninsula (from Knight *et al.* 2008, fig. 3).

ITINERARY

This itinerary is dependent on tide and weather conditions and may deviate from the schedule described in this guidebook.

Day 1. Thursday, June 15

3:00 pm – Meeting at ‘arrivals’ in Deer Lake airport.

4:00 pm – Departure by bus to Stephenville.

We will drive on Trans Canada Highway 1 (TCH) passing Deer Lake with a view to Deer Lake to right. Approaching Corner Brook the water of the lake runs out into the Humber River. Depending on the time of the day and/or weather we can make a stop at Corner Brook ‘viewpoint’ on the Trans Canada Highway for an overview of the geology of the Humber Zone of Newfoundland. To the Southeast, the hills are made of limestone that accumulated on the Laurentian plate and formed the carbonate platform succession that is now preserved in the thrust sheets of the Long Range Mountains. The boundary between the platform succession and the Humber Arm Allochthon is next to the viewpoint. The Humber Arm allochthon underlies the entire vista visible to the west. The rocks have been transported during the Taconian and Acadian orogenies. Their original place of deposition was east of the present location, but they have been thrust and preserved in the allochthons.

We continue along the Trans Canada Highway and turn right onto Route 460. This is a slow road with a low speed limit. We will follow this road to Stephenville and stop at the Dreamcatcher Lodge.

The drive from Deer Lake Airport via Corner Brook to Stephenville takes approximately two hours.

ca. 6:00 pm – Arrival in Stephenville – check in.

6:30 pm – Dinner - you are free to go wherever you choose, the trip leaders will provide recommendations.

We will stay two nights at the Dreamcatcher Lodge in Stephenville.

Day 2. Friday, June 16

8:00–9:00 am – Breakfast

9:00 am – Departure

Leaving the Dreamcatcher Lodge and drive on Route 460 towards to the west crossing ‘the Gravels’ and onto the Port au Port Peninsula (Figures 11, 13). At the first intersection turn left and continue on Route 463.

Stop 1

Green Head – The section is exposed along the coast and access is steep.

This section gives an example of the Lower Ordovician mounds typical of St. George Group on western Newfoundland, however this location displays the most prominent composite mounds on the whole island.

Return to bus and continue the drive to the west, stop at Felix Cove.

Stop 2

Felix Cove – Cliff exposures on the southern shore of the Port au Port Peninsula.

The ‘SPICE’ carbon isotope excursion has been recorded from here from the Petit Jardin Formation and is dated by trilobites, the base of the Furongian Series and the Sauk II to Sauk III sequence boundary can be studied. An ‘extinction’ event among Laurentian trilobites has been identified at the top of the Sauk II.

Return to bus and drive to the west. At intersection turn right and continue on Route 463 heading towards Piccadilly Provincial Park. Pass the entrance to the park and stop at the quarry on the left side of road opposite the convenience store.

Stop 3

Piccadilly Quarry – Exposures in the abandoned quarry and at the beach on the opposite side of the road with deep-water deposits structurally overlain by the Humber Arm Allochthon.

Table Point and Table Cove Formation carbonates and ribbon limestones with well preserved graptolites (and chitinozoans). At the coast there is a mylonite above the Table Cove Formation, i.e. the structural boundary with the Humber Arm allochthon, which is composed of turbidites (green sandstones and shaly mudstones).

Continue to the west on road 463 to Stop 4: Cape Cormorant section at Mainland.

Stop 4

Cape Cormorant at Mainland – The collapse of the carbonate platform.

Steeply dipping exposures along the beach. Slope deposits (Darriwilian, Middle Ordovician), debris flows etc. with carbonate conglomerates - expression of the collapse of the stable carbonate platform. Beds with conodonts, chitinozoans and graptolites.

Return to vehicles and continue the drive to the west on Route 463.

Cape St. George – Viewpoint – weather permitting.

After visit go back to the bus and we drive on Route 460 towards the east. At intersection turn left and follow Route 460-13 to the Aguathuna Quarry.

Stop 5

Aguathuna Quarry – Section with the St. George Unconformity.

A large exposure in an inactive quarry. This classical locality shows the platform carbonates of the Catoche and Aguathuna formations (St. George Group) unconformably overlain by carbonate deposits of the Table Point Formation (Table Head Group; foreland setting).

The spectacular angular St George unconformity is seen in the wall of the quarry. It represents the laterally extended unconformity created during the collision of the Taconic landmass and Laurentia.

Carboniferous ‘cold-seep’ limestones with vent fauna of vestimentiferans, crustaceans, brachiopods and conulariids also present in the quarry.

Return to vehicles and drive to intersection at the Convenience store and continue drive in the direction of Stephenville, passing through ‘the Gravels’. On Route 460 turn right at Roberts Drive, which is just across the small Tourist Chalet (closed) on the left side of the road, and about 1000 m southwest of Romaines; continue drive passing the houses to your left onto the unpaved trail and stop at – preferably before (!) –the edge of the small seacliff.

Stop 6

East Isthmus Bay section – Barry Head Formation and Watts Bight Formation.

Approximately 200 m of exposure along the beach. Succession starts in the Berry Head Formation (Cambrian; top of the Port au Port Group) and ends in the Watts Bight Formation (Lower Ordovician; St. George Group). The Cambrian–Ordovician system boundary is here developed in platform carbonate facies (dolostones and dolomitized limestones).

Return and drive to the east on Route 463 to Stephenville and return to Hotel.

Day 3. Saturday, June 17

Departure from Dreamcatcher Lodge on Route 460 and drive to the Trans Canada Highway, and turn left and drive towards Corner Brook, continuing past Corner Brook to Deer Lake. Turn to the right and continue North on the 'Viking Trail' (Route 430).

At the Wiltondale intersection turn left and drive on Route 431. We are heading for Woody Point-Trout River (Tablelands) inspecting the Humber Arm allochthon - a traverse across Moho, and oceanic crust of the Iapetus Ocean – a cross section from ultramafic rocks and ophiolite suite in a barren yellow-brown (iron and chromium rich) landscape analogous to that of Mars.

Stop 7

Woody Point viewpoint – View of rocks of the Humber Arm Allochthon and Tablelands.

Mainly a stop for photo, with a brief explanation of the Little Port Complex.

Continue on Route 431 in the direction of Trout River.

Stop 8

Visit to world famous exposures of the rock suite representing the mantle of the earth. The mineralogical Mohorovicic Discontinuity (MOHO) is exposed close to the top of the escarpment. The ophiolite sequence overlain by deep-water marine radiolarian red chert and shale deposits.

Stop 9

Trout River viewpoint – Another spectacular view in the Gros More National Park.

From Trout River drive back on Route 431 and turn left at intersection at Wiltondale. Continue on Route 430 North in the direction of Rocky Harbour crossing the Long Range Mountains. Weather permitting, this can be an exceptional scenic route and we may be able to stop for photos - if desired.

Many exposures on the road of Labrador Group are composed mainly of siliciclastic sedimentary rocks. The basal Bradore Formation is a quartzarenitic sandstone. This unit caps the Gros Morne mountain, which is seen also from Rocky Harbour. The Bradore Formation is overlain by the Forteau Formation (Bonella-Olenellus Zone). The Forteau Formation is overlain by the thick sandstone unit referred to the Hawkes Bay Formation.

Time, and weather, permitting we may have short stops along Route 430 inspecting outcrops of the Forteau Formation and a brief look at the Precambrian–Cambrian boundary, ca. 9.5 km north from the Route 430/431 junction in Wiltondale, where Precambrian gneiss is unconformably overlain by basal Cambrian quartzite of the Bradore Formation.

ca. 6:00 pm – Arrival at hotel in Rocky Harbour – check in.

Rocky Harbour will function as 'base camp' for the rest of the fieldtrip and we stay for two nights.

Day 4. Sunday, June 18

8:00–9:00 am – Breakfast.

9:00 am – Departure from hotel.

Drive to north on Route 430 to Cow Head Peninsula; ca. 45 minutes.

Stop 10

Cow Head Peninsula –Middle Cambrian to Middle Ordovician proximal slope deposits.

The famous and classic locality for the Cow Head Group (mid Cambrian to Middle Ordovician). Proximal slope deposits sourced from the Laurentian carbon platform shelf and shelf margin.

Cambrian fauna composed mainly by abundant trilobites and conodonts. Ordovician macrofauna is characterized by the evolution of graptolites; brachiopods and trilobites are abundant in the conglomerates. Additional microfossils i.e. chitinozoans, sponge spicules and radiolarians are abundant.

Time permitting there will be two stops: one will go Beachy Cove on the north coast, which is the classic trilobite location. At lighthouse a view towards the north over to Stearing Island, White Rock Islets and Lower Head (Stop 11) composed of ‘megabreccias’ or huge carbonate blocks. The second trip will be a traverse from the Point of Head to the Ledge section on the southwest coast of the peninsula.

Return to bus and drive to Route 430. Turn left and head towards the north.

Stop 11

Lower Head west – Mega-conglomerate Bed 14.

Note: It is a longer walk along the beach to Lower Head (requires low tide and perhaps rubber boots unless you are a good jumper).

Exotic biohermal ‘white’ limestone boulders rich in fossils and up to 200 long and 50 m across; overlain by sandstone of the Lower Head Formation. Source to the blocks were probably algal mounds from the shallow water platform margin.

Walk back to vehicles and drive to hotel.

ca. 6:00 pm – Dinner

You are free to go wherever you choose, the trip leaders will provide recommendations.

Day 5. Monday, June 19

8:00–9:00 am – Breakfast

9:00 am – Departure

Heading north on Route 430 to Broom Point.

Stop 12

Broom Point – Oldest deposits of the Cow Head Group. Classic section for Cambrian trilobites. Cambrian to Ordovician boundary is well exposed.

Two sections – Broom Point N and Broom Point S. Broom Point S was previously a GSSP candidate for the Cambrian–Ordovician Boundary. We will focus on the Broom Point South section.

Return to bus and heading south to Green Point.

Stop 13

Green Point – The GSSP section for the Cambrian–Ordovician boundary.

Distal slope deposits composed of shale ribbon and parted limestone and conglomerates. Conodonts, radiolarians, graptolites and few trilobites. Carbon isotope profiles (HERB, HSS and C/O boundary) and geochemical anomaly.

Return to vehicles and return to hotel. This is the last overnight in Rocky Harbour.

6:00 pm – Dinner

Day 6. Tuesday, June 20

8:00–9:00 am – Breakfast, checking out

9:00 am – Departure

Drive north on route 430 to the Martin Point section.

Stop 14

Martin Point South section – Middle Cambrian–Lower Ordovician distal slope succession.

Long section along with cliff exposures along the shore and in the beach zone. Martin Point is a lateral equivalent succession to the Green Point GSSP section with HERB Carbon isotope excursion. Stage 10 of the Furongian Series and the Cambrian–Ordovician boundary are well exposed in the cliffs. Martin Point display nearly the same Cambrian conodont faunal succession as in obtained from the Humber Arm Allochthon. Radiolarians are recorded from two levels. The section starts in the Cambrian and reaches the Middle Ordovician Lower Head Formation (Darriwilian). Our inspection concludes with a brief stop at the upper Tremadocian exposure with well-preserved anisograptid graptolites.

Return to bus and drive south of Route 430, crossing the Long Range Mountains to Trans Canada Highway. Turn right and drive east and turn left to the Deer Lake Airport.

Departure for several participants to St. John's is 1:15 pm and later in order to get to St. John's in time for the conference ice breaker event. The arrival at the Deer Lake airport concludes the fieldtrip.

Return to Deer Lake Airport YDF and fly to St. John's YYT - for some with a departure at 13:15 - to arrive in time to St. John's for the conference ice-breaker.

DESCRIPTION OF FIELD TRIP STOPS

DAY 2

Stop 1

Green Head – South coast of Port au Port Peninsula.

Location On Route 460; about 1.1 km west of the grocery store on the south shore of the Port au Port Peninsula.

Targets Lower Ordovician cryptalgal-metazoan bioherm structures, named Green Head complex, in the Watts Bight Formation of the St. George Group.

Description The strata at Green Head are from the Watts Bight Formation of the St. George Group. Further to the northeast the Watts Bight Formation is overlain by the Boat Harbour Formation. It is composed of rhythms of peritidal limestone-dolostone capped by dolostone. A disconformity marked by chert on top of thick dolostone is developed next to the ladder to the inn. Silicified brachiopods are scattered throughout the outcrop.

The Green Head location is noteworthy and famous for the exposures of large and spectacular subtidal thrombolite-metazoan mounds, 4–6 m in diameter (Pratt and James 1982; Knight *et al.* 2008). The mounds have clotted and digitate structure and are composed of both thrombolites and sponges or corals. The Green Head mounds represent a thrombolite-*Renalcis-Lichenaria* reef complex, up to 12m thick, with an estimated depositional relief of up to 1.5 m. The stromatoporoid-like, spicular lamellar organism *Pulchrilamina*, which is an encrusting taxon with a convex-upward form, the primitive coral *Lichenaria* and primitive sponges are inter-grown in the mounds.

The mounds are very fossiliferous and mottled with light grey weathering dolomite and brown weathering chert. Smaller mounds, 15 to 20 cm in diameter occur above the larger mounds. All mounds are surrounded by thick-bedded grainstones.

Similar mounds to bioherms composed of algae and sponges have been described by Stevens and James (1976) from Hare Bay on Great Northern

Peninsula. However, the Green Head mounds, also known as the ‘Green Head complex’, are the most complex mound structures in Newfoundland.

Zones/age Flower (1978) identified lower Gasconadian (Tremadoc, Lower Ordovician) cephalopods from this horizon. Boyce (1979) obtained a *Hystricurus* sp., similar to forms found in Zone B of Utah, USA.

Stop 2

Felix Cove – South coast of Port au Port Peninsula.

Location Drive to Port au Port Peninsula and approx. 1.5 km west of the general store at the intersection of Route 463.

Targets The Petit Jardin Formation, ‘Steptoean Positive Carbon Isotope Excursion’ (SPICE) and the SAUK II to Sauk III sequence boundary. Trilobite extinction event: base of the international Furongian Series (Paibian Stage).

History The section has been investigated previously by Chow and James (1987a, b). Cowan and James (1989, 1993) developed a sequence stratigraphic model for the succession, and Westrop (1992) provided the Steptoean trilobite biostratigraphy from the section. Salzman *et al.* (2004) presented the complete $\delta^{13}\text{C}$ isotope curve from the Felix Cove locality and identified the SPICE isotope excursion from the exposures at this locality. The SPICE event is related to sealevel change and is linked with a significant extinction event among the marine fauna including the trilobites of Laurentia.

Description The succession is composed of dolostone, sandstone and dolomitised limestone of the Petit Jardin Formation of the Port au Port Group and referred to the Felix Cove Member and the overlying Man O’War Member (Cowan and James 1993).

Chow and James (1987a, b), Cowan and James (1992, 1993) and Westrop (1992) have described the succession at this locality.

The trilobite zones include the Laurentian *Crepicephalus* Zone to the *Aphelaspis* Zone (Dresbachian to Franconian or Marjuman to Steptoean (Westrop 1992)). Sandstone beds reflect periods of terrigenous input within the *Aphelaspis* Zone. The *Aphelaspis* Zone is followed by *Elvinia* Zone (Steptonian) approx. 8 m

above the sandstone interval. The sandstone units have been interpreted to result from the Sauk II to III regression (James *et al.* 1989; Cowan and James 1993).

The SPICE excursion is recorded from the upper 20 m of the Felix Cove and the Man O'War members, and reaches a peak above the quartzarenitic bed at the Sauk II to III sequence boundary.

The trilobite fauna of the Marjuman suffered from an extinction event at the base of SPICE now termed the 'Dresbachian Extinction' (Westrop and Ludvigsen 1987; Palmer 1995; Westrop and Cuggy 1999). During this event approximately 40% of marine genera disappeared. The inferred drivers for the extinction event include sea-level change, increase in temperature and/or destabilization of the carbon cycle, since it is related to the SPICE carbon excursion, and because the trilobite losses occurred at the onset of the $\delta^{13}\text{C}$ shift; but the causes are neither clear or conclusive, and should be considered speculative at this time.

The Furongian global Series and Paibian Stage are defined by the FAD of the agnostid trilobite species *Glyptagnostus reticulatus*, which is not present here. The start of the $\delta^{13}\text{C}$ isotope positive SPICE excursion, however, suggests that the base of the Furongian Series should be placed close the SAUK II and SAUK III boundary in the Felix Cove section.

Stop 3

Piccadilly Quarry – North coast of Port au Port Peninsula.

Location South side of the road of Route 463, ca 1.5 km west of Piccadilly Head Provincial Park on the north coast of the Port au Port Peninsula; ca. 20 km west of the Isthmus.

Targets Top of Table Point Formation and the Table Cove Formation, both of the Table Head Group. Black Cove Formation (Middle Ordovician) of the Goose Tickle Group.

Excellent preserved graptolites and few trilobites. chitinozoans, conodonts, sponge spicules and radiolarians can be extracted from the limestone and shale.

Previous work Previous palaeontological investigations on the strata of the Table Head Group includes Morris and Kay (1966), Finney and Skevington (1979), Achab (1983), Finney and Chen (1984), Williams *et al.* (1996, p. 52), Maletz (1998), Zhang and Pratt (2000), Maletz *et al.* (2011), and Carrera and Maletz (2014). Additionally, Sell *et al.* (2011) provided an absolute age from a K-bentonite bed in the section.

Description The Piccadilly Quarry section is an abandoned quarry and also known as the West Bay Centre section. The strata are well exposed in '3D' by vertical walls and the strata dip gently to the north (Figure 13). The West Bay Centre is an important locality on the Port au Port Peninsula due to the presence of many fossil groups.

The exposures continue on the opposite side of the road and along the coast, where the base of the allochthon structurally overlies strata of the deformed Table



Figure 13. Photo of section with Table Point Formation at base overlain by Table Cove Formation.

Head and Goose Tickle groups. The deposits of the allochthon are referred to Green Point Formation of the Cow Head Group.

Succession The basal part of the quarry is limestone from the top of the Table Point Formation and conformably overlain by the Table Cove Formation both of the Table Head Group (Stenzel *et al.* 1990; Figures 13, 14). Table Cove Formation is the main part of the exposure in the quarry wall. The Table Cove Formation is overlain by the Black Cove Formation, and Daniels Harbour conglomerate of the Goose Tickle Group, the latter unit, however, may be covered and not exposed.

The lithologies seen in the quarry comprise bedded limestone of the Table Point Formation; uneven to wavy-bedded limestone, ribbon limestone and calcareous shaly mudstones of the Table Cove Formation. The limestone of the ribbon limestone is fine-grained at times laminated and rarely coarse-grained limestone. The overlying dark grey organic rich shale of the Black Cove Formation is exposed near the top of the succession. The Daniels' Harbour Member is a thin conglomerate and may be seen on the upper terrace of the west face of the quarry.

Some intervals show evidence of initial slumping within the succession. Several thin light-grey to pale yellow K-bentonite beds are easy to spot in the black shale of the Table Cove Formation.

The sedimentary rocks of the Table Cove Formation deposited in slope to basin environment in the foreland basin setting formed during the early stage of the Taconic orogeny. The upper contact of the succession is structural. The structurally overlying siltstone unit is interpreted as a flysch deposit. The silt deposition derived from the east or southeast and was sourced by the Taconian allochthons to the east.

Zones/Age *Holmograptus spinosus* and *Nicholsonograptus fasciculatus* graptolite zones (Maletz *et al.* 2011), *Cybelurus mirus* trilobite Zone (Boyce 1997), *Periodon macrodentatus* and *P. zgierensis* conodont zones (Stouge 2012) and *Cyathochitina turgida* - *C. subcylindrica* chitinozoan Zone (Albani *et al.* 2001; Esselin *et al.* 2004) (Darriwilian, Middle Ordovician).

The faunas from the quarry include very well-preserved graptolites. Trilobites and inarticulate brachiopods are found on the bedding planes of the Table Cove Formation. The microfossil assemblage consists of chitinozoans, conodonts, sponge spicules and radiolarians. The excellent graptolite and chitinozoan fauna is found in the shale and limestone of the Table Cove Formation. Conodonts are recorded from the limestone of the Table Point Formation and lowermost nodular argillaceous limestone of the Table Cove Formation; the finely laminated and dense limestone beds of the upper Table Cove Formation have proven to be barren - or nearly so- of conodonts. The sponge spicules are recorded from the Table Cove Formation (*Holmograptus spinosus* Zone).

The graptolite fauna of the Table Cove Formation includes *Bergstroemograptus crawfordi* and *Isograptus forcipiformis* (Maletz 1988; Maletz *et al.* 2011). The graptolite assemblage is representing the *Holmograptus spinosus* Zone but the important index taxa have not recorded in the quarry (Finney and Skevington 1979; Maletz *et al.* 2011). The *Nicholsonograptus fasciculatus* Zone (Darriwilian, Middle Ordovician) is recorded from the overlying Black Cove Formation (Maletz *et al.* 2011; Figure 14).

The chitinozoans are assigned to the *Cyathochitina turgida* - *C. subcylindrica* Zone (Achab 1983; Esselin *et al.* 2004). Conodonts from the limestone of the Table Point Formation include *Periodon macrodentatus*, *Histiodella* sp. A and compares well with the conodont fauna described from the type locality of the Table Point Formation (Stouge 1984) (Figure 15). The Table Cove fauna belongs to the uppermost *Periodon macrodentatus* Zone extending into the *P. zgierensis* Zone with *Dzikodus newfoundlandensis* and *Histiodella kristinae* (Stouge 2012).

One K-bentonite bed, ca 3 m above the base of the section, contains zircon and has been dated to 464.57 \pm 0.95 ($^{206}\text{Pb}/^{238}\text{U}$; MSWD = 1.5) (Sell *et al.* 2011).

The structurally overlying siltstone contains graptolites of the *Pterograptus elegans* Zone (Maletz *et al.* 2011).

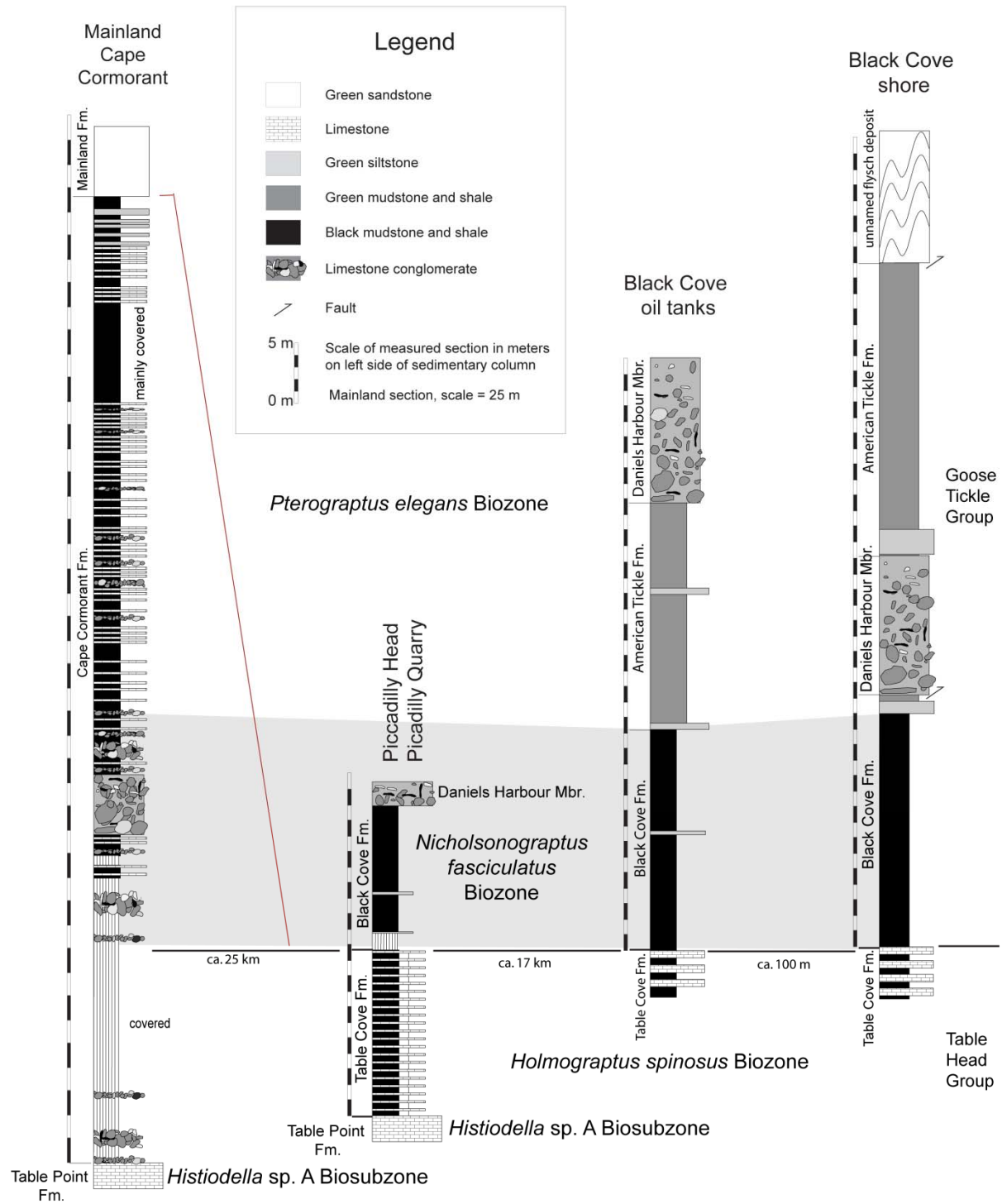


Figure 14. Graptolite zones and correlation from Cape Cormorant to Black Cove (modified from Maletz *et al.* 2011).

System	Stage	Stage slice	Conodont zones and subzones		Graptolite zones	
ORDOVICIAN	Darrivillian	Dw3	<i>Pygodus serra</i>		<i>Pterograptus elegans</i>	
		Dw2	<i>Periodon zgerensis</i>	<i>Histiodella bellburnensis</i>	<i>Nicholsonograptus fasciculatus</i>	
				<i>Histiodella kristinae</i>		
			<i>Periodon macrodentatus</i>	<i>Histiodella sp. A</i>	<i>Holmograptus spinosus</i>	
		Dw1	<i>Periodon macrodentatus</i>	<i>Histiodella holodentata</i>	<i>Holmograptus lentus</i>	
				<i>Histiodella sinuosa</i>	<i>Levisograptus dentatus</i>	
	Dapingian	Dp3	<i>Periodon hankensis</i>			(Not recorded)
		Dp2		(not established)	<i>Isograptus (v.) maximodivergens</i>	

Figure 15. Correlation of graptolite and conodont zones (from Stouge 2012).

Stop 4

Mainland section – On the northwestern coast of Port au Port Peninsula.

Location Caribou Brook, a small stream 1,5 km SW of Mainland on the western side of Port au Port Peninsula.

Targets Cape Cormorant Formation, Table Head Group and type section and Mainland Sandstone. Graptolites and chitinozoans.

Previous work Previous paleontological investigations on the strata of the Cape Cormorant Formation include Neville (1974) and Maletz (1998). Neville (1974) described the first known chitinozoans recorded from Newfoundland in sections located north of Cape Cormorant and between Mainland and Round Head on the

southwestern coast of the Port au Port Peninsula. Albani *et al.* (2001) investigated the section at Caribou Brook and described the graptolite, chitinozoan and conodont fauna from the section. Sell *et al.* (2011) provided an absolute age from one K-bentonite bed in the section.

Description The Mainland section will start at Caribou Brook and be followed along the boulder beach from the Caribou Brook. Caribou Brook is small stream along which the Table Point Formation is overlain by Table Cove Formation and the lower part of the Cape Cormorant Formation. The higher part of the stream with the Table Head exposures is not easy to access due to a 10 m high waterfall. The transition from Table Head Group and Cape Cormorant is covered in the stream. Only the middle and high parts of the Cape Cormorant Formation and the Mainland Sandstone will be visited.

The exposures along the coast are steeply dipping (50–80° to the NW) and the studied succession (Figure 16) will start at the mouth of the Caribou Brook.

Note: the steeply dipping bedding planes are unstable.

Succession The Cape Cormorant Formation is the upper part of the Table Head Group and is geographically constrained to the Port au Port Peninsula. It is about 180 m thick, where the upper 65 m will be inspected at the Mainland section.

The succession (Figure 17) consists of calcareous shale interbedded with fine-grained at times laminated and rarely coarse-grained limestone and distinct carbonate breccia beds 0.1–30 cm thick. The polymict carbonate conglomerates and breccias are often distinctive. Occasionally slumped horizons occur within the succession. Several thin light-grey to pale yellow K-bentonite beds are easy to see in the black shale.

The distinctive carbonate conglomerates and breccias record episodic deposition of turbidity currents and debris flows into a shale dominated, slope to basin setting.



Figure 16. Steeply dipping beds of the Cape Cormorant Formation.

The Cape Cormorant Formation is conformably overlain by ca 1500 m of chromite bearing, graded and green sandstone known as the Mainland Sandstone Formation of the Goose Tickle Group. It is interpreted as a flysch deposit with a derivation from the east or southeast i.e. sourced by the Taconian allochthons to the east and accumulated in the foreland basin.

The Cape Cormorant Formation and the overlying Mainland Sandstone (Middle Ordovician) accumulated in the foreland basin formed during the early stage of the Taconic orogeny and represent the collapse of the Cambrian – early Middle Ordovician carbonate platform.

Zones/Age The faunas from the upper part of the Cape Cormorant Formation include well-preserved graptolites and chitinozoans (Figure 18) allowing for a close tie between the two fossil groups (Figure 19).

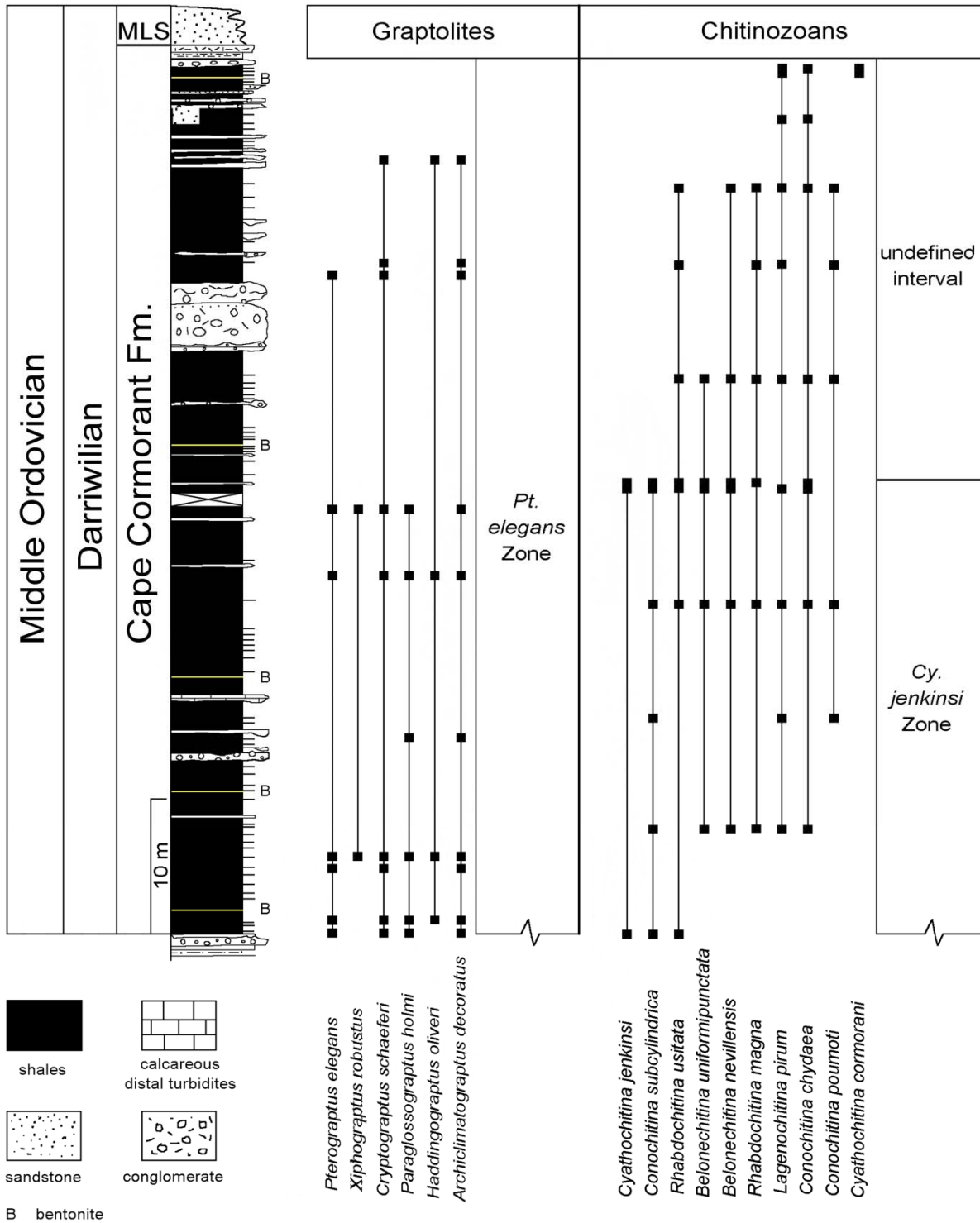


Figure 17. Section showing ranges of graptolites and chitinozoans.

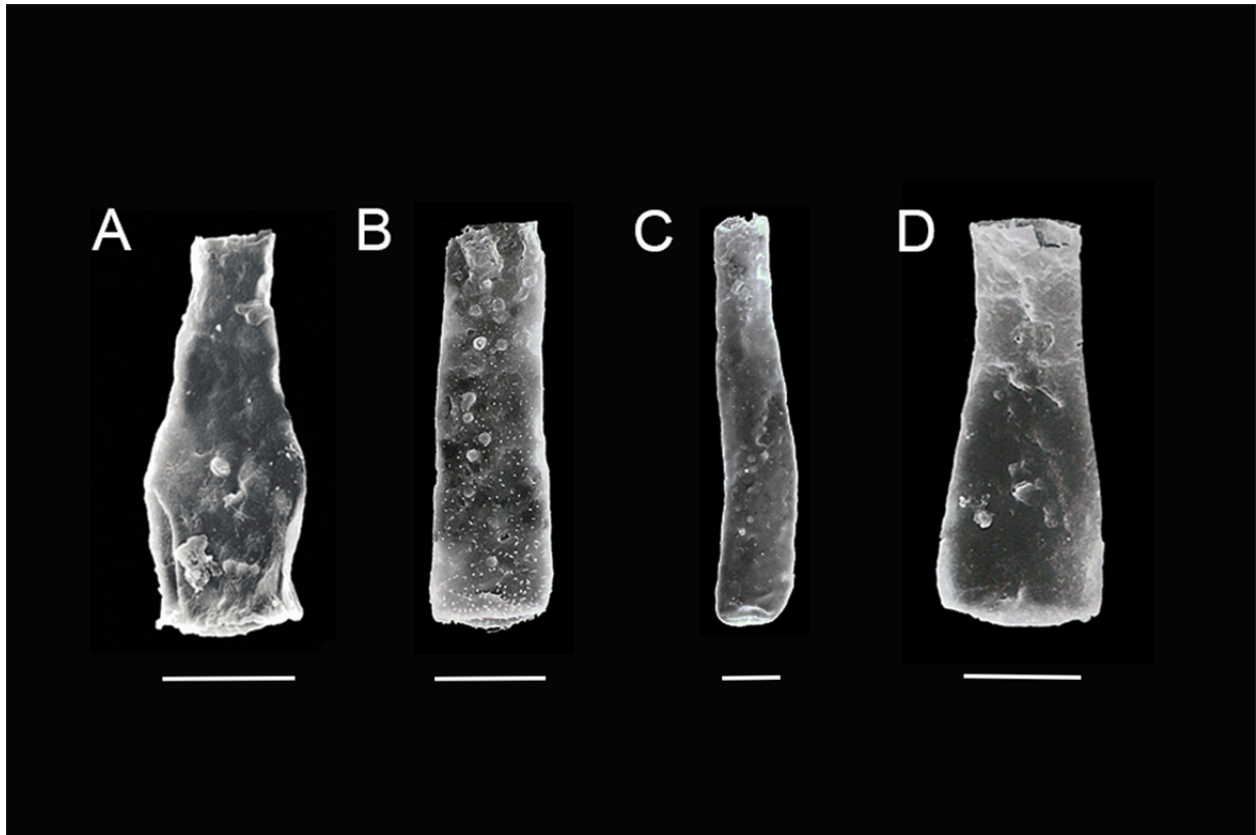


Figure 18. Chitinozoans of the Cap Cormorant section; scale bars represent 0.5 mm. **A.** *Cyathochitina jenkinsi* Neville, 1974, sample CC1. **B.** *Belonechitina nevellensis* Albani *et al.*, 2001, sample CC5. **C.** *Conochitina poumoti* Combaz and Péniquel, 1972, sample CC6. **D.** *Conochitina chydaea* Jenkins, 1967, sample CC8.

Phyllocarids, phosphatic brachiopods and conodonts are present to rare. The excellent graptolite and chitinozoan fauna is found in the shale and limestone. The graptolites are referred to the *Pterograptus elegans* Zone (Darriwilian, Middle Ordovician). The chitinozoans (Figures 17, 18) are assigned to the *Cyathochitina jenkinsi* Zone (Figures 17, 19). The record of conodonts from the limestones is low and those that have been recorded are not zonal diagnostic (Albani *et al.* 2001), but may be equivalent to the *Periodon zgierensis* conodont Phylozone (Stouge 2012).

One K-bentonite bed, 41 m above the base of the section, contains zircon and has been dated to 464.5 ± 0.4 ($^{206}\text{Pb}/^{238}\text{U}$; MSWD = 1.5) (Sell *et al.* 2011).

Port au Port NE of the gravels		Graptolites	Chitinozoans	Conodonts	Stage	Series
Mainland Fm.					Darrivilian	Middle Ordovician
Table Head Group	Cape Cormorant Fm.	<i>Pterograptus elegans</i>	Undefined <i>Cyathochitina jenkinsi</i>	<i>Histiodella bellburnensis</i> (not zoned)		
		<i>Nicholsono- graptus fasciculatus</i>	<i>Conochitina turgida</i> - <i>Conochitina subcylindrica</i>	<i>Histiodella kristinae</i>		

Figure 19. Integration of graptolite and conodont zones.

Stop 5

Aguathuna Quarry – Eastern Port au Port Peninsula.

Location Approx. 3.4 km west of the Isthmus on Route 463-13 next to the coast of Port au Port Bay.

Units Aguathuna Formation (St. George Group) and Table Point Formation (Table Head Group).

Targets The St. George Unconformity and the boundary between the St. George Group and Table Head Group.

Description The Aguathuna Quarry is an abandoned quarry that was operated from 1913 to 1969 removing the limestone of the Table Point Formation. Today, the active operating quarry lies just south of the Aguathuna Quarry locality.

The Aguathuna Quarry is the classical location on western Newfoundland showing the erosional contact between the St. George Group and the overlying Table Head Group (Knight *et al.* 1991) (Figures 20, 21).

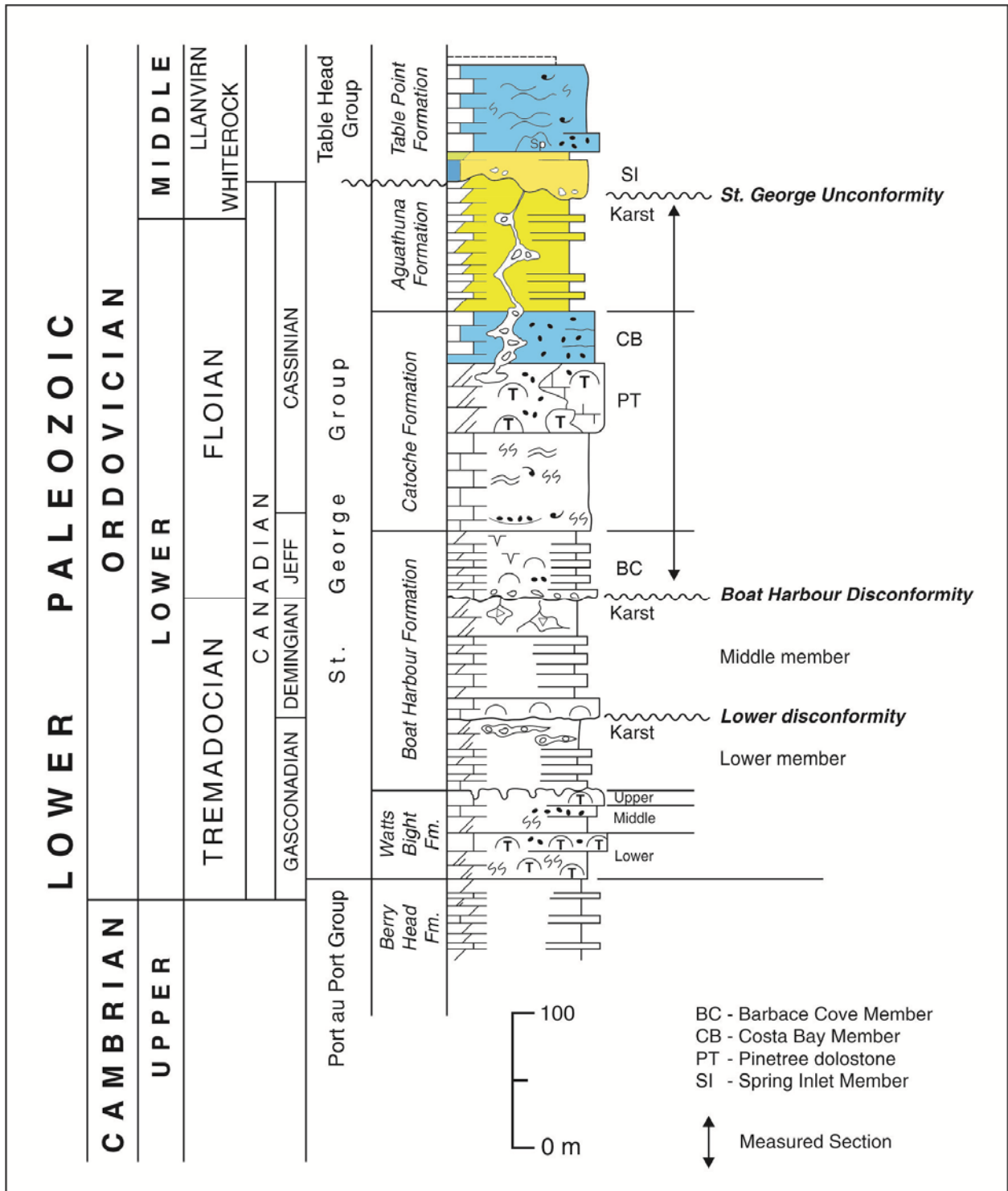


Figure 20. Simplified lithostratigraphy of the upper Port au Port Group and the St. George Group showing the Aguathuna Unconformity (from Knight *et al.* 2008).

The lower exposures at this locality comprise the main part of the Aguathuna Formation, the top unit of the St. George Group. The Table Point Formation unconformably overlies the St. George Group (Boyce *et al.* 2000; Knight and James 1987; Knight *et al.* 1991). The strata strike E-W and dip to the north thus the succession is getting increasing younger to the north and along Route 463-13 where the limestone of the Table Point Formation is exposed along the coast and in road-cuts.

The steep vertical wall of the quarry consists of dolostone beds. These are burrowed mottled, yellow weathering dolostone, light grey, pale, algal laminated dolostone and grey subtidal dolomitic limestone with stromatolitic and thrombolitic horizons. The succession is rhythmic bedded forming peritidal cycles and macrofossils (gastropods) may be found in the dolomitic, subtidal limestone.

The surface of the St. George Group is wavy or folded. The upper boundary to the disconformably overlying Table Point Formation of the Table Head Group is erosional and cuts into the upper dolostone beds of the Aguathuna Formation (Figure 21). The contact is marked by channels in the wall and a basal conglomerate with cherty clasts is developed; dissolution features such as minor caves can be seen (Knight *et al.* 1991).

The overlying limestone beds of the Table Point Formation are grey and thicker bedded laminated limestone with fenestrae followed by bioturbated grey limestone representing respectively intertidal to shallow water subtidal environments.

The formation of karst is related to the uplift caused by the formation of a peripheral bulge (Jacobi 1961; Knight *et al.* 1991) as a response to the loading of thrust sheets on the outer margin of the shelf during the Taconic Orogeny and before the deposition of the transgressive Table Point Formation.

The St. George Unconformity is a regional unconformity that can be trace throughout the Great Northern Peninsula (Knight *et al.* 1991). However, it correlates with lateral equivalent and largely coeval unconformities that developed along the passive margin i.e. the Knox and Beekmantown



Figure 21. Photo of St. George Unconformity (red arrow).

unconformities in the Appalachians further to the south (Hibbard *et al.* 2007). The unconformity also marks the conclusion of the Sauk sequence II.

In the centre of the quarry the Codroy Formation (Mississippian, Carboniferous) is exposed and unconformably overlies the Ordovician strata (Dix and James 1987).

The Mississippian limestone of the Codroy Formation is richly fossiliferous. The isolated block represents part of several bryozoan/microbial buildups that developed in drowned karst valleys that eroded into the underlying Ordovician carbonates in Mississippian time (Dix and James 1987). The buildups are lateral equivalents to the white evaporites seen at Romaines Brook (between Stephenville and ‘The Gravels’).

Zones/age The top carbonates of the St. George Group yield a sporadic trilobite fauna (Boyce and Stouge 1997; Boyce *et al.* 2000) and *Didymograptus bifidus* graptolite Zone (Floian Stage, Lower Ordovician) is represented in the upper Catoche

Formation. A characteristic conodont faunal succession is recorded across the unconformity in the quarry. A lower fauna includes the nominate species *Pteracontiodus cryptodens*, but also *Fahraeusodus* cf. *F. marathonensis* and *Oepikodus intermedius* characterize the lower to middle Aguathuna Formation (lower Whiterockian Series, Middle Ordovician; Dapingian Stage of the international Middle Ordovician Series). The overlying top dolostone beds and up to the unconformity are barren.

The basal peritidal strata of the overlying Table Point Formation yields the characteristic conodont species *Discidognathus primus* and *Paraprioniodus neocostatus* succeeded by a fauna of the *Histiodella holodentata* Zone (mid Darriwilian), and recorded from the grey subtidal limestones of the Table Point Formation in the quarry (Stouge 1984).

The base of the Laurentian Whiterockian Series (Middle Ordovician) lies below the unconformity with a boundary close to the base of the Aguathuna Formation. The lack of *Histiodella altifrons* and *H. sinuosa* in the succession indicates that parts the early Whiterock to early Mid Ordovician hiatus had a maximum extent corresponding to the Laurentian Kanoshian Stage of the Whiterockian Series (upper Dapingian, Middle Ordovician), which lasted for about 1 to 1.5 Ma.

Stop 6

Section East Isthmus Bay – South coast to the east of the Isthmus.

- Location On Route 460, 1 km to the west of Romaines.
- History This locality has been described by Ji and Barnes (1994, appendix A, p. 75). Ji and Barnes (1994) also recorded conodonts from the section.
- Targets March Point and Watts Bight formations; stable isotope curve of C from a platform setting (Figure 22).
- Description More than 200 m thick carbonate succession, fully exposed along the coast, composed of peritidal dolostone and dolomitic limestone of the March Point Formation (Port au Port Group) and the lower part of the overlying subtidal (dolomitic) limestone of the Watts Bight Formation (St. George Group).

System	Series	Conodont	Group	Formation
ORDOVICIAN	Lower	<i>C. lindstromi</i>	St. George	Watts Bight
CAMBRIAN	Furongian	<i>C. intermedius</i>	Port au Port	Berry Head
			<i>Cordylodus caboti</i>	
	<i>C. proavus</i>			
	<i>E. notchpeakensis</i>			

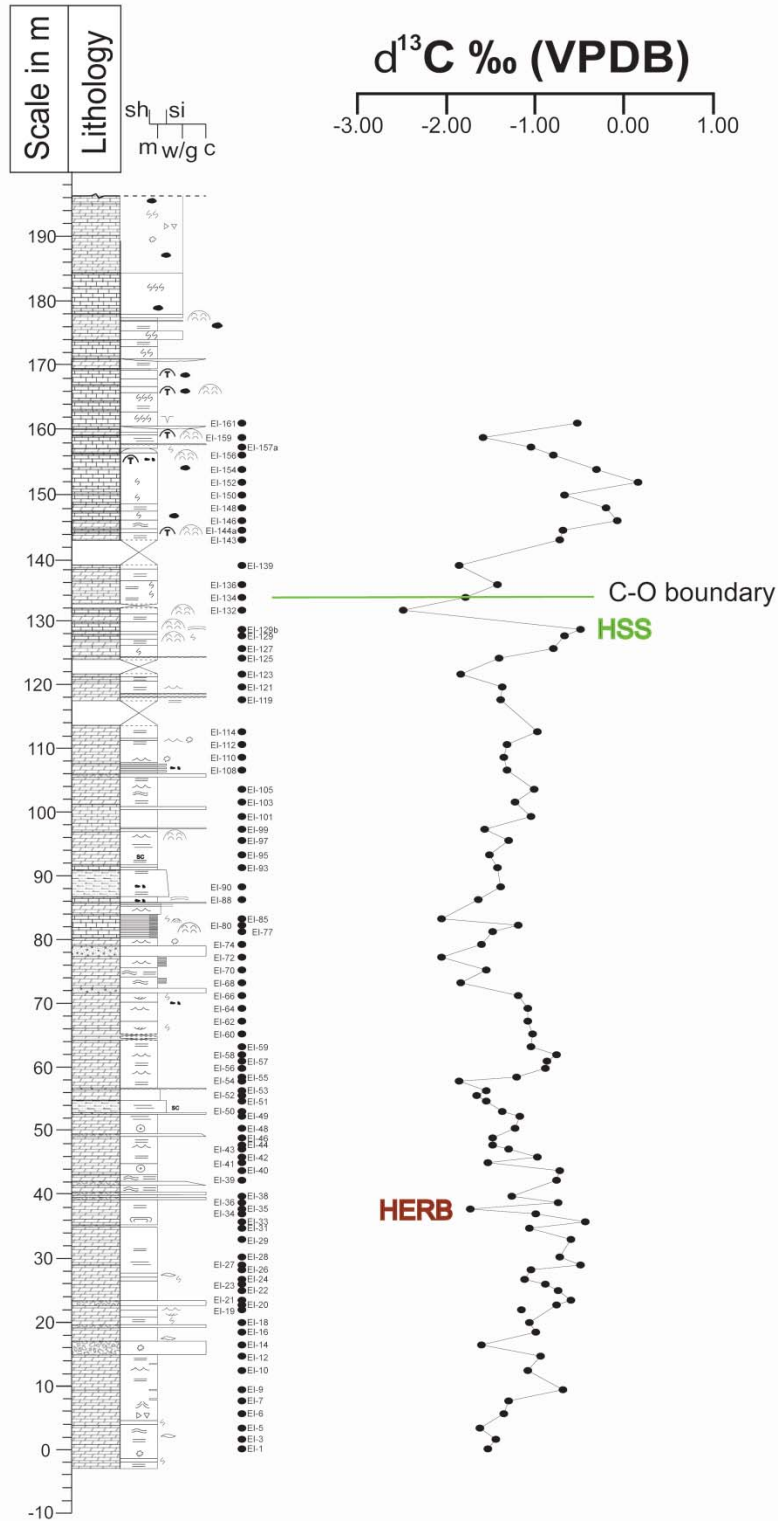


Figure 22. Section of the East Isthmus section and C isotope curve (from S. Scorer in prep.).

The March Point Formation (approx 160 m of thickness exposed) is composed of rhythmic to cyclic, thin- to thick-bedded, peritidal dolostone, dolomitic limestone, minor limestone, oolites and small breccia beds (Figure 22). The dolostone may be homogeneously dense, laminated, burrowed and bioturbated; it is a grey, often buff weathering unit. Desiccation cracks are present. The dolomitic limestone is grey, pale yellow to light grey weathering, medium to thick bedded with chert and minor oolitic horizons.

The Watts Bight Formation (> 40 m of exposure) consists of subtidal, dark grey, medium- to thick-bedded bioturbated limestone and dolomitic limestone with peritidal dolostone - often laminated - interbeds. Massive, high-energy thrombolitic mound complex concludes the exposed succession, which is getting increasingly structural disturbed upsection.

The section displays the change from the uppermost Cambrian shallow marine, high energy, carbonate platform (Port au Port Group) to the lowermost Ordovician, low-energy, carbonate platform of the St. George Group (James *et al.* 1989). The deposition of the Watts Bight sedimentary rocks initiated the change from the narrow, high-energy carbonate platform to the widespread more muddy carbonate deposition typical of St. George Group (James *et al.* 1989).

Palaeontology Stromatolite and thrombolite mounds are frequent in the succession, the latter become massive bedded in the Watts Bight Formation. Trace fossils are present, but except for the stromatolite and thrombolite mounds the succession is practically barren of shelly macrofossils.

Zones/age Just above the base of the Watts Bight Formation (Figure 23), in the upper part of the exposures in the section, a low diverse conodont fauna composed of *Cordylodus lindstromi*, *Semiacontiodus nogamii* and *Teridontus nakamurai* have been recorded (Ji and Barnes 1994). The appearance of *Cordylodus lindstromi* demonstrates that in this section the lowermost strata of the Watts Bight Formation are Ordovician (i.e. Ji and Barnes 1994; Barnes 1998; Cooper *et al.* 2001).



Figure 23. Photo of the conformable boundary between the Port au Port Group and overlying St. George Group (i.e. base of the Watts Bight Formation).

Geochemistry The high-resolution $\delta^{13}\text{C}_{\text{carb}}$ (whole rock) isotope curve (Figure 22) is reproduced with permission by Sebastian Scorer, who is currently investigating the succession (MSc. Project, MUN, in prep.). The isotope curve displays the carbon isotope pattern, which is typical for the uppermost Cambrian and the lowermost Ordovician in Newfoundland. The isotopic Cambrian–Ordovician boundary is identified in the upper part of the section (Figure 22).

At 38 m above the base of the section the characteristic negative excursion is interpreted to represent the HERB excursion. From the HERB level the carbon isotope curve display an overall rise and with values that become increasingly positive and with a peak characteristic of the *Hirsutodontus simplex* positive spike (HSS) of the uppermost Cambrian. Above HSS follows the abrupt negative trend

towards the transition from the Cambrian to Ordovician with a maximal negative peak in the Cambrian followed by positive-negative excursions in the Ordovician. The inferred position of the Cambrian–Ordovician boundary is placed at 134 m, which is just below the recorded first occurrence of *Cordylodus lindstromi* in the section (i.e. Ji and Barnes 1994).

Return to Dreamcatcher Lodge Hotel in Stephenville.

DAY 3

Departure to the Great Northern Peninsula. Turn at Wiltondale and drive on Route 431 towards Woody Point.

Stop 7

Location Viewpoint east of Woody Point; western shore of Bonne Bay.

Targets Scenic view over the Tablelands; photostop.

Description View to the Tablelands across Bonne Bay, the community seen on the opposite side is Norris Point. The conical peak is formed by the amphibolitic dynamothermal aureole of the ophiolite. The flat-topped mountain is made up, in part of transported volcanic rocks of rift origin from the late Precambrian part of Summerside Formation. The east shore of East Arm consists of greywackes of the Summerside Formation.

East Arm cuts into a mélange zone, patches of which are exposed along the west shore. A deformed gabbro belonging to the ophiolitic suite of the Little Port Complex is exposed on the opposite side of the road.

Stop 8

From Woody Point drive on Route 431 towards Trout River.

Location Stop on road approx. 4.5 km from the Discovery Centre and Park. Explanation board at the road between Woody Point and Trout River.

Targets Moho and ocean floor deposits.

Description The rusty brown large body is the mantle and cumulate sequence of the Tablelands.

The pillow lavas and volcanic breccias; sediments (chert and shale) of the ocean floor represent the uppermost part of an ophiolite sequence (Figure 24).

The exposure shows pillow lavas, volcanic breccias, red shale and chert. The rusty zone may represent seafloor hydrothermal alteration and sulphide deposition.

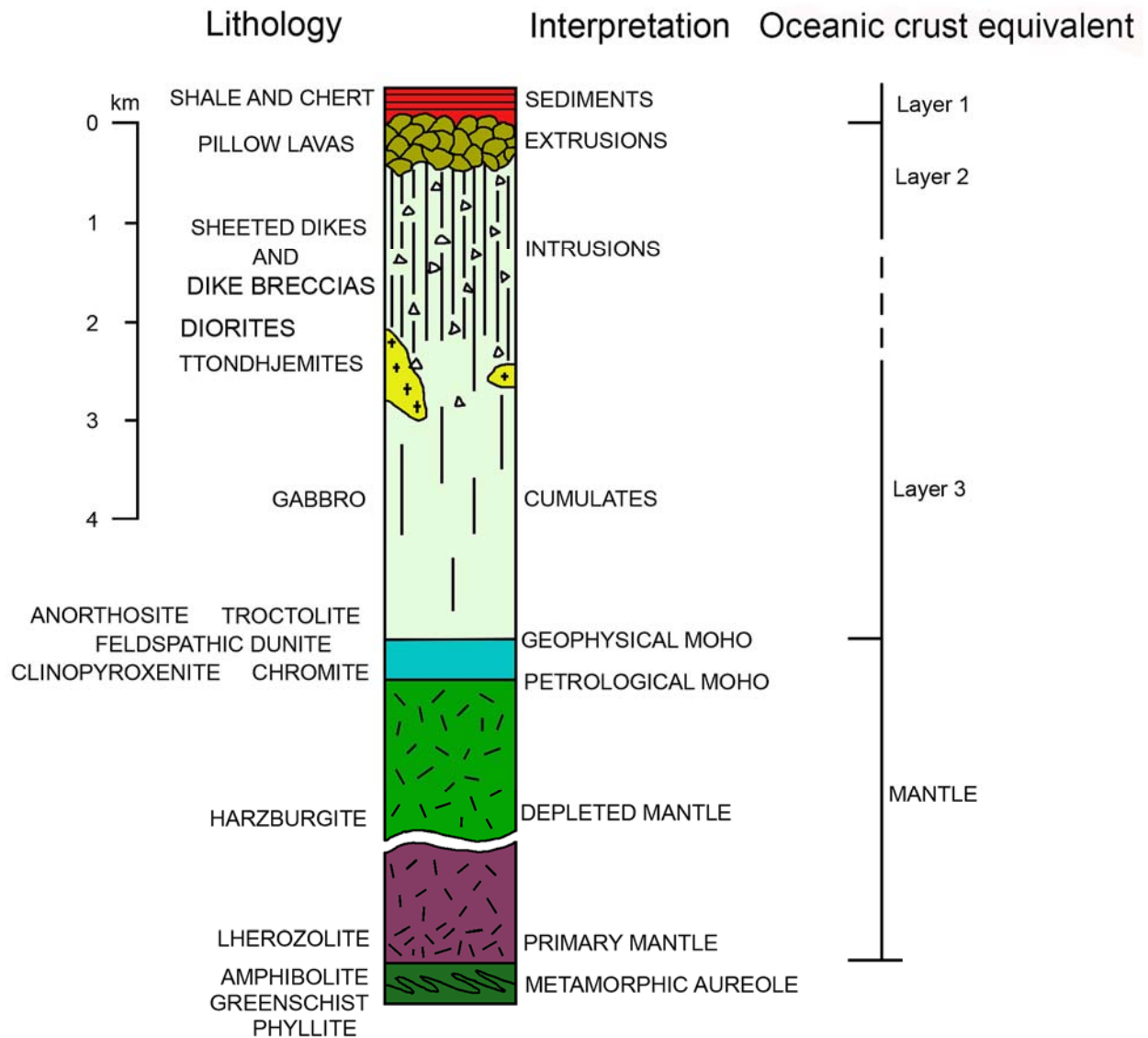


Figure 24. General section of an ophiolite sequence.

The rocks are considered to represent the upper part of an ophiolitic sequence. Sheeted dykes are exposed in the road cut west of the Discovery Centre. Altogether, the deformed gabbro, the sheeted dykes, the pillow lavas, pelites and cherts are collectively referred to the Little Port Complex.

Zones/age The chert has been dated as Floian Stage, Lower Ordovician. Radiolarians from the cherts occur together with *Oepikodus evae*, which is Lower Ordovician (Won and Iams 2013).

Stop 9

- Location Viewpoint at the Trout River campground.
- Description Viewpoint to the south side of the Tablelands Ophiolite. The contrast between the yellow brown ultramafic rocks and the grey-weathering gabbro is sharp. Miner's Point is a gabbro. This viewpoint has been described and illustrated by Berger *et al.* (1992).

Optional stops on route Route 430

- Location About 9.6 km north from the Route 430/431 junction in Wiltondale.
- Description Outcrops with Grenvillian basement rocks overlain by Cambrian conglomerates and sandstones and of the Bradore Formation (Labrador Group).
- Location 29 km from the Route 430/431 junction in Wiltondale.
- Description Outcrop of Forteau Formation composed of shales and siltstones. The trilobite *Olenellus thompsonii* may be found, but fossils are difficult to see.

Drive to Rocky Harbour and check in to the Fishermans Landing.

DAY 4

The following two days will focus on the Cow Head Group of the Humber Arm Allochthon. The Cow Head Group crops out through the Cow Head region of central west Newfoundland. Laterally equivalent strata are known from Humber Arm and Port au Port Peninsula. The sequence has been studied since the 1860's and is the subject of intensive, ongoing research in the fields of stratigraphy, sedimentology and palaeontology.

Oil seeps are common in the region, and also on Port au Port Peninsula. Several exploration wells have been drilled in the region some intervals of the black shale from the Cow Head Group display high total organic carbon. These black, high organic shale intervals (mainly Green Point Formation) of the Cow Head Group are considered to be the source rocks for the oil stains and showings in the region (Cooper, M. et al. 2001, Hinchey et al. 2015). An exploration license for exploitation of these resources was recently revoked due to public outcry at the potential use of hydrofracturing from an onshore drill site at Sally's Cove (an enclave within Gros Morne National Park). Newfoundland currently has a moratorium on hydraulic fracturing.

Our first stop will go to the Cow Head Peninsula itself. It is probably the most important locality of all localities of the Cow Head Group, because it has a nearly complete succession of fossiliferous sedimentary rocks starting from the mid Cambrian and concluding in the Middle Ordovician.

Stop 10

Cow Head Peninsula – World famous locality, proximal slope facies.

Location 1 km west of Cow Head village, 43 km north of Rocky Harbour. Drive to the peninsula, and park below the radio-mast. A trail to the Point of the Head is starting from the radio-mast and ends at the Point of The Head.

Targets Cambrian to Middle Ordovician proximal or upper slope deposits, Cow Head Group, western Newfoundland covering the disciplines sedimentology (including sequence stratigraphy), palaeontology, biostratigraphy and geochemistry.

History

The historical outline is given in James and Stevens (1986). The Cow Head Peninsula gives the name to the Cow Head Group, but the origin to the name is unclear. Apparently or perhaps obviously it refers to resemblance of some of the weathered conglomerates having a profile like the head of a cow. Another interpretation is the ‘spotted’ appearance of in particular Bed 7, which is composed of light grey blocks in grey grainstone matrix and resembles the hide of cows - this latter explanation, however, requires a bit of a good imagination and ‘liquid inspiration’.

The development of ideas on the Cow Head succession, and their significance has been a gradual process, but the expeditions by Yale University, USA became an important keystone forward in the understanding of the succession during which a huge number of fossils have been collected (Schuchert and Dunbar 1934).

Another remarkable pioneer working on the Cow Head Group worthy of mention is Kindle. The first known graptolites were found by Kindle, and subsequently described by Ruedemann (1947), which clearly demonstrated the Ordovician age of the group. However, Kindle worked for decades on the Great Northern Peninsula of Newfoundland, where he investigated and sampled fossils especially from the large boulders in the conglomerates of the Cow Head Group (e.g. Kindle 1982). His large and impressive trilobite collection has been, and is still being, investigated by subsequent trilobite workers and many published systematic papers on the trilobite genera and species from the Cow Head Group have been published (Ludvigsen *et al.* 1989; Westrop and Dengler 2017 and references therein).

Kindle and Whittington (1958) defined the Cow Head Group as an orderly succession of sedimentary rocks and the succession was placed into numbered beds (i.e. Bed 1 to Bed 14), a system that still is used in the field. Significantly, they recognized that the fossiliferous boulders from any layer containing trilobites were of limited age and about the same age as the underlying strata. The trilobite faunas were described in several, now classical, papers (i.e. Kindle and Whittington 1958, 1959, 1969; Whittington 1963; Kindle 1982). Kindle and

Whittington (1958) also provided additional formation to the graptolite fauna and correlated the succession with the Australian zonal system.

The impressive work of James and Stevens (1986) was the next milestone in the progress of the study of the Cow Head Group. They provided detailed measured sections and descriptions of the exposures of the Cow Head Group, and today this work is standard reference for almost all publications on the Cow Head Group. James and Stevens (1986) subdivided the Cow Head Group into two formal formations and seven members, which are used today (see Figure 8).

Following the James and Stevens (1986) monograph, numerous papers and monographs on the trilobite fauna (Ludvigsen *et al.* 1989; Westrop and Dengler 2017 and references therein) and the graptolites (Erdtmann 1970; Fortey *et al.* 1982) followed. Williams and Stevens (1988) described the graptolite specimens collected by James and Stevens during their fieldwork.

Conodonts from the Cow Head Group have been described in several papers first mentioned by Fåhræus (1970) then by Fåhræus and Nowlan (1978). Bagnoli *et al.* (1987) focused on the late Cambrian to Early Ordovician, and both Landing (in Fortey *et al.* 1982) and Barnes (1988) provided the biostratigraphical details and basis for the choice of the Green Point section as GSSP for global Cambrian–Ordovician boundary in the Cow Head Group (summarized by Cooper *et al.* 2001). Stouge and Bagnoli (1988) and Pohler (1984), Johnston and Barnes (2000, 2001) and Stouge (2012) dealt with the Ordovician conodont fauna, but much work is still in progress.

Recently, papers from the Cow Head Group on trilobites (Karim 2008) and radiolarians (Won and Iams 2002, 2011, 2013; Won *et al.* 2007a, b; Pouille *et al.* 2014) have appeared covering the late Cambrian and Early Ordovician.

Also $\delta^{13}\text{C}_{\text{carb}}$ isotope geochemistry excursions have been investigated from the Cow Head Group (Azmy *et al.* 2014 and in press; Pruss *et al.* 2016).

Description The succession of the Cow Head Group is nearly completely exposed around the coastline of the peninsula (Figure 25). It comprises a succession of marine sediments 300 to 500 m thick of mid Cambrian to early Middle Ordovician age. Much of the succession consists of shale, siltstone, thin-bedded limestone, but the

COW HEAD PENINSULA

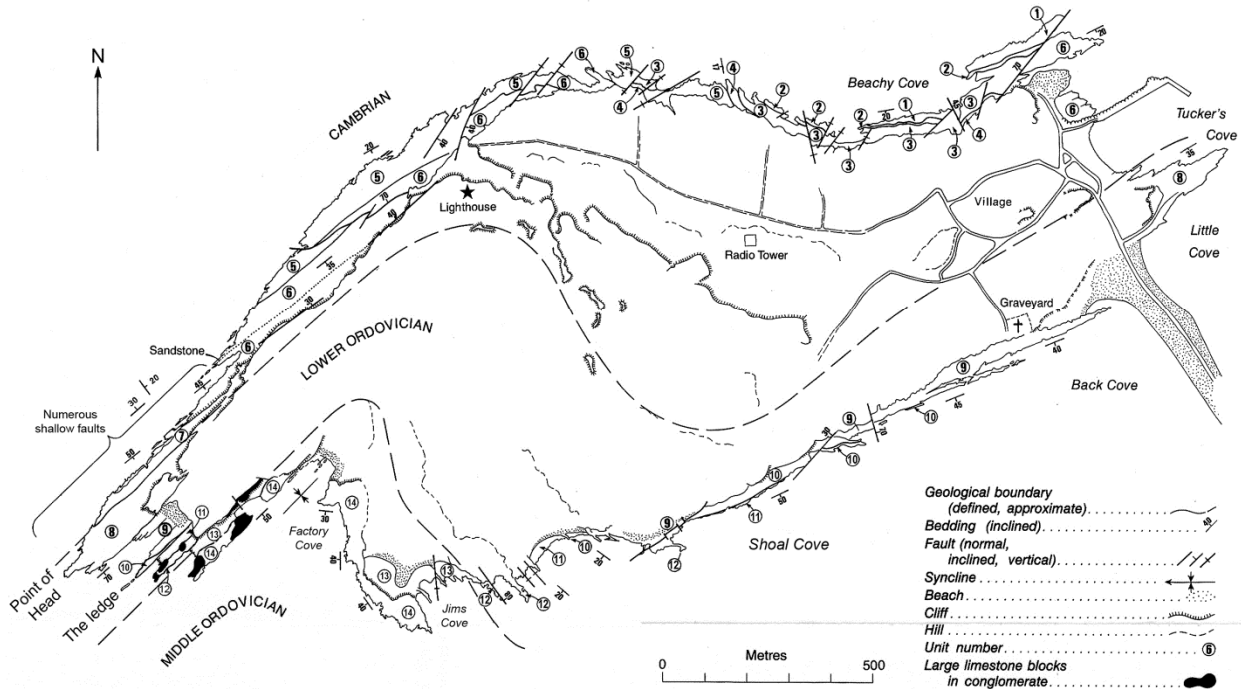


Figure 25. Cambrian to Ordovician geology of Cow Head (modified from Fåhræus and Nowlan 1978 and James and Stevens 1986).

most striking characteristic of the Cow Head Group is the occurrence of massive limestone breccias and conglomerates. Some clasts exceed 100 m thick while one block at Lower Head exceeds 200 metres in length.

The base of the Cow Head Group is covered by the sea, and the exposed top is marked by Bed 14, a prominent mega-conglomerate, which is the marker horizon for the top of the group. The strata are folded into a gentle southwest-plunging syncline and anticline with beds generally dipping to the southeast. The succession is interrupted by minor faults and the succession is repeated around the peninsula. The bed numbers used in the description are those of Kindle and Whittington (1958).

Zones/Age Upper Cambrian (Stage 10) to lower Darriwilian (Middle Ordovician).

For practical reasons and because of time constraints we will focus on two intervals exposed on the peninsula. The northern part around Beachy Cove, with Cambrian deposits, will be visited

only briefly in order to see the conglomerates with numerous trilobites in boulders (collected previously by Kindle and others).

The second part of the visit will be a traverse from the Point of Head of the peninsula starting with the Cambrian Bed 7 crossing the Ledge (Beds 9 and 10) and concluding with the Middle Ordovician Bed 14.

First stop – Beachy Cove (Downes Point Member, Beds 1–5; Figure 26)

Note. - With strong winds, rain and high sea/tide this portion of the succession may have to be omitted; Bed 7 however can be reached from the Point of Head instead.

Description The oldest beds on Cow Head Peninsula are exposed in the tidal zone and in the cliffs at Beachy Cove (Figure 26). The basal conglomerates of the Cow Head Group are exposed at Broom Point to the south of Shallow Bay (named Bed 0 by James and Stevens 1986, p. 61). The visited beds on Cow Head Peninsula are also referred to Beds 1–5 (Kindle and Whittington 1958; James and Stevens 1986). The strata extend along the north coast and include the overlying Beds 6 and 7.

 The succession at Beachy Cove is dominated by conglomerate and breccia beds. The clasts are rich in upper Cambrian trilobites (Beds 1–4: *Cedaria-Crepicephalus* Zone; Bed 5: *Conaspsis* Zone of Kindle and Whittington 1958). The fauna is referred to the Furongian Series (Stage 10; Cambrian).

Second stop – Point of Head (Steering Island Member; Bed 7 and Bed 8) to the Ledge (Factory Cove Member; Bed 9 to Bed 14; Figure 27).

Description *Steering Island Member*

Bed 7 White boulders are characteristic for Bed 7, which is a 16 m cliff-forming unit. It is composed of three conglomerates containing large, white limestone boulders in the darker grey coarse-grained matrix. The white boulders are composed of *Epiphyton* and *Girvanella* representing a shelf margin to upper slope facies

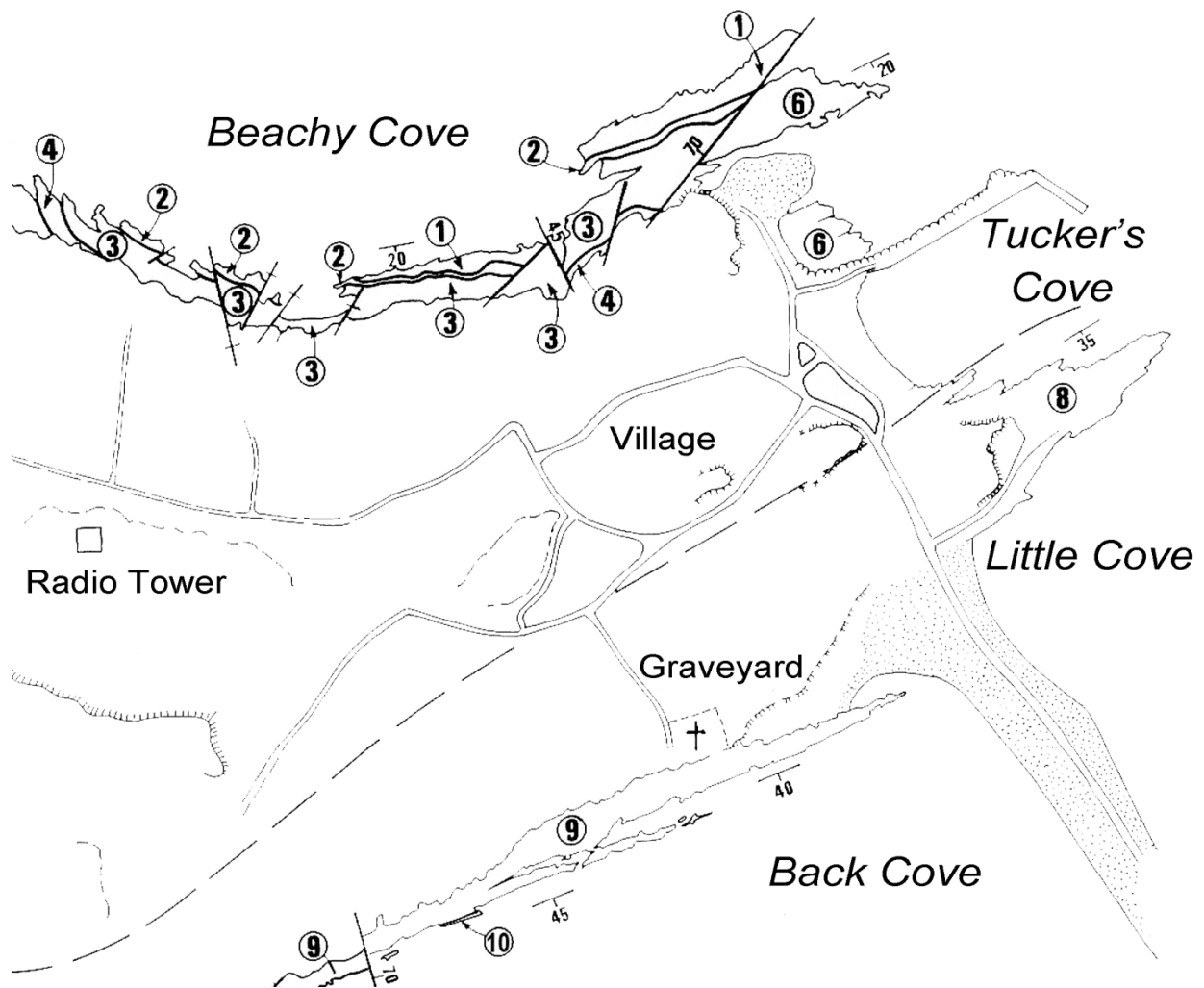


Figure 26. Detailed map of the Beachy Cove locality (outcrops of Beds 1–5).

(James 1981). The trilobite fauna from Bed 7 and to the top of Bed 7 is typically latest Cambrian (*Saukia* sp.).

Bed 8 The Point of Head of Cow Head Peninsula is formed by Bed 8, about 63 m thick. The lowermost part of Bed 8 is a graded grainstone followed by conglomerates. The higher and upper part consists of parted limestone, shale, ribbon limestone, grainstone and interbedded conglomerates. Black organic rich cherts occur in Bed 8 as both beds and clasts. Additionally, trace fossils and phosphate grains become frequent at this level.

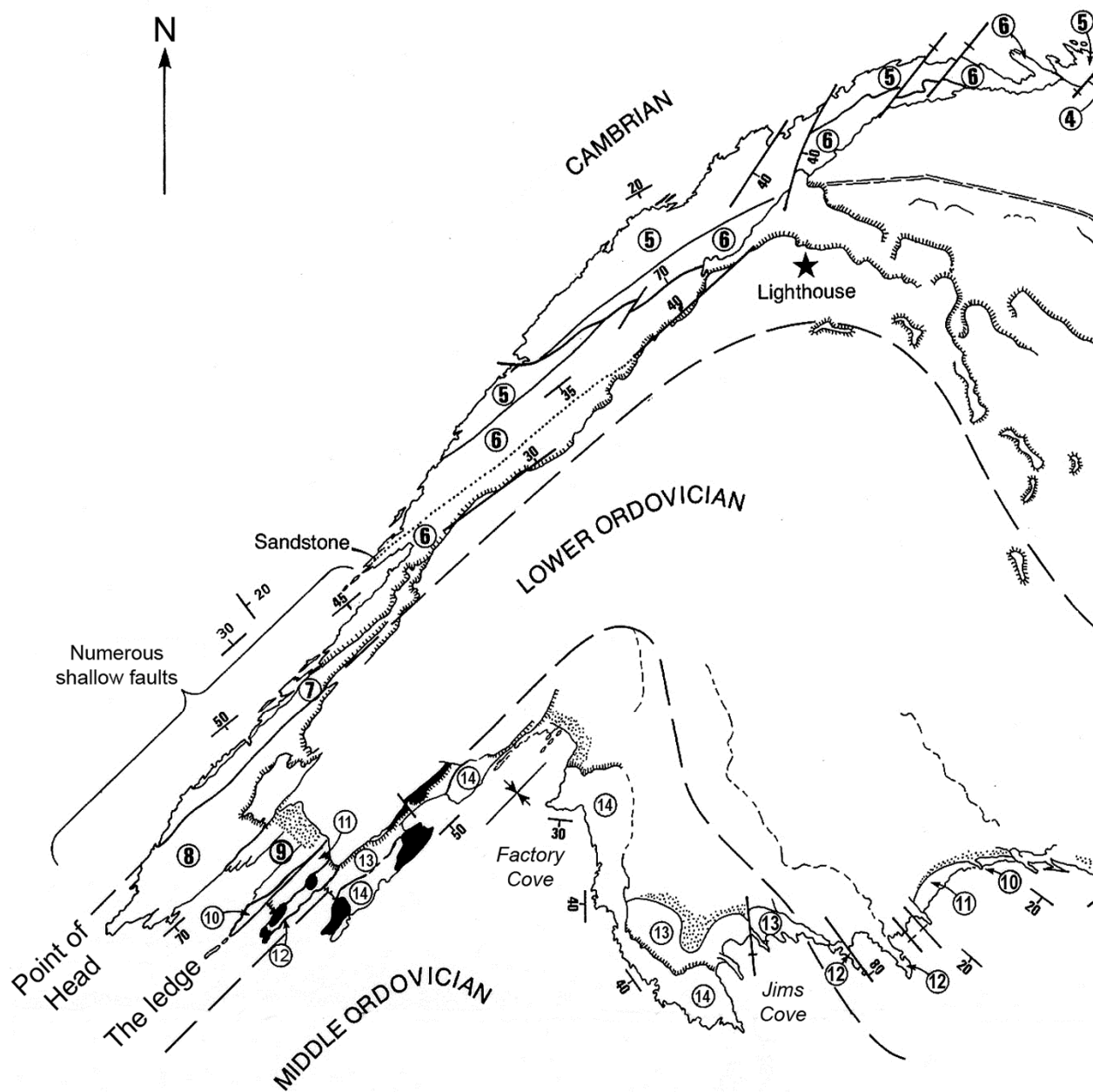


Figure 27. Detailed map of the Point of Head – and Ledge sections (modified from James and Stevens 1986).

The Cambrian–Ordovician boundary is not clearly exposed on the Cow Head Peninsula, but fossils in Bed 8, includes *Rhabdinopora* sp., *Adelograptus* sp. and *Clonograptus* sp. The presence of the trilobites *Symphysurina* sp. and *Hystricurus*

sp. demonstrate that Bed 8 is Ordovician (Tremadoc). Bed 8 conodonts are referred to Fauna C and the *Macerodus diana* Zone (Fåhræus and Nowlan 1978) and the top beds of Bed 8 are within the *Prioniodus gilberti* conodont Zone (Stouge and Bagnoli 1988).

Description *Factory Cove Member*

Bed 9 Bed 9 consists of parted, ribbon limestone and dark and green shale, interrupted by smaller conglomerate beds. The parted and ribbon limestone are lime mudstones and wackestones. Trace fossils (few *Zoophycus*) and other burrows (e.g. *Arenicolites*; Jansa 1974) are common in the parted lime mudstone.

Bed 9 is rich in graptolites (Williams and Stevens 1988). It represents the base of the Floian Stage defined by the FAD of *Tetragraptus approximatus*. *T. akzharensis* Zone was established by Williams and Stevens (1988) from the top of Bed 9. Bed 9 has also been proposed GSSP candidate for the base of the global Floian Stage (Williams *et al.* 2011).

Conodonts from Bed 9 are characterised by the conodont genus *Prioniodus* Pander and three zones have been defined from this section (Stouge and Bagnoli 1988).

Bed 9 also yields sponge spicules and some phosphatic, inarticulate brachiopods.

Description *The Ledge*

Bed 10 Bed 10 is a mega-conglomerate. It is laterally extensive but highly variable in thickness (from 0.8 m to over 50 m). The lithology of the clasts, and the size of the individual clasts is also highly variable. A brown-weathering chert bed caps the top of the conglomerate.

Trilobites, brachiopods and conodonts recovered from the blocks are known from Bed 9, and from the coeval shallow-water carbonate deposits of the upper Boat Harbour and lower Catoche formations (St. George Group).

Bed 11 Bed 11 is composed of deep-water, fine-grained limestone, interbedded with black to red, siliceous, graptolite-rich shale and brown-weathering chert and

phosphate-rich conglomerates. The upper part, above a buff-weathering burrowed dolomite, is composed of parted to ribbon limestones.

The shaly mudstones and some of the limestones are very rich in graptolites, and the *Pendeograptus fruticosus* and *Didymograptus bifidus* graptolite zones are identified from Bed 11 (Williams and Stevens 1988; Maletz *et al.* 2003). In other sections, representing more distal deposits of Bed 11, the *Isograptus (v.) lunatus* and *I. (v.) victoriae* graptolite zones has been identified from the top of Bed 11 (Maletz *et al.* 2003).

Sponge spicules and radiolarians (Won and Iams 2002) are present, but conodonts are abundant in the limestone from the lower portion of Bed 11, which is dominated by the nominate species *Oepikodus evae* Lindström (Stouge and Bagnoli 1988).

Bed 11 represents the largest Early Ordovician sea-level rise or the 'evae transgression' and the conodont fauna from Bed 11 displays a peak in conodont diversity, which is the highest in the entire conodont succession of the Cow Head Group.

Bed 12 Bed 12 is another massive mega-conglomerate with clasts up to 20m in size. Bed 12 is similar to Bed 10 in the chaotic nature of the fabric and wide variety of the clasts. The matrix however is green shale.

The clasts contain a diverse fauna of trilobites, brachiopods, gastropods and sponges. The fauna from the blocks includes elements of the *Orthidiella* Biozone (Whiterockian; Middle Ordovician; Ross and James 1987). The conodont from the blocks are high Lower to low Middle Ordovician (Pohler 1994).

Bed 13 This unit is composed of ribbon and parted limestone. The lower part is composed of peloidal to intraclastic grainstones with silicified tops. The beds are slumped.

Graptolites from Bed 13 are referred to *Isograptus (v.) maximus* and *I. (v.) maximodivergens* graptolite zones (Castlemainian; Dapingian; Williams and Stevens 1988; Maletz *et al.* 2003). The conodont fauna is rich and dominated by the genus *Periodon*. The *Periodon hankensis* and *Periodon macrodentatus* zones have been established from Bed 13 (Stouge 2012). Bed 13 also yields the Whiterockian *Pteracontiodus cryptodens*, which is the nominate species of the

biozone of the Aguathuna Formation known from the Port au Port platformal succession (Stop 5; Ji and Barnes 1994).

Bed 14 Bed 14 is the top and also the most impressive mega-conglomerate of the Cow Head Group. It is 15.0 m thick and cuts down into underlying strata to depths of 4 m. Clasts vary from rounded shallow-water boulders to plastically deformed masses of slope carbonate beds. The green argillaceous matrix, at least in part, is derived from green-grey argillaceous limestone that were soft when re-deposited.

Brachiopods and trilobites in boulders of Bed 14 indicate a Whiterock (early Middle Ordovician), *Orthidiella* Zone, fauna (Ross and James 1987). The conodont fauna from the boulders are referred to Whiterockian (Dapingian to lower Darriwilian, Middle Ordovician; Pohler 1994; Stouge 2012).

This concludes the traverse of the entire Cow Head Peninsula; from here we will walk back along the trail to the bus.

Stop 11

Note: - This is within Gros Morne National Park so no collecting/hammering is allowed.

Lower Head – Huge conglomerates, Whiterockian (Middle Ordovician).

Location 5.2 km north of the town of Cow Head; from parking place near Stanfords Brook follow trail along the north side of the brook to the sea and continue to the north along the shoreline to the head.

Targets Large boulders of biohermal limestone exposed at the Lower Head west location very rich in fossils, especially trilobites and gastropods, in conglomerates derived from a proximal depositional setting.

History This locality was made famous by Whittington and Kindle (1963) and is a 'must' for Ordovician trilobite workers to visit.

Description Low outcrops seen in the tidal zone on the route to the head are the Lower Head Formation (Middle Ordovician) that directly overlies the Cow Head Group.

Lower Head is composed of massive, chaotic mega-conglomerate, which was deposited in the mid Middle Ordovician (Whiterockian; Darriwilian); it is

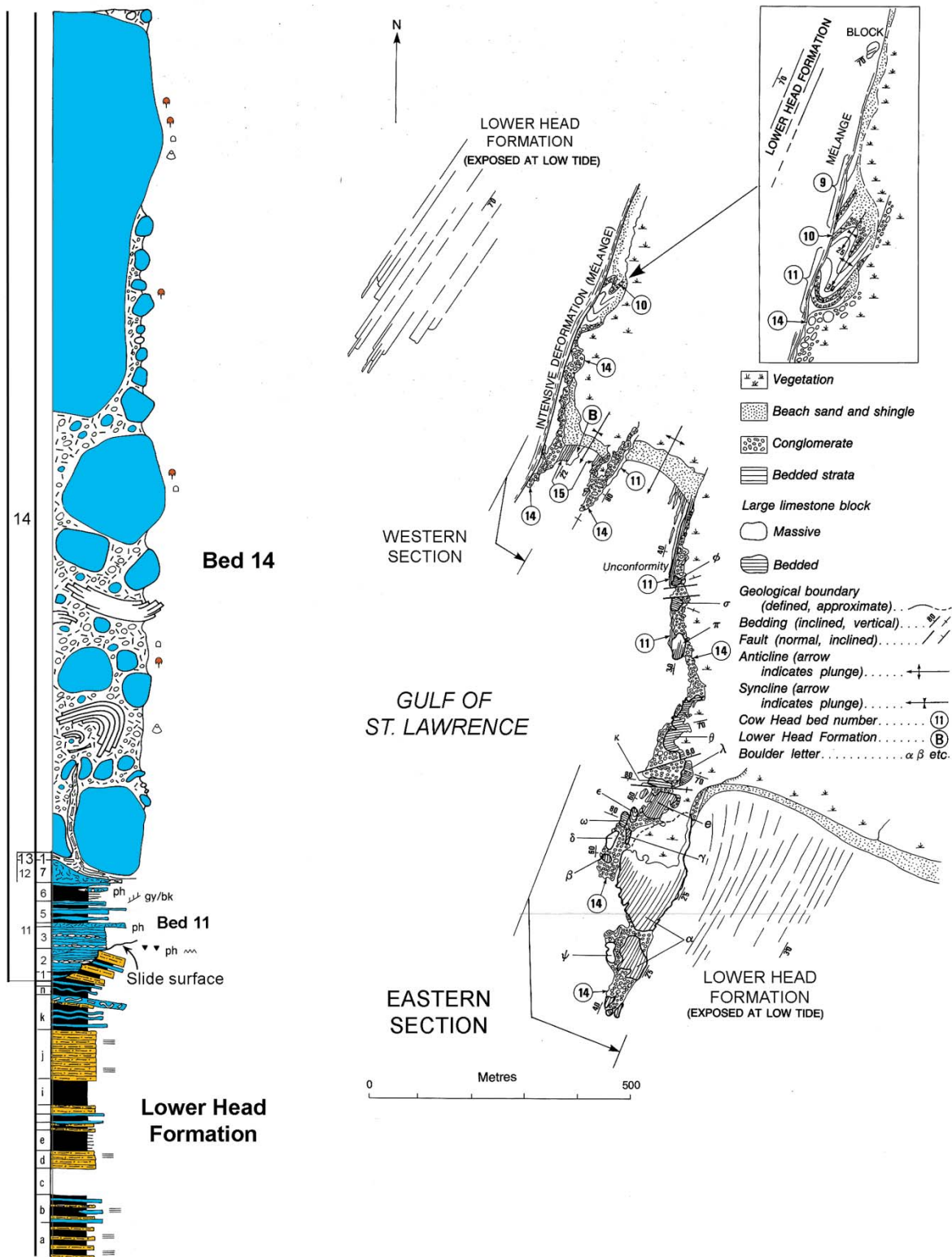


Figure 28. Section of the Lower Head west locality (modified from James and Stevens 1986).

considered to be the lateral equivalent of Bed 14 on the Cow Head Peninsula. The mega-conglomerate is underlain by parted limestone, cherts and thin conglomerates, which probably are equivalent to Bed 11 at the Cow Head Peninsula (James and Stevens 1986; Pohler and James 1989). Beds 12 and 13 are not seen but have been cut out by Bed 14.

The mega-breccia is composed of a wide variety of boulders composed of fossiliferous wackestone in an argillaceous matrix. The soft-sediment deformation seen in some of these blocks demonstrates that they were plastic and soft at the time they were re-deposited and incorporated in the breccia. The boulders range from clearly shallow-water sediments to cemented breccias (Pohler and James 1989).

The largest and most spectacular blocks are the 'white blocks' named α , β and γ blocks (Whittington and Kindle 1963; James and Stevens 1986). They are composed of light-coloured to white limestone. The biggest block (block α) is forming a low cliff at the point. This block (ca. 200 m x 50 m) contains the well-known Middle Ordovician trilobite fauna described by Whittington and Kindle (1963).

The internal structure is visible in many blocks; it includes *Girvanella* clast grainstone facies and biohermal mudstone facies.

The biohermal mudstone facies is very fossiliferous containing trilobites, cephalopods, brachiopods, *Epiphyton*, and sponges. The other large blocks are of similar composition.

Some blocks consist of algal mounds or heads, and large gastropods may be abundant locally. The stromatoporoid/coelenterate *Pulchrilamina* is also represented in some blocks.

The deposits Bed 11 to 14 are interpreted as one large debris flow, representing a detached very proximal upper slope facies that is not represented elsewhere in the Cow Head (Coniglio 1985). The whole mega-breccia at Lower Head is an olistostrome that was slid downslope to its present position (Coniglio 1985).

Bed 14 and Bed 15 are overlain by the turbiditic sandstones of the Lower Head Formation (Blamey *et al.* 2015).

Equivalent deposits have not been recorded or seen in the Humber Arm Allocthon, which makes the exposure with the 'white blocks' unique for Western Newfoundland.

Zones/Age The beds 11 to 14 range from Floian (Lower Ordovician) to Dapingian (Middle Ordovician) (Pohler and James 1989). Boulders from Bed 14 yield the conodont species *Pteracontiodus cryptodens* and *Paraprioniodus neocostatus* (Pohler 1994), which covers the time interval represented by the St. George Unconformity in the Aguathuna Formation of the St. George Group to the base of the Table Point Formation.

Bed 15 and the overlying Lower Head Formation are referred to the lower Darriwilian *Histiodela holodentata* Subzone of the *Periodon macrodentatus* conodont Zone (Middle Ordovician; Stouge 2012).

Walk back along the beach to the bus and return to hotel.

DAY 5

Stop 12

Note: - **This is within Gros Morne National Park so no collecting/hammering is allowed.**

Broom Point – Mid-slope deposits.

Location From Rocky Harbour we will drive approx. 31 km north on Route 430; this locality lies 0.8 km north of the bridge over Western Brook; turn left on Parks Canada track and stop at the coast.

History The general succession was summarized by Kindle and Whittington (1958, 1959) based on trilobite material that Kindle collected from boulders of the Downes Point Member over a period of several decades constituting some 20,000 specimens. Kindle (1982) also introduced a series of eight informal trilobite zones for the Cambrian strata (Kindle 1982). Westrop *et al.* (1996), Ludvigsen and Westrop (1989), Young and Ludvigsen (1989), Westrop and Ludvigsen (2000), Westrop and Eoff (2012) and most recently Westrop and Dengler (2014, 2016, 2017) have continued revising and describing the trilobite fauna collected from the limestone blocks in the conglomerates from Broom Point and Hickeys Cove (The point to the east of Broom Point, Figure 29).

The detailed logs of Broom Point North and Broom Point South sections (Figure 29) were published by James and Stevens (1986).

Initially, the Broom Point South section was proposed as GSSP candidate for the definition of the boundary between the Cambrian and Ordovician (Fortey and Skevington 1980), Shortly after, Fortey *et al.* (1982) carefully documented the graptolite, trilobite and conodont faunal successions for the Broom Point sections.

Bagnoli *et al.* (1987) described species of the *Cordylodus* lineage, followed by Barnes (1988), who described the conodont succession from the two sections, together with general stratigraphy and proposing correlation between Broom Point and other localities in the Cow Head Group. He concluded that the Green Point section was a better GSSP candidate for the Cambrian–Ordovician boundary. Won and Iams (2002) and Pouille *et al.* (2014) recorded radiolarian

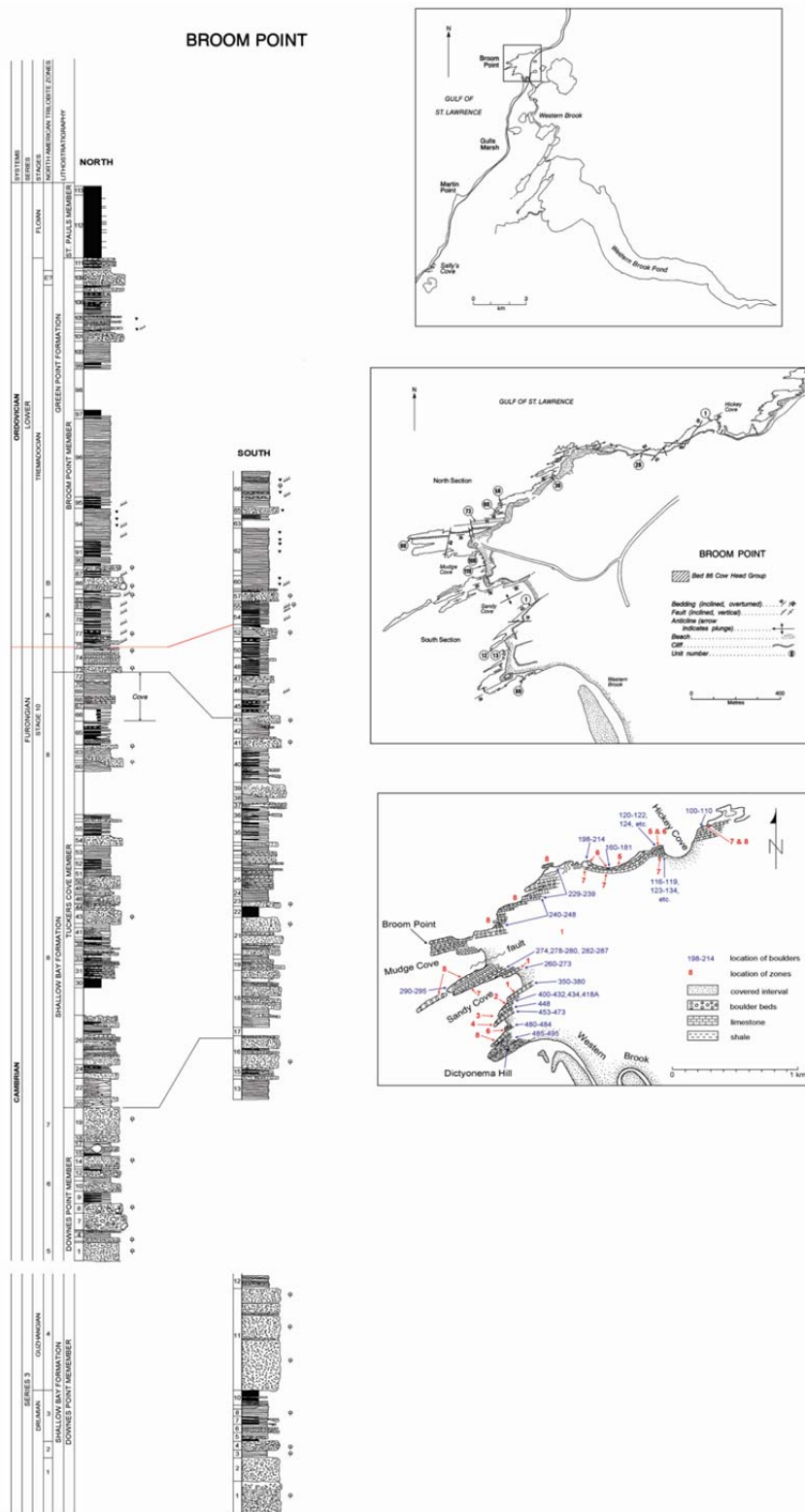


Figure 29. Location and sections of the Broom Point locality showing trilobite horizons (modified from Kindle 1982 and James and Stevens 1986).

assemblages from the Broom Point South section, and Carrera and Maletz (2014) briefly reported on the presence of sponge spicules from the lower Tremadocian of Broom Point.

Targets The transition from Drumian Stage, Furongian (top Stage 10, Cambrian) to Lower Ordovician. At Broom Point, the succession through mid Cambrian and Lower Ordovician strata are seen in two sections. The focus will be on the Broom Point South, where also the stratigraphic oldest strata – i.e. Downes Point Member - in the Cow Head Group are exposed. Prolific trilobite faunas and graptolite succession are present.

Description The Cow Head Group is folded and faulted at Broom Point, but the limbs of the large antiform show two similar sections (Figure 29). The Cambrian–Ordovician boundary is well-exposed in the two sections at Broom Point: one i.e. Broom Point S lies between the mouth of Western Brook and Anticlinal (or Sandy Cove); the other or Broom Point N is on the north side of Broom Point (Figure 29).

The following description with reference to numbered units are those from the precise and detailed outline of the two sections provided by James and Stevens (1986).

Broom Point North

The northern section extends from Hickey Cove west along the coast to Mudge Cove (Figure 29). The upper part of the Downes Point Member is overlain by quartzose, coarse-grained limestone and graded-stratified conglomerate and debris flows of the Tuckers Cove Member passing upwards into parted limestones, shaly mudstones, and minor conglomerates of the Broom Point Member. At the Point, the succession consists of ribbon to parted lime mudstones to grainstones with some conglomerates (Unit 62, Unit 64), along with interbedded grey shale, and rare silty dolostones (Unit 68). Units 70–72 form a small cliff ledge capped by the 1.1 m conglomerate of Unit 73. Unit 73 is the base of the Broom Point Member of the Green Point Formation. The member is 87.1 m thick in this section.

St. Pauls Member, which is 56.4 m thick, overlies the Broom Point Member at the top of the section. The units 60–95 (50 m) in the Broom Point North section span the Trempealeuan through early Tremadocian. The trilobite-bearing

horizons occur both within clasts in the conglomerates and *in situ*. Graptolites first appear in Unit 77, then diversify in Unit 78, and zonal species occur higher in the section. Conodonts are recorded throughout the section and the biozones are well documented (Landing in Fortey *et al.* 1982; Bagnoli *et al.* 1987; Barnes 1988).

At Broom Point North, units 73–86 comprise the interval with the Cambrian–Ordovician boundary. Unit 73 is the base of the Fortey *et al.* (1982) section. The interval consists of parted limestones, ribbon limestones and conglomerates with interbedded grainstones and packstones.

Broom Point South

The southern section forms the headland between Sandy Cove and Western Brook. The oldest sediments in the entire Cow Head Group are exposed at the base of this section. These are separated from the upper Cambrian and Lower Ordovician strata at the point by a fault. The Broom Point South section is faunally richer than the Broom Point North section.

The oldest strata are a series of welded conglomerates and overlying shaly mudstones, overlain by a massive 15 m thick unit of amalgamated conglomerates. These conglomerates contain several trilobite genera and species described by Kindle (1982).

The Shallow Bay Formation (top is Unit 41) is overlain by 58.3 m of the Broom Point Member; units 42–62 are, in total, 43 m thick, and form to the lower part of the member.

Zones/age Cow Head Group strata exposed at Broom Point range in age from Drumian (Stage 3) into Early Ordovician (Kindle 1982; Fortey *et al.* 1982). Trilobites are mostly present in larger clasts in the thicker conglomerates, and more rarely *in situ* within the parted limestone. The limestone blocks of the Downes Point Member conglomerates (Shallow Bay Formation) provide information on the trilobite zones 1 to 2 of Kindle (1982). The Laurentian Marjuman Stage covers Kindle 1982's Zone 3 (= Drumian Stage) and Zone 4 (= *Lejopyge laevigata* Zone, Guzhangian Stage), all of which are well represented in the Broom Point South section.

The pelagic graptolite succession in the south section is nearly complete. The evolutionary development of *Rhabdinopora* species (Figure 30) is recorded from the shale, but also from dissolved parted limestone (Erdtmann 1982a, b; Fortey and Skevington 1980; Fortey *et al.* 1982).

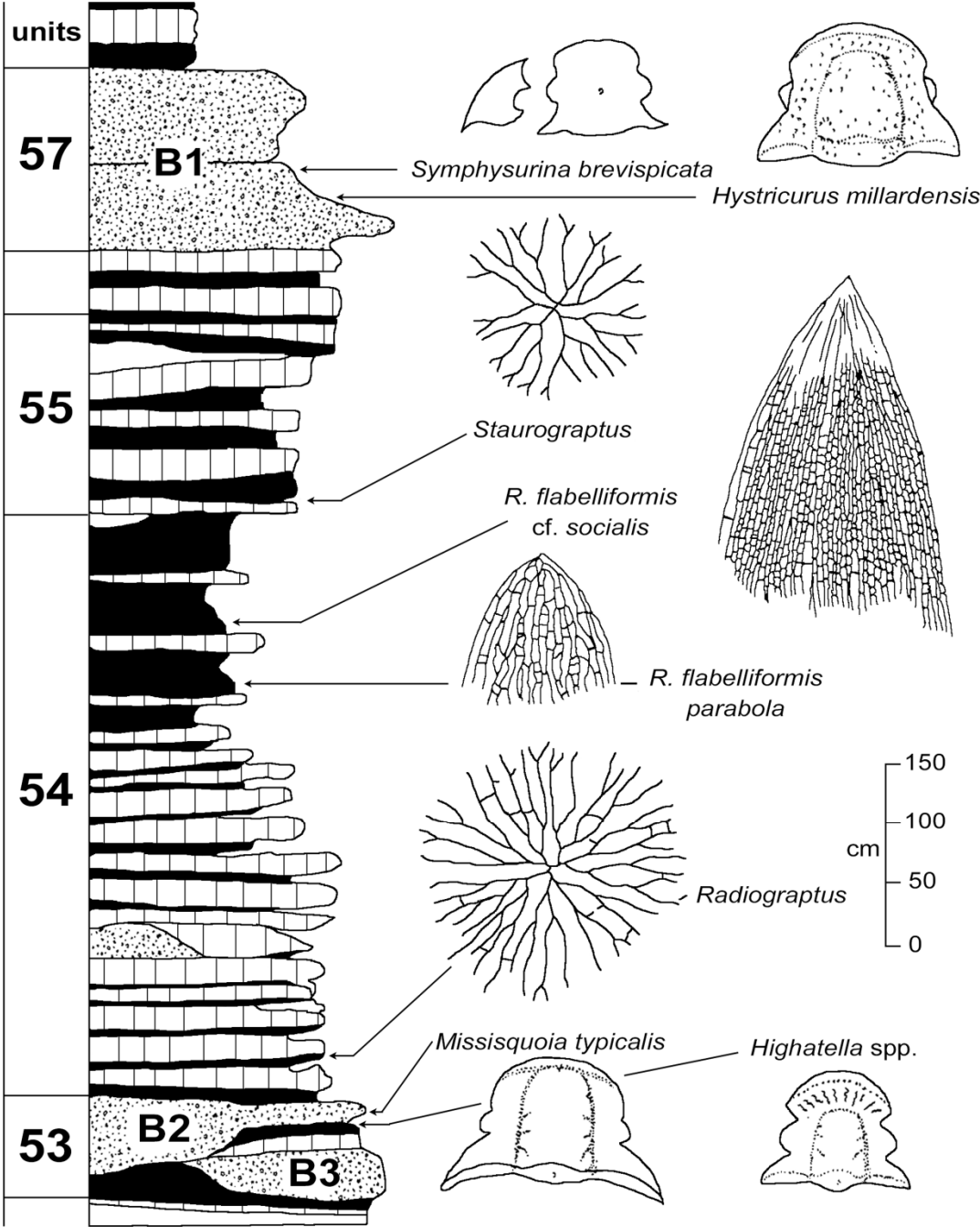


Figure 30. Broom Point South section showing the first planktic graptolite succession (based on James *et al.* 1980).

The succession is preserved between the *Missisquoia*-bearing conglomerate (= B2) and the *Symphysurina*-bearing conglomerate (= B1) (Figure 30). The latter conglomerate yields *Symphysurina brevispicata* and *Hystericurus millardensis*. Tremadocian graptolites are preserved in the shaly mudstones above the top of breccia B1.

Landing in Fortey *et al.* (1982) established the conodont species *Iapetognathus preaengensis* from the Broom Point locality from ca. 1 m above the graptolite fauna.

Stop 13

Note: - This is within Gros Morne National Park so no collecting/hammering is allowed.

Green Point – The GSSP section for the Cambrian–Ordovician boundary.

Location First road north of the Green Point campground, turn at road sign and drive down to small harbour, park and walk along the steep wall to right to the GSSP level.

History It took more than 20 years before the Cambrian–Ordovician boundary became fixed with a 'golden spike' at the Green Point section, western Newfoundland, Canada. In January 1999 the International Working Group on the Cambrian–Ordovician Boundary (COBWG) decided that the Green Point section should be the Global Stratotype and section and Point for the base of the Ordovician System. The International Subcommittee on Ordovician Stratigraphy (ISOS) approved this decision in September 1999, followed by the International Union of Geological Sciences in January 2000.

The strata exposed at the Green Point section are alternating black, grey and green shale, micritic nodular and ribbon limestones and grainstones, and are the most distal representation of a base-of-slope depositional environment in the region.

The base level is within Unit 23 and lies 4.8 m below the first appearance of planktonic graptolites (Cooper, R.A. *et al.* 2001).

The Green Point section lies within the Gros Morne National Park and the park authorities are maintaining and administrate access to the section providing permission for scientists to work on the section.

Targets Cambrian–Ordovician boundary, HERB excursion (Furongian) and HSS (top of Cambrian).

Description The strata are overturned at Green Point (**Figure 31**). The deposits of the whole section cover the interval from late Cambrian (Trempealeuan; upper Stage 10, Furongian) to Middle Ordovician (Darriwilian). However, the excursion will examine the well-exposed upper Cambrian (Stage 10, Furongian) and lowermost Ordovician (Tremadoc) strata exposed in the steep cliff.

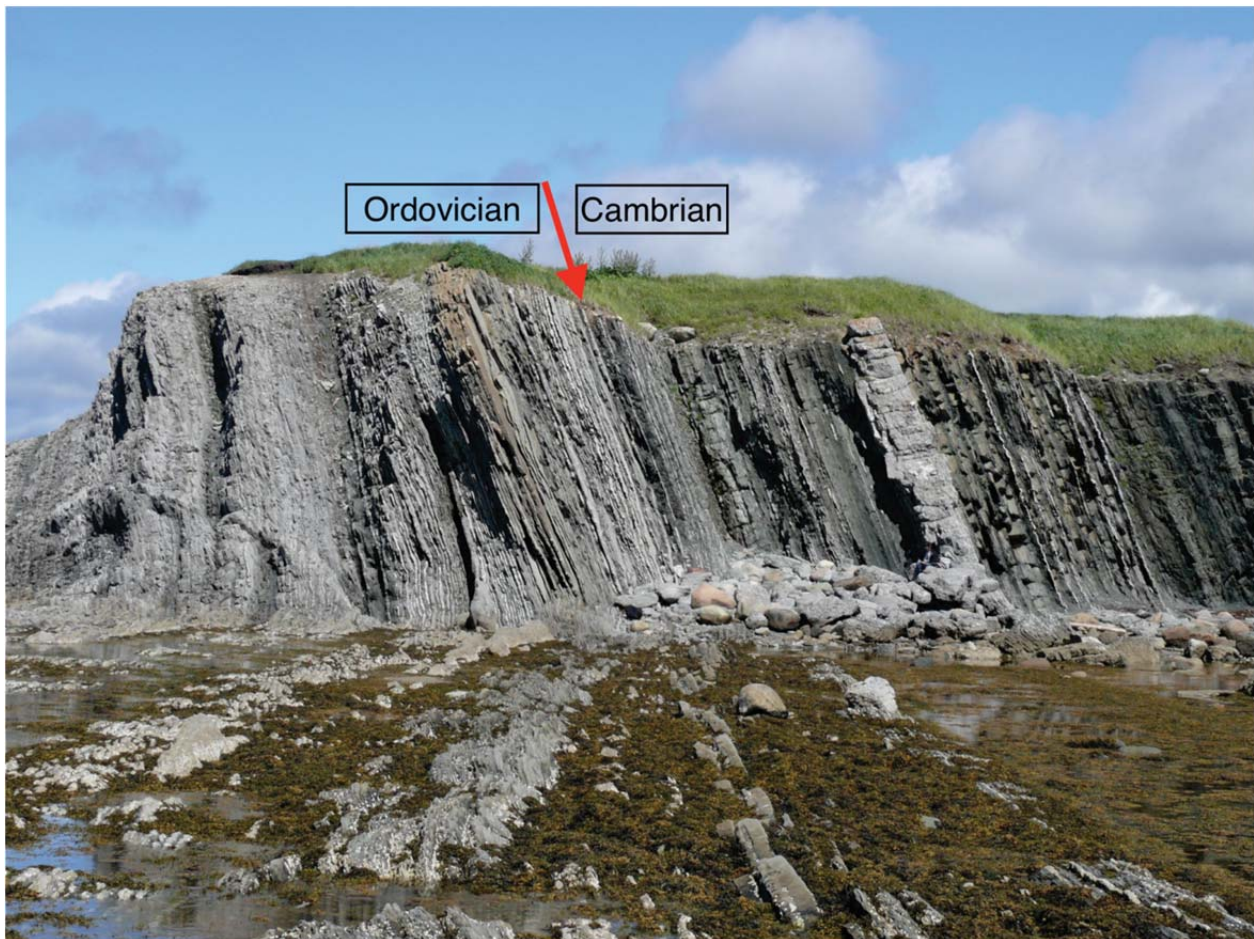


Figure 31. Overview of the Green Point section with overturned strata.

The Martin Point Member consists of green and black shaly mudstones with thin beds of lime mudstone, dolomitic siltstone, and ribbon limestone. Apart from small lenses, the only significant conglomerate bed, is Unit 19, which is 1.1–1.2 m thick. Higher in the section some local slumped horizons are seen (e.g. Units 27, 28).

The Broom Point Member is 82.6 m thick and is fully exposed at Green Point. It consists of ribbon and parted limestones with interbedded grey-green and black shaly mudstones.

The section represents the most distal facies of the Cow Head Group. The strata are referred to the upper Martin Point Member and the lower Broom Point Member.

Zones/age The well-preserved graptolites have made Green Point famous (Figure 32). They range through a 41 m interval in the Green Point section. The early nematophorous graptolites occur both in the shale and are preserved in three dimensions in the limestones. The first nematophorous graptolite, *Rhabdinopora praeparabola*, appears in Unit 25 followed by *Rhabdinopora parabola*. *Anisograptus matanensis* appears high in Unit 26 and just below the FAD of *Cordylodus angulatus* in Unit 27 (Bagnoli *et al.* 1987; Barnes 1988; Cooper, R.A. *et al.* 2001).

The graptolite succession comprises the Assemblages 1, 2A, and 2B of Cooper, R.A. *et al.* (1999, 2001).

Several conodont zones have been established in the section (Barnes 1988; Cooper, R.A. *et al.* 2001; Terfelt *et al.* 2012; Figure 33). Units 17–18 yield very few conodonts but the interval represents *C. caboti* Zone. Below Unit 17 the sedimentary rocks appear to be devoid for any fossils. Blocks from the conglomerate Unit 19 contains *Cordylodus caboti*. The fauna in Unit 22 is from the *C. intermedius* Zone and *C. lindstromi* Zone is present in Unit 23 (Barnes 1998; Cooper *et al.* 2001; Terfelt *et al.* 2012). The *C. angulatus* Zone as mentioned above is first recognized in Unit 27 (Bagnoli *et al.* 1987; Barnes 1988).

Cooper, R.A. *et al.* (2001) characterized the GSSP level within Unit 23 (Figure 34) by the first appearance datum (FAD) of *Iapetognathus fluctivagus*

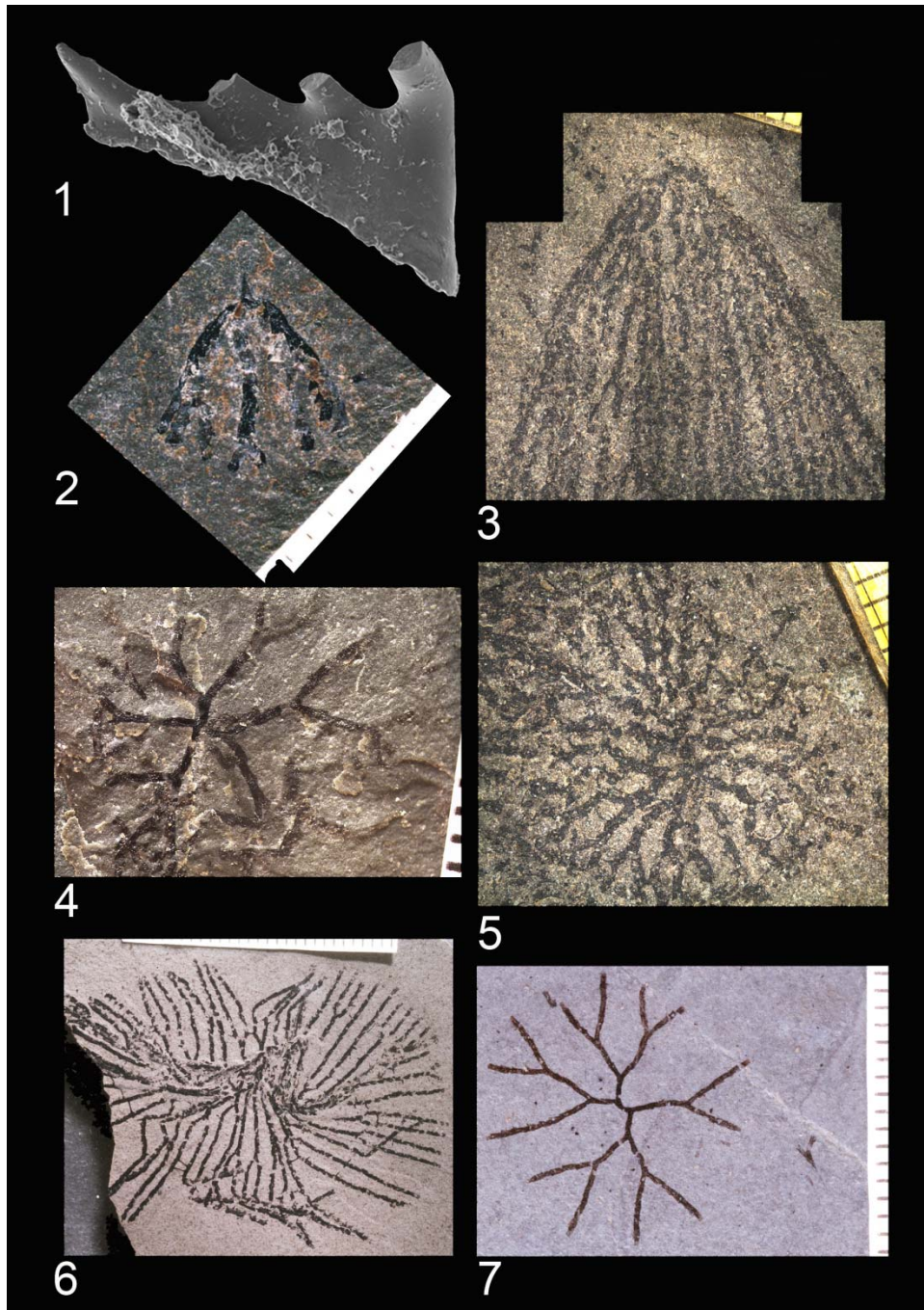


Figure 32. (1) *Iapetognathus preaengensis* sensu Landing (in Fortey *et al.* 1982). Dolobrate multidenticulate Sc element, lateral view. From Unit 23, sample 33 of Barnes (1988); Green Point section, western Newfoundland, Canada. (2) *Rhabdinopora parabola* Bulman, 1954. Green Point section, western Newfoundland, Canada (coll. B.-D. Erdtmann). (3, 5) *Rhabdinopora parabola* (Bulman, 1954). Green Point Section (J. Maletz, coll. and iden.). (4) *Staurogaptus dichotomous* Emmons, 1855. 2 m above small conglomerate in unit 25, Green Point section (J. Maletz, coll. and iden.). (6) *Rhabdinopora flabelliformis anglica* (Bulman, 1950). Green Point section. (7) *Anisograptus matanensis* Ruedemann, 1937. Green Point section (J. Maletz, coll. and iden.).

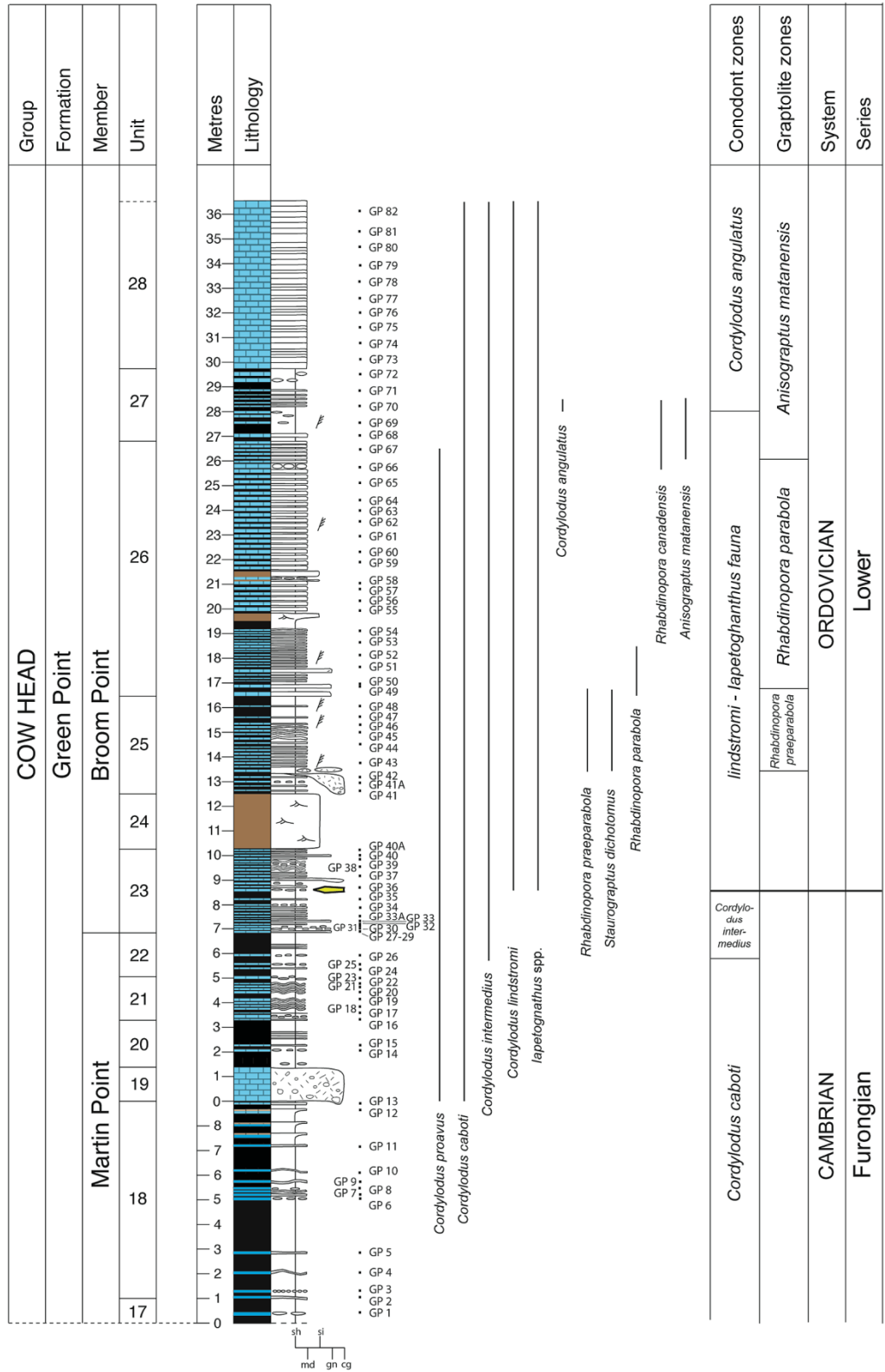


Figure 33. Section, ranges of graptolites and conodonts and zonation of the GSSP section (based on Cooper, R.A. *et al.* 2001).

Nicoll *et al.*, 1999. Terfelt *et al.* (2012) in their study of the Green Point succession reached to a different conclusion and found that the base level in the Green Point section is marked by the FAD of *Iapetognathus preaengensis* Landing (*in* Fortey *et al.* 1982). The first occurrence of *Cordylodus lindstromi* in the section is at the same horizon (Barnes 1988; Cooper R.A. *et al.* 2001; Terfelt *et al.* 2012) and the FAD of *C. lindstromi s.l.* may be taken as a reasonable proxy for the boundary.

The Cambrian–Ordovician boundary is not marked by a physical ‘golden spike’ in the section, but the level and the boundary bed is situated within Unit 23 of the Broom Point Member (Figure 34). The boundary horizon is - as mentioned above - ca. 4.8 m below the first appearance of the pelagic graptolites in Unit 25 (Cooper, R.A. *et al.* 2001).



Figure 34. Close view of top unit 22 to lower unit 23 of the Green Point section. The base of Ordovician is to the left of the photo.

The international correlation - using conodonts - is shown in Figure 35.

Shelly fossils are rare in the Green Point section but also only limited investigations have been undertaken. A lens of conglomerate, 0–0, 30 m thick, in Unit 25 contains *Symphysurina*. This is 0.9 m above the base of Unit 25 and directly below the first appearance of planktic graptolites.

Radiolarians are common in the upper part of Unit 23, Unit 25 and Unit 26 representing the basal Tremadocian *Protoentictinia kuzuriana* assemblage in the section (Won and Iams 2005; Pouille *et al.* 2014). Carrera and Maletz (2014) have recorded sponge spicules from Unit 23 i.e. the lowermost Ordovician from Green Point.

		Laurentia		North China		South China		
System	GSSP	Lawson Cove	Dayangcha		Hunan			
	Slope	Platform	Deep platform		Platform			
ORDOVICIAN	<i>Cordylodus angulatus</i>	<i>Cordylodus angulatus</i>	F a u n a B	<i>Cordylodus angulatus</i> - <i>Chosonodina herfurthi</i>		<i>Cordylodus angulatus</i>		
	<i>lindstromi</i> - <i>lapetognathus</i> Fauna	<i>lapetognathus</i>		<i>Cordylodus lindstromi</i>		<i>C. lindstromi</i> (upper part)- <i>lapetognathus fluctivagus</i>		
<i>Cordylodus lindstromi s.l.</i>		<i>Cordylodus lindstromi</i> (lower part)						
CAMBRIAN	<i>Cordylodus intermedius</i>	<i>Cordylodus intermedius</i>	F a u n a A	<i>Cordylodus intermedius</i>		<i>Cordylodus intermedius</i>		
								<i>Clavohamulus hintzei</i>
	<i>Cordylodus caboti</i>	<i>Cordylodus proavus</i>		<i>Hirsutodontus simplex</i>	<i>Cordylodus caboti</i>		<i>Cordylodus proavus</i>	
				<i>Clavohamulus elongatus</i>				
	<i>Cordylodus proavus</i>	<i>Cordylodus proavus</i>		<i>Fryxellodontus inornatus</i>	<i>Cordylodus proavus</i>		<i>Cordylodus proavus</i>	
<i>Hirsutodontus hirsutus</i>								
<i>Eoconodontus notchpeakensis</i>	<i>Eoconodontus</i>	<i>Cambroistodus minutus</i>	<i>Cambroistodus</i>		<i>Eoconodontus</i>			
<i>Proconodontus muelleri</i>		<i>Eoconodontus notchpeakensis</i>					<i>Proconodontus muelleri</i>	
			<i>Proconodontus muelleri</i>	<i>Proconodontus muelleri</i>		<i>Proconodontus muelleri</i>		

Figure 35. International correlation of the GSSP section (modified from Terfelt *et al.* 2012 and Dong and Zhang 2017).

Geochemistry High resolution $\delta^{13}\text{C}_{\text{carb}}$ isotope curve, almost collected bed by bed, have been constructed (Figure 36) covering the late Furongian and into the Early Ordovician (Azmi *et al.* 2014).

The positive HSS excursion in Unit 22 (Figure 36) is associated with the occurrence of *Cordylodus intermedius*. Up-section follows the Cambrian–Ordovician boundary negative excursion in Unit 23 and at the FAD of *Cordylodus lindstromi* and *Iapetognathus fluctivagus sensu Nicoll et al.* (1999).

The HERB double excursion is seen in the lower non fossiliferous part of the Green Point section. However, the HERB double spike is confidently tied to the base of the *Eoconodontus notchpeakensis* Zone in the Martin Point section (Stouge *et al.* 2016) suggesting that the base of the *E. notchpeakensis* Zone in the Green Point Section is close to the base of Unit 11 in the Green Point section (Figure 37).

An additional negative marker (SFNN on Figure 37) can be matched to many locations. It may represent the subzonal boundary of the *E. notchpeakensis* Zone seen in platform deposits but cannot biostratigraphically be identified in deep-water sections.

Additional negative/positive turnovers below the marker conglomerate Unit 19 are interpreted to represent the bases of respectively *Cordylodus proavus* and *Cordylodus caboti* zones.

Return to bus and drive to hotel.

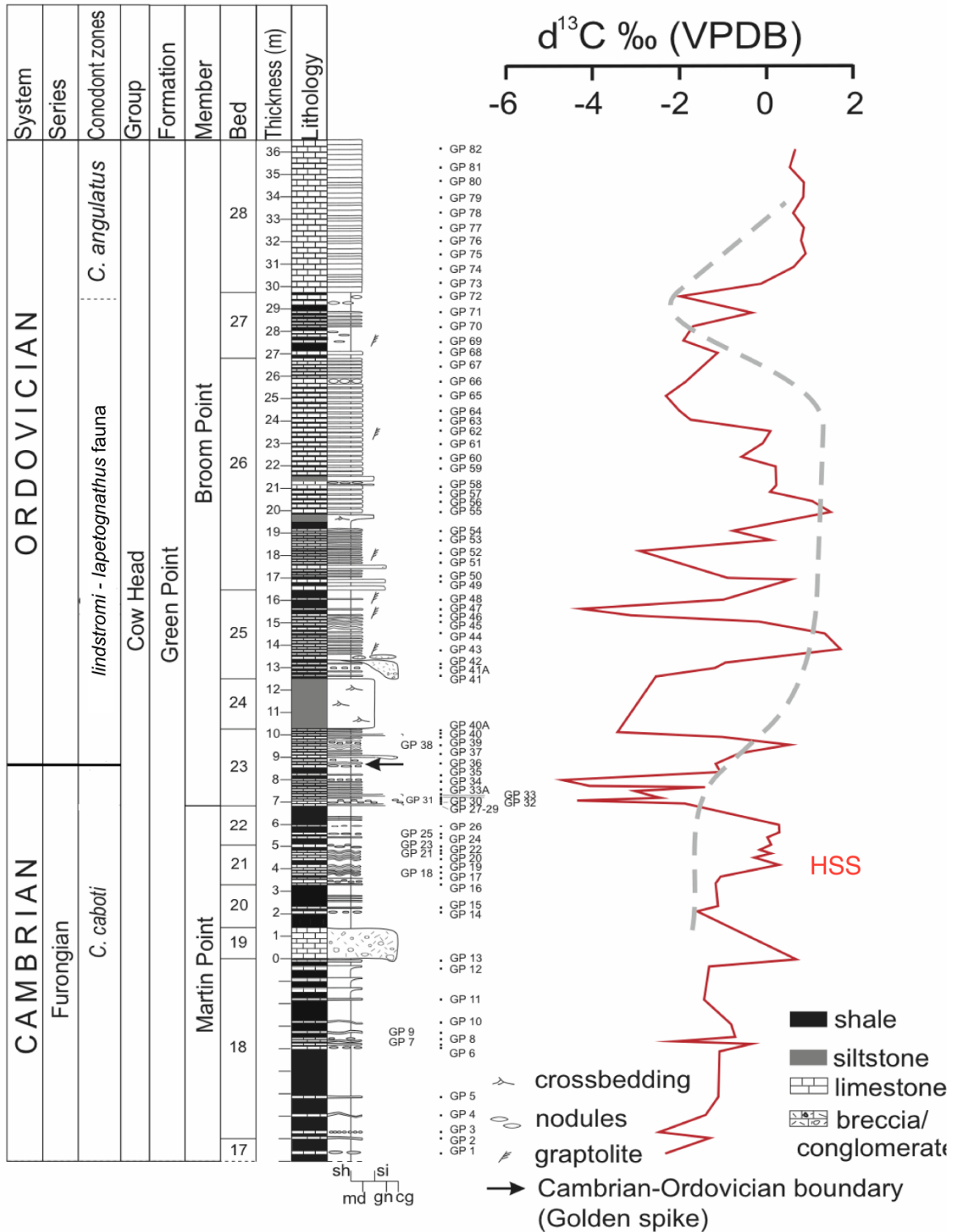


Figure 36. High resolution $\delta^{13}\text{C}$ isotope curve of the Green Point GSSP section. The dashed grey curve is from Nowlan (1995; unpublished).

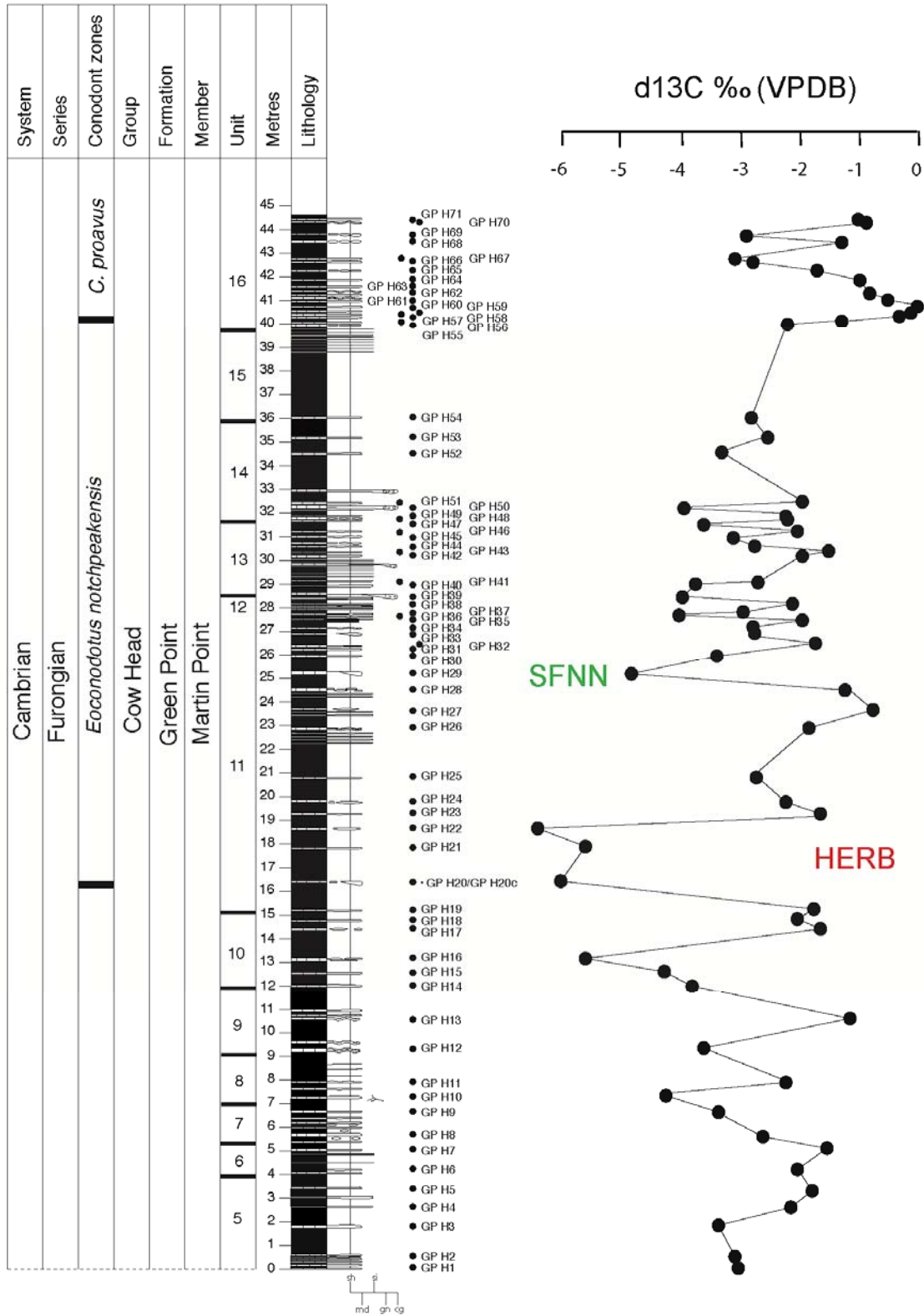


Figure 37. High resolution $\delta^{13}\text{C}_{\text{carb}}$ isotope curve of the lower Green Point GSSP section showing the double negative excursion of HERB.

DAY 6

Stop 14

Note: - **This is within Gros Morne National Park so no collecting/hammering is allowed.**

Martin Point section – Long section starting in Furongian (Cambrian) and concluding in Middle Ordovician.

Location 1 7.6 km to the north of Rocky Harbour. Park at parking space at top of the steep track down to the fishing shacks. Descend the steep track passing the fishing shacks and go the exposed cliff section.

Note: *Walking on the rocks along the shore at this first stop may be difficult due to seaweed and wet slippery rocks.*

Location 2 7 km to the north of Rocky Harbour; access to the main Martin Point section. Park along the roadside. Walk across the field covered by grass and smaller plants and go down the scree to the gravel beach. Walk towards the north along the beach to the point with exposures of Units 15–16.

Note: *It is a strenuous walk on the beach due to the abundance of polished pebbles. Two megaconglomerates extending from the wall and reaching the seawater make crossing of these two conglomerates impossible at high tide, so do not get stuck and be left behind (the tidal cycle is about 12 hours).*

Targets *Location 1:* Base of the Martin Point section. The prominent limestone breccias and conglomerates interbedded with ribbon limestone and some green shale and minor siltstone.

Location 2: Furongian to Lower Ordovician (Tremadocian); type locality of the Martin Point Member. The proposed base of Stage 10 and the C–O boundary are exposed in the section.

History Kindle (1982) provided a brief fauna list from the Martin Point section. James and Stevens (1986) logged the section in detail. William and Stevens (1991) described Tremadocian (Lower Ordovician) graptolites from this section. Won and Iams (2002) and Pouille *et al.* (2014) described excellent preserved radiolarian assemblages from the Cambrian Unit 23 and the Lower Ordovician Unit 36s in the Martin Point section. Conodonts from the overlying Lower

(Floian) to Middle (Dapingian–lower Darriwilian) Ordovician succession were described by Johnston and Barnes (1999, 2000). The $\delta^{13}\text{C}$ isotope curve of the Cambrian into lowermost Ordovician sequence and precisely dated by conodonts is currently under study (Azmy *et al.* submitted).

Description *Location 1: Northern steep wall of Martin Point composed of several conglomerate beds (Tuckers Cove Member).* The cliff exposes numerous chip, plate and boulder conglomerates of the Tuckers Cove Member (**Figure 38**).

The basal exposed beds (Unit 1) of the base of the Martin Point section are exposed in the tidal zone and only seen at low tide. Unit 1 extends into the foot of the cliff. The succession continues up in the steep cliff and the visited beds are referred to Units 2–8 by James and Stevens (1986).

The conglomerates are interbedded with ribbon to parted limestone, shale and siltstone. The massive to thick-bedded conglomerates and breccia beds are laterally inconsistent and can amalgamate laterally, squeezing out the interbedded units composed of shale and ribbon limestone.

Trilobites of zones 6 and 7 have been reported from Unit 3 and Unit 7 (Kindle 1982; James and Stevens 1986). Conodonts (paraconodonts only) are present in the limestone, starting from the base of the succession (work in progress).



Figure 38. Photo of the northern wall composed mostly of conglomerates; trilobite zones 6-7 of Kindle (1982).

Location 2 and south of Martin Point. The succession around the point of the Martin Point extends along the coast towards the south for about 1 km. The succession is a continuation of the cliff section and Furongian and Lower Ordovician strata will be assessed from location 2.

The strata above the conglomerates pass upwards into green-grey shale, siltstone, minor sandstone and ribbon limestone of the upper Cambrian Martin Point Member. The Lower Ordovician Broom Point Member here is succession of ribbon to parted limestones with prominent boulder conglomerates near the top.

Scattered outcrops of the Ordovician sedimentary rocks extend further south along the shoreline. The low cliff tops are shaly mudstone with parted to ribbon limestones and occasional conglomerate horizons (St. Pauls Member). The thin Unit 63 caps the sequence; it is overlain by green sandstones and siltstones of the Lower Head Formation.

Detailed log description

Tuckers Cove Member

Units 8–22 The succession starts from Unit 8 of the Tucker Cove Member and the exposures are followed in southern direction i.e. up-section. The interval is predominated by coarse-grained limestones and conglomerates. Unit 22 is a parted and folded grainstone (**Figure 39**). Trilobite fragments are present in Unit 22.

Unit 23 Exposed in the cave – it is a sequence composed of ribbon to parted limestone, ca. 9 m thick (Figure 39). Unit 23 yields the radiolarian *Subechidnina* assemblage of the Franconian (Won and Iams 2002; Pouille *et al.* 2014).

Units 24–29 Conglomerates and interbedded ribbon limestones (Figure 40). Dendroid graptolites may be found.

Units 30 –32 Conglomerates, limestones, sandstone, shaly mudstones and grainstones (brown weathering, rich in quartz grains). This is the top of Tuckers Cove Member. Trilobites are recorded from the conglomeratic Unit 30 (Kindle 1982; **Figure 40**).

Martin Point Member

Unit 33 Ribbon grainstones succeeded by Unit 34 (0.6 m).

Unit 34 Conglomerate (0.6 m).



Figure 39. Units 22 and 23 at Martin Point; Unit 23 yields radiolarians (Won and Iams 2002; Pouille *et al.* 2014).

Unit 35 Grainstones, conglomerates, rich in quarts, and ribbon limestones (3.2 m). Base of the *Proconodontus muelleri* conodont Zone.

Unit 36 An extensive unit, 140 m thick and composed of mainly black to green shaly mudstones, minor brownish weathering dolomitic shaly mudstones and interbedded limestones and nodular ribbon limestones. Some limestone beds are wrinkled. Deposition is predominantly cyclic. The unit comprises *Eoconodontus notchpeakensis*, *Cordylodus proavus* and *Cordylodus caboti* conodonts zones from Unit 36d to Unit 36n. Unit 36n is a thin conglomerate that can be used as a marker bed within the section.

Unit 36r Unit 36r is 11 m thick and is the top bed of the Martin Point Member. It consists of green-grey shaly mudstone, and beds of wrinkled limestone. The same interval is developed in the same facies at the Green Point GSSP section (Units 20–22), where FAD of *C. intermedius* has been found in Unit 22. The *Hirsutodontus simplex* (HSS) positive spike was first observed in the Dayangcha section of



Figure 40. Photo of Units 29-30. Unit 30 yields Trempealeauan trilobites.

North China (Chen *et al.* 1985), but it can also be identified in the Cow Head Group (Stouge *et al.* 2016, in prep.).

Broom Point Member

Bed 36s Ribbon limestones and minor grainstones. *Rhabdinoplaura 'flabelliforme'* and *Staurograptus dichotomus* representing the basal Ordovician *Rhabdinopleura praeparabola* Zone appears in Unit 36s (Figure 41). This graptolite fauna is equivalent to the graptolite fauna known from Unit 25 at the Green Point GSSP

section (Cooper, R.A. *et al.* 2001), but the interval at Martin Point has not been investigated in the same detail. Conodonts recorded from the grainstone bed at the base of Unit 36s include: *Cordylodus caboti* and *Utahconus utahensis* and several paraconodont taxa.

The radiolarian *Protoentactinia kozuriana* assemblage is recovered from Unit 36s; the same radiolarian assemblage is also found in Unit 23 at Green Point and just above the GSSP horizon (Pouille *et al.* 2014).



Figure 41. Photo of Units 36s and 36t; Unit 36s contains *Rhabdinopora* spp. The Cambrian Ordovician boundary is situated below Unit 36s according to the C isotope curve (see Figure 42).

Age The lower section 1 comprises the basal Furongian (upper Cambrian). Location 2 is Furongian (covering Stage 10) to mid Tremadocian (Lower Ordovician).

Geochemistry The $d^{13}C$ isotope curve of the Martin Point section marks the base of the *Eoconodontus notchpeakensis* Zone where the characteristic 'double-peaked' HERB excursion occurs, which also has been identified from the Green Point (Azmy *et al.* in press).

The *Hirsutodontus simplex* (HSS) spike is recorded from Unit 36r, 2 m below the top of the Martin Point Member (Figure 42). The same positive excursion has

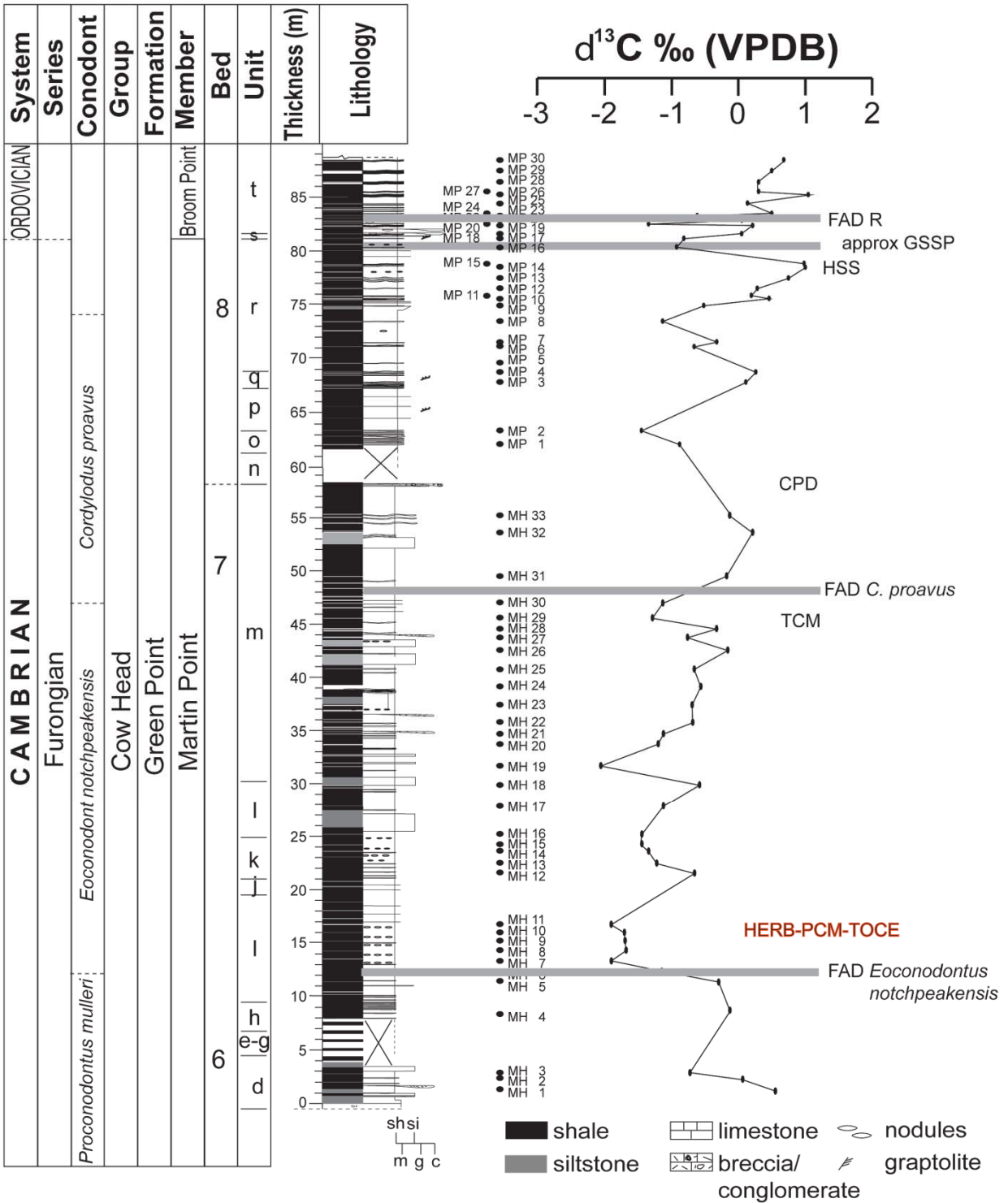


Figure 42. The $d^{13}C$ isotope curve for the lower Martin Point section. The $\delta^{13}C$ isotope curve of the Cambrian into lowermost Ordovician sequence is precisely dated by conodonts. The Cambrian–Ordovician boundary is situated just above HSS.

been found at Green Point section where it is associated with *Cordylodus intermedius*. Hence the top strata of Unit 36r of the Martin Point Member probably represent the *Cordylodus intermedius* conodont Zone in the Martin Point section.

Return to road – however, if time permits a brief stop at the Tremadocian graptolite locality described by Williams and Stevens (1991).

Drive to Deer Lake Airport

Acknowledgments

The financial support from the Carlsberg Foundation, Denmark to Svend Stouge is gratefully acknowledged. Parks Canada and the Staff of Gros Morne National Park are thanked for their support. The support of the Geological Survey of Newfoundland and Labrador (part of the Department of Natural Resource) in printing the field trip guide is gratefully acknowledged.

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