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GEOLOGICAL OVERVIEW AND HYDROCARBON POTENTIAL OF CAMBRIAN–ORDOVICIAN STRATA OF THE OUTER HUMBER ZONE, WESTERN NEWFOUNDLAND

A.M. Hinchey, I. Knight, G. Kilfoil[1] and L. Hicks[2]
Regional Geology
[1]Geophysics, Geochemistry and Terrain Sciences
[2]Energy Branch

ABSTRACT

Naturally occurring hydrocarbon seeps and shows have been documented along the coast of western Newfoundland through the 1800s. Historically, hydrocarbon exploration and drilling have targeted conventional oil and gas resources within Cambrian–Ordovician sedimentary rocks of the western (outer) part of the Humber (tectonostratigraphic) Zone. However, to date, the hydrocarbon potential of western Newfoundland has not been fully evaluated, even though much of the Cambro-Ordovician rocks of the outer Humber Zone reside within the oil-window. Earlier studies described and illustrated a successful petroleum play within the western part of the zone and proposed two petroleum fairways; one extensional, the other inversional, with reservoirs anticipated to be principally in the lower autochthonous Paleozoic shelf rocks.

The Cambro-Ordovician Green Point shale (part of the Green Point Formation, Cow Head Group of the Taconic Humber Arm Allochthon) is the principal source rock for hydrocarbons in western Newfoundland; thick sections of these rocks are known, and have potential as an unconventional shale resource. Previous geochemical studies have shown that the shales are rich in Type BI organic matter of mostly algal origin and Type I/II Kerogen and that the chemistry of its oils are similar to those of the oil seeps and is consistent with a pre-Devonian clastic source rock. Regional geochemistry studies indicate that the shale ranges from thermally immature to mature (possibly ranging up to overmature) and that thermal maturity increases (at surface) from west to east and from south to north (late mature); Green Point shale, occurring north of Parson's Pond, may reside in the gas window.

The Green Point shale was complexly deformed during multiple tectonic events and its distribution, stratigraphy and structure are generally poorly understood. There is no robust model of the subsurface because of limited onshore mapping, the scarcity of well data, and the fine-grained nature of the rocks that make seismic resolution and interpretation difficult. Further study of the stratigraphy, sedimentology, geochemistry, maturity, and mineralogy, together with structural and mapping studies of the Green Point Formation and associated rocks, would lead to a better understanding of the shale's hydrocarbon potential.

INTRODUCTION

Oil has been known on the west coast of Newfoundland since the 1800s and exploration has been ongoing, periodically, for about a hundred years (Figure 1); this exploration (and drilling) targeted conventional oil and gas resources. In the last decade, however, the shales' potential itself is the primary target; producing gas and oil economically from shale is difficult. Unlike conventional reservoirs, unconventional shale resources serve as source rock, reservoir and seal for the hydrocarbons, principally gas, so that very few shale wells can achieve commercial production without stimulation. Those that do achieve economic recovery benefit from significant natural fractures in the shale. Nonetheless, such fields have many vertical wells that produce at low rates over long periods of time *e.g.,* the Antrim Shale, Michigan Basin (U.S. Department of Energy, 2009, 2013). Recent advances in drilling techniques, such as horizontal wells together with innovative methods of stimulating flow in historically 'tight' reservoirs, have propelled a new interest in unconventional resources of hydrocarbons in the shale basins of North America. This interest also includes the west coast of Newfoundland where the target is shale of the Green Point Formation.

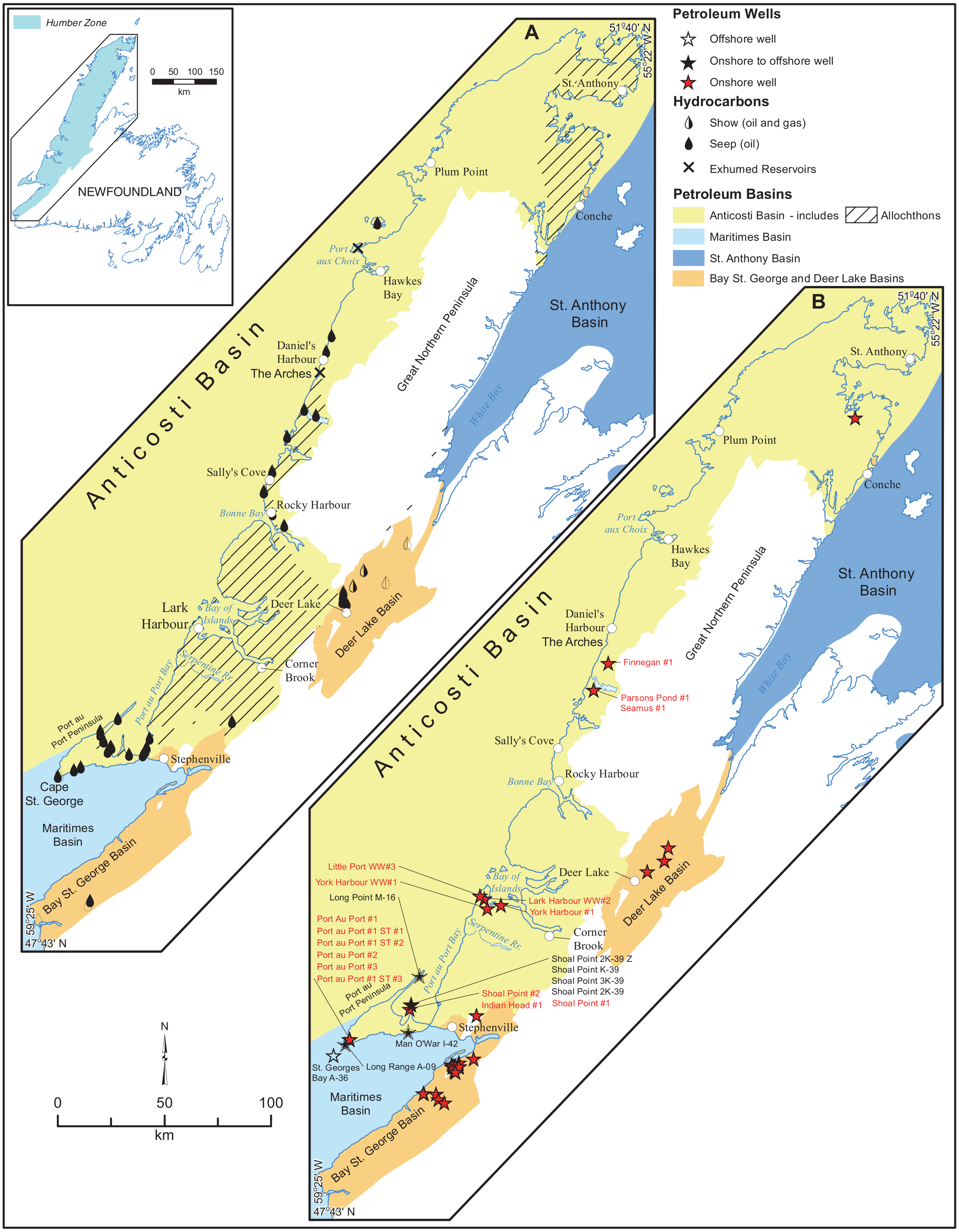

Figure 1. *Onshore and offshore petroleum basins in western Newfoundland displaying* A) *the location of hydrocarbon shows; and* B) *The locations of recent (since 1991) onshore petroleum exploration wells.*

This report addresses the geology of the Green Point shale (part of the Green Point Formation, Cow Head Group) within the context of onshore hydrocarbon exploration in western Newfoundland. The focus on its source-rock potential and its potential as a shale-oil/shale-gas exploration target, centres particularly in the Port au Port area. It is important to note that the term Green Point shale refers to allochthonous Cow Head Group shale in the Port au Port region, which is correlated with the Green Point Formation type section, at Green Point, near Rocky Harbour. The Green Point Formation occurs extensively from Rocky Harbour to Parson's Pond, where it contains significant organic-rich shale associated with other shale units that are not hydrocarbon-rich. It is also projected to occur at depth in the subsea off the west coast of Newfoundland, south of Bonne Bay to Bay of Islands and into Port au Port Bay. In the Port au Port region, the Green Point shale also includes rock types such as organic-poor shale and formations that are not the "Green Point shale *senso-stricto*." Allochthonous rock units such as the Cooks Brook and Middle Arm Point formations that occur many kilometres east of Port au Port Peninsula, near Corner Brook, are interpreted as the lateral equivalent of the Green Point shale and the Cow Head Group (James *et al.*, 1989). Deformed and metamorphosed, they are not relevant to this discussion. This report is an abstracted version of a comprehensive report co-authored by Hinchey *et al.* (2014).

GEOLOGY OF WESTERN NEWFOUNDLAND

MAJOR GEOLOGICAL SUBDIVISIONS

The Humber (tectonostratigraphic) Zone of western Newfoundland formed along the ancient margin of eastern North America about 500 million years ago, and now largely outcrops along the western edge of the Appalachian Mountains from Newfoundland to Tennessee. The focus of this report is on the unmetamorphosed western portion of the external Humber Zone and its adjoining Appalachian foreland.

The geological context of western Newfoundland is based primarily on studies of the federal and provincial geological surveys, and industry and university research, including amongst others, Bostock *et al.* (1983), James and Stevens (1986), James *et al.* (1988a, 1989), Knight (1983, 1994, 1995, 1997, 2013), Knight and James (1987), Waldron and Stockmal (1991), Stockmal and Waldron (1990), Knight and Boyce (1991), Knight and Cawood, (1991), Knight *et al.* (1991, 2007, 2008), Hyde (1995), van de Poll *et al.* (1995), Waldron *et al.* (1998), Waldron and Palmer (2000), Cooper *et al.* (2001), and Williams *et al.* (2001).

The External Humber Zone

The external Humber Zone of western Newfoundland is host to rocks that preserve the history of part of North America's lower Paleozoic (*ca.* 610–390 Ma) continental margin. The region includes six main geological terrains (Figure 2).

Basement Rocks

Precambrian granitic and metamorphic crystalline rocks of the Canadian Shield form the continental basement upon which were deposited sedimentary rocks of the lower Paleozoic continental margin. The Long Range Mountains of the Great Northern Peninsula (GNP), from Gros Morne to Canada Bay, are the principal areas of basement rocks in western Newfoundland; basement is also exposed near Port au Port in the Phillips Brook and North Brook anticlines, is known to underlie the Port au Port Peninsula and Table Mountain structure, and form inliers within the Carboniferous basin just south and east of Port au Port.

Rift Rocks

The continental margin of Laurentia formed with the opening of the Iapetus Ocean between *ca.* 610 and 520 Ma. Volcanic rocks and thick successions of sandstone, shale and conglomerate were deposited in narrow rift-valley basins and oceanic seaways (*e.g.*, the Taconic Seaway *of* van Staal and Barr, 2012) that fringed the formative edge of Laurentia. Thick rift successions of sandstone, shale and conglomerate (now deformed parts of the two Taconic allochthons) are discussed below. Autochthonous, late Neoproterozoic rift rocks (belonging to the lower part of the Labrador Group (Williams and Stevens, 1969; Bostock *et al.*, 1983)) confined to small areas on the GNP are not considered further in this discussion.

Sedimentary Rocks of the Lower Paleozoic Continental Shelf

They include shale, sandstone, limestone and dolostone deposited in shallow, tropical continental shelf seas. The warm shelf sea stretched for over 400 km southwest to northeast and then beyond into Québec and into Greenland and Scotland. The shelf deposits that are about 1.5 km thick were laid down from *ca.* 520 to 468 Ma, a period spanning much of the Cambrian and the Early Ordovician.

Only the inner to middle shelf sequence is preserved in western Newfoundland; the outer shelf and the shelf margin were destroyed or deeply buried during Appalachian orogenesis. Contemporaneous lower Paleozoic sedimentary rocks, deposited on the shelf slope and deep-sea floor are preserved in the Taconic allochthons of western Newfound-

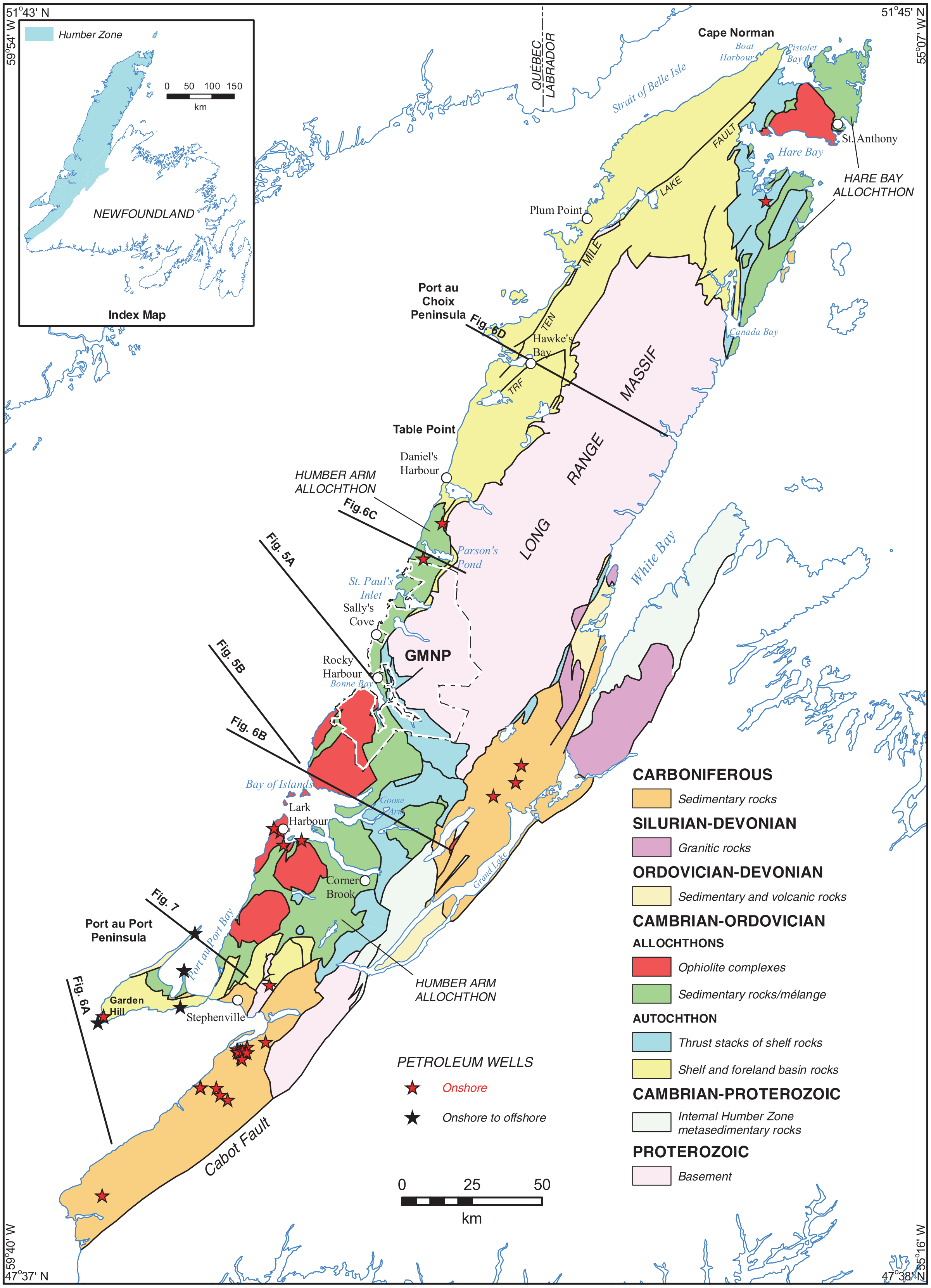

Figure 2. *Simplified geology of western Newfoundland showing the main geological terrains and the location of drilled wells and cross-sections discussed in the text (modified from Knight 2013). GMNP = Gros Morne National Park.*

land. They host, in the conglomerates, eroded blocks of the coeval ancient continental shelf margin that allow its paleo-reconstruction (James, 1981; James and Stevens, 1986). The shelf succession is little deformed except southwest and northeast of Corner Brook, near Deer Lake, Gros Morne, and from Canada Bay north to Pistolet Bay on the GNP. The Cow Head Group (including the Green Point Formation shale) is complexly folded and faulted within the Taconic Humber Arm Allochthon (HAA).

The shelf succession, preserved in western Newfoundland, is divided into three groups: the Labrador, Port au Port and St. George (Figure 3). Lower to Middle Cambrian sandstone, limestone and shale of the Labrador Group were deposited from *ca.* 520 to 510 Ma. They are overlain by a succession of Middle Cambrian to Lower Ordovician carbonate rocks of the Port au Port and St. George groups deposited from *ca.* 510 to 470 Ma. The latter two groups formed a carbonate platform of shallow-water limestone and dolostone deposited in a variety of settings. When sea level was high, the shelf was dominated by fine-grained carbonate mud rich in organisms; extensive barrier complexes of carbonate sand and algal–sponge mounds dominated large tracts of the shelf at various times. When sea level was lower, the succession is characteristically cyclical at a metre scale and consisted of shallow, peritidal rocks deposited on a shallow shelf, in lagoons, tidal flats and islands. Microbial mounds and shoreline carbonate sand bodies were also common along the shallow shoreline.

The St. George Unconformity, which marks the top of the Early Ordovician St. George Group, is correlated with similar sequence boundaries throughout eastern Laurentia as far south as Texas, *e.g.*, Beekmantown and Knox unconformities, and likely marks a global sea-level lowstand at *ca.* 470 Ma. Evidence in western Newfoundland indicates that the shelf top was exposed as the sea fell below the shelf edge, and the earliest events of the Taconic orogeny affected the shelf with the passage of a peripheral forebulge. Consequently, it was extensively faulted and warped prior to, and contemporaneous with, the formation of the unconformity (Lane, 1990; Knight *et al.*, 1991; Baker and Knight, 1993). Significant relief developed on the exposed shelf due to local fault uplift and karst erosion that produced a hilly landscape; cave systems formed in the subsurface, particularly close to faults (Lane, 1990; Knight *et al.*, 1991; Baker and Knight, 1993). Evidence of this relief and of the cave systems occurs on the Port au Port Peninsula, and near Port au Choix and Daniel's Harbour (Knight *et al.*, 2007). Rock formations beneath the St. George Unconformity host reservoirs and are important to the hydrocarbon evolution of western Newfoundland; they include the Catoche and Aguathuna formations of the St. George Group (Baker and Knight, 1993; Cooper *et al.*, 2001).

Sedimentary rocks deposited on the shelf slope and deep-sea floor (described below) are confined to the Taconic allochthons of western Newfoundland (Figures 2 and 3; James *et al.*, 1989).

Foreland Basin Rocks

The western Newfoundland foreland basin is the eastern part of the Anticosti Basin; the succession consists of limestone, shale, sandstone and conglomerate. Like its underlying shelf counterpart, the foreland basin occurs in both the autochthon and allochthon (Figure 3). The autochthonous part comprises a number of unconformity-bounded sequences that widely preserve Middle Ordovician (*ca.* 470 Ma.) strata (Table Head Group and American Tickle Formation, part of the Goose Tickle Group) throughout western Newfoundland. Subsequent pulses of deposition, exposed only on the Port au Port Peninsula but easily correlated seismically westward into the offshore beneath the Gulf of St. Lawrence, occurred in the Late Ordovician (Long Point Group, *ca.* 455 Ma) and again in the Late Silurian (*ca.* 420 Ma, Clam Bank Formation) through to the late Early Devonian (Red Island Road Formation, *ca.* 400 Ma) indicating a prolonged evolution of the basin (Cooper *et al.*, 2001; Quinn *et al.*, 2004; Williams *et al.*, 2001; Waldron *et al.*, 2012). Allochthonous rocks consist of Middle Ordovician clastic flysch and conglomerate of the Lower Head and Eagle Island formations, Goose Tickle Group, that conformably overlie rocks of the Laurentian slope sequences (Quinn, 1996).

The foreland basin was initiated when the Appalachian mountain fold belt first began to form, and oceanic rocks, including rocks from the lower Paleozoic continental slope and sea floor, were thrust up over the shelf margin as several Taconic allochthons. Based largely on interpretation of offshore seismic, the eastern Anticosti foreland basin is interpreted to have a northeast–southwest axis and the basin succession thins to the west and north.

The deeping-upward autochthonous Middle Ordovician succession consisted of a lower carbonate shelf ramp (peritidal to subtidal limestone to slope limestone and shale, Table Head Group) overlain by a deep basinal shale (Black Cove Formation) and a younger clastic flysch (American Tickle Formation, Mainland Sandstone). The succession was deposited following the submersion of the St. George Unconformity as eustatic- and tectonic-driven sea-level rise rapidly drowned the foundering Laurentian margin (James *et al.*, 1989; Stenzel *et al.*, 1990; Quinn, 1996). Common slump folds and scars deforming the succession of fossiliferous, subtidal, ramp limestone and shale of the Table Head Group and bodies of limestone conglomerate and breccia, enclosed within the overlying clastic flysch of the American

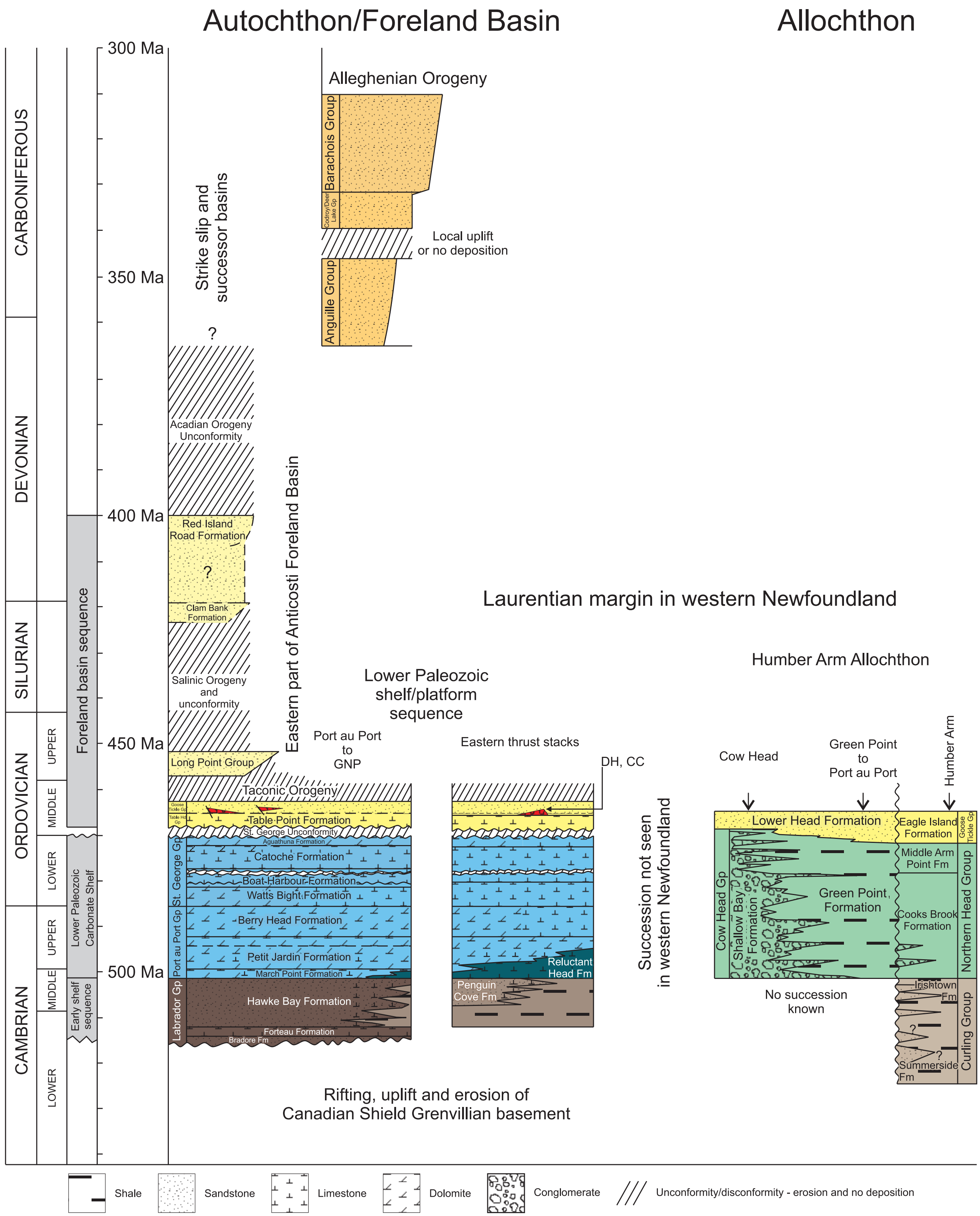

Figure 3. *Simplified stratigraphy of Lower Paleozoic sequences in western Newfoundland (modified after Cooper* et al.*, 2001). DH = Daniels Harbour conglomerate, CC = Cape Cormorant conglomerate.*

Tickle Formation, indicate that tectonism was ongoing throughout the early development of the foreland basin. The limestone conglomerate and breccia was deposited in hanging-wall basins adjacent to active normal faults that uplifted and locally exposed the underlying carbonate shelf as well as, locally, the sub-St. George Unconformity platform to erosion. Such faults were late inverted, *e.g.*, Round Head Thrust (Stockmal *et al.*, 2004).

Black shale of the Black Cove Formation, Goose Tickle Group, is known to be organic-rich, hosts total organic carbon (TOC) of up to 2% and is believed to be gas prone rather than likely to produce oil (Hamblin, 2006). The shale is analogous to, although older than, the Utica Shale of the western Anticosti Basin in Québec and New York State and is a known producer of hydrocarbons in New York and Ohio.

Detritus derived from erosion of the Taconic ophiolites is long noted in the Middle Ordovician and Late Ordovician flysch deposits (Rodgers and Neale, 1963; Stevens, 1970; Quinn, 1996; Waldron *et al.*, 2002). Shale pebbles of Green Point Formation in the allochthonous conglomeratic flysch indicates that underlying Lower Ordovician slope deposits were uplifted and eroded as the flysch was generated; Quinn (1996) also noted the presence of detritus in the Goose Tickle Group flysch that implied sediment was also sourced from a granitic basement terrain.

Taconic Allochthons: Humber Arm and Hare Bay

Allochthonous rocks form the Humber Arm and Hare Bay allochthons in western Newfoundland. The two allochthons consist of two parts: i) lower structural levels consist of sedimentary rocks deposited in rift basins, on the continental shelf slope, adjacent sea floor (*see* below), and during the early stages of the foreland basin (*see* above); ii) ophiolite complexes are emplaced above the sedimentary rocks; they form the Lewis Hills, Blow-me-Down, and other mountain plateaus in western Newfoundland between the Port au Port Peninsula and Rocky Harbour, Bonne Bay and an isolated ophiolite near Hare Bay in the north of the GNP. The sedimentary rocks are grouped together in the Humber Arm Supergroup that includes the Cow Head (*see* below) and Northern Arm groups as well as flysch of the Lower Head and Eagle Island formations.

The Hare Bay and Humber Arm allochthons were tectonically transported up to 200 km from the east in the early Paleozoic to their present locations near Bay of Islands and Hare Bay, GNP (James *et al.*, 1989). The timing of their emplacement is less certain; rock relationships on the Port au Port Peninsula and mineral composition of sandstone in the foreland basin successions (*see* above) have suggested to some that the allochthons arrived close to their present position by the Late Ordovician (*ca*. 455 to 450 Ma); an alternative interpretation is for final emplacement during Middle to Late Devonian (*ca*. 375 Ma; Waldron and Stockmal, 1991). If the early thrusting occurred, the allochthons overrode the foreland basin. If the later timing is accepted then the allochthons thrusting essentially postdates the history of the foreland basin.

Carboniferous Sedimentary Basins

Two Carboniferous sedimentary basins (the Deer Lake and Bay St. George basins) are located onshore western Newfoundland (Figure 2). The Bay St. George Basin extends offshore into the southern Gulf of St. Lawrence where it merges with its parent Maritimes Basin; seismic profiles show the rocks lie offshore off the Port au Port Peninsula. The two sedimentary basins occur along the trace of the southwest-trending wrench system of the Cabot Fault. They contain indications of hydrocarbons and are analogous to Carboniferous basins in New Brunswick that host producing oil and gas fields including shale-gas resources.

DEFORMATION OF THE ROCKS OF WESTERN NEWFOUNDLAND

Newfoundland's Appalachian mountain fold belt is distinguished by three major orogenic episodes: Taconic, Salinic and Acadian (van Staal and Barr, 2012). Subsequently the Alleghenian Orogeny resulted in brittle faulting of the Carboniferous basins, but the Appalachian fold belt in Newfoundland largely escaped the penetrative effects of this orogeny (van Staal and Barr, 2012). The effects of the three major orogenic deformation episodes are discussed below.

The Taconic Orogeny has a long history beginning in the Late Cambrian and culminating in the Late Ordovician (*ca.* 475 to 455 Ma), and the obduction of the Taconic allochthons of the deep sea floor and continental slope to their present position in western Newfoundland (van Staal, 2007; van Staal and Barr, 2012).

The orogeny influenced sedimentation in western Newfoundland from about 478 to 468 Ma, affecting the last deposits of the carbonate platform, and driving the development and infill of the first phase of the eastern Anticosti foreland basin. The deformation of the Taconic HAA occurred when the tectonic slices were transported to their present position off the Port au Port Peninsula to Parson's Pond. Mapping of the Cow Head Group and associated rocks north of Bonne Bay show the succession is assembled into a serial stack of imbricate thrust slices, each consisting of the Cow Head rocks overlain by Lower Head flysch (Williams and Cawood, 1989). The succession is polyde-

Plate 1. A) *A field photograph of the Green Point Formation at Green Point, illustrating the steeply dipping, overturned bedding; and* B) *core photograph of black shale in the Green Point shale from the Shoal Point well 3K39.*

formed and ranges from gently dipping to overturned (Plate 1A) and is folded in many places. The rocks rimming the shores of Port au Port Bay are similarly deformed although mapping, to date, is only at a reconnaissance level (Cooper *et al.*, 2001).

The Salinic Orogeny is Middle to Late Silurian (*ca.* 440–420 Ma). Deformation is best preserved in central Newfoundland (Van Staal and Barr, 2012); however, rocks in the western Newfoundland foreland basin and in the deformed shelf rocks near Corner Brook, Deer Lake and Canada Bay were also affected by this orogenic event.

The Acadian Orogeny of Middle to Late Devonian (*ca.* 393–360 Ma) is recognized throughout Newfoundland and, because it is the youngest of the orogenies, it deformed most rocks in western Newfoundland except those of Carboniferous age. In western Newfoundland, its best known feature are a suite of inversion faults, of which the Round Head Fault on Port au Port Peninsula is a prominent example, as it features in the formation of the Garden Hill Oil Field discovered in 1995.

Carboniferous sedimentary rocks of the Bay St. George and Deer Lake basins were both syndepositional with, and deformed by, repeated Alleghenian wrench movement along the Cabot Fault system. Carboniferous faults also offset lower Paleozoic rocks of the Humber Zone.

THE COW HEAD GROUP AND GREEN POINT FORMATION

Sedimentary rocks, deposited on the lower Paleozoic continental slope, are preserved in the Cow Head Group and are well exposed from Rocky Harbour north to Parson's Pond. The Cow Head Group consists of two lithological end members (Figure 3; James and Stevens, 1986). A succession of limestone and shale dominated by limestone conglomerate, calcarenite and thinly bedded limestone are assigned to the Shallow Bay Formation, and a succession of shale with minor limestone conglomerate, arenite and thin beds to the Green Point Formation; in between these two end members, the slope succession consists of a mixed succession of the two end members (Figure 3).

The conglomeratic limestone was deposited on the lower continental slope adjacent to the continental margin. The limestone was generated by erosion and periodic collapse of the shallow margin itself, when storms, sea-level fall and shelf exposure, and early Taconic tectonism de-stabilized the margin. Boulders and, locally, house-sized blocks of limestone in the Shallow Bay conglomerates were part of the rim of the ancient continental margin. The limestone in the boulders indicates that the margin rim included robust barrier complexes of algal- and sponge-rich reef-like mounds throughout much of the 20 million years the margin existed. The Green Point Formation shale formed the distal foot of the slope and adjacent ocean floor away from the margin edge and in deeper water than the conglomerates; black, organic-rich shale is believed to be the source of the oil known widely throughout western Newfoundland.

The Green Point Formation, formally defined at Green Point near Rocky Harbour (Plate 1A), occurs extensively from Rocky Harbour to the eastern part of Parson's Pond. Shale exposed along the northern shore of the Port au Port Peninsula, and encountered in exploration wells directionally drilled beneath Port au Port Bay (PanCanadian Resources, 1999; Shoal Point Energy Ltd., 2009, 2011), is correlated with the Green Point Formation and informally called the Green Point shale (Plate 1B). The shale is also projected to lie in the deep subsurface off the west coast of Newfoundland from Port au Port Bay north past Bay of Islands to Bonne Bay. The Green Point Formation shale is commonly black and green and contains locally up to 10.4% total organic carbon, making it the principal source rock in the hydrocarbon system in western Newfoundland and a potential significant target for future exploration (Fowler *et al.*, 1995; Cooper *et al.*, 2001; Hamblin, 2006). The succession also includes red and green shale that has no or low hydrocarbon potential and some rare beds of carbonate conglomerate, sandstone and calcareous siltstone, such as that observed along the shores of Port au Port Bay.

The Green Point shale in Port au Port Bay and at Cow Head is generally overlain by thick successions of flyschoid sandstone, conglomerate and shale that were deposited as the foreland basin evolved along the Paleozoic Newfoundland margin. The conglomerates contain abundant shale pebbles derived by erosion of the Green Point Formation.

GEOPHYSICAL SURVEYS

Seismic Reflection Data

Seismic 2-D surveys, commonly utilized until the mid-1990s, are now routinely superseded by large-scale high-resolution 3-D surveys. Sophisticated computer programs can rework 2-D seismic into quasi-3-D models, and this technique has been used in western Newfoundland where 3-D seismic has yet to be attempted (CNLOPB, 2010).

Approximately 12 000-line km of 2-D seismics have been collected, in the offshore of western Newfoundland, since 1969 (Figure 4). Onshore, the approximately 1100-line km of seismic coverage is geographically restricted to the Parsons Pond, Port au Port Peninsula, northern Bay St. George and Deer Lake basin regions (Figure 4). Most of the seismic data was collected in the late 1980s to mid- 1990s, and is not up to modern standards.

It was the earliest 2-D seismic data collected offshore Port au Port Peninsula, and interpreted by Stockmal and Waldron (1990) that refocused exploration attention on western Newfoundland. Seismic data, from lines collected by Hunt Oil Company in the early 1990s illustrate the nature of the Appalachian structural front described by Stockmal and Waldron (1990; Figure 5). All the images show three sets of reflections: i) a lower set of parallel reflections interpreted as basement rocks overlain by lower Paleozoic shelf and Middle Ordovician foreland basin rocks that dip consistently to the east; ii) an upper set of parallel reflections interpreted as the Late Ordovician to Devonian foreland basin rocks which are tilted steeply to moderately to the west and are locally folded; and iii) a middle, wedge-shaped set of discontinuous, ambiguous internal reflections devoid of marker beds which is interpreted as the HAA (*see* also Rowe, 2003). This interpretation of the wedge-shaped set of

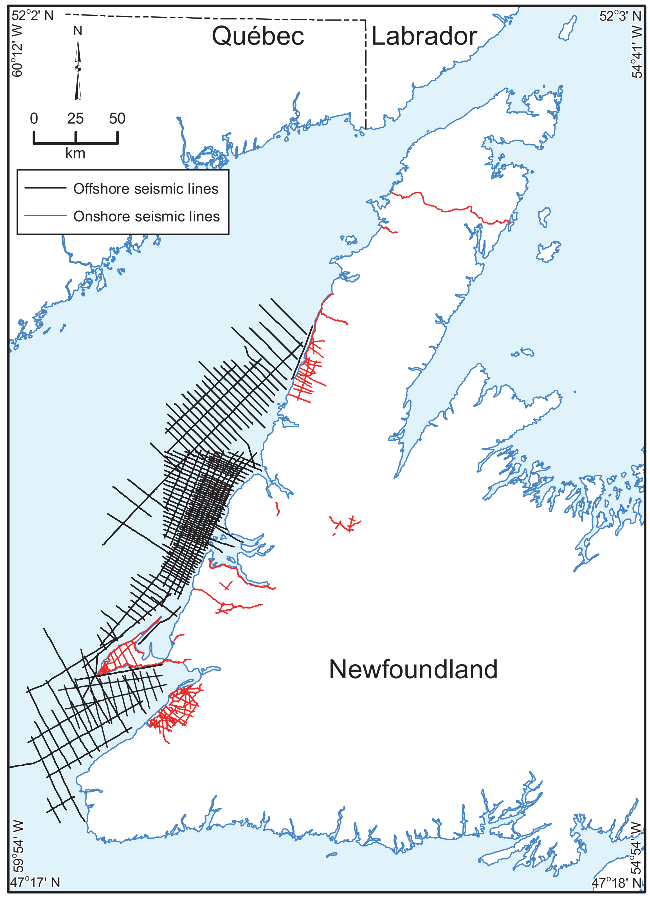

Figure 4. *Distribution of seismic lines, onshore and offshore, western Newfoundland.*

discontinuous, ambiguous internal reflections being part of the HAA is confirmed by drilling at Shoal Point (PanCanadian Resources, 1999; Shoal Point Energy Ltd, 2009, 2011). The contact of the upper set of reflectors with the HAA is interpreted as the Tea Cove Thrust.

The three-part seismic package outlined above can be traced widely in the offshore from south to north, and although the seismic lines terminate short of the west coast, the offshore geology is projected onshore as shown in a series of regional cross-sections (Figures 6 and 7; Cooper *et al.*, 2001). To the west, the allochthonous package extends below Long Point and is seismically imaged beneath the overlying Carboniferous strata. Although the seismic data shows no regional seismic markers and an extremely discontinuous structure in the HAA (Figures 8 and 9; Rowe, 2003), it does, however, allow for the calculation of the overall thickness of the allochthonous package within the Port au Port Bay area. The style of folding and faulting of the shale in outcrops around the shores and inland of Port au Port Bay is thought to provide a good guide to the deformation that likely occurs in the subsurface (Figure 9).

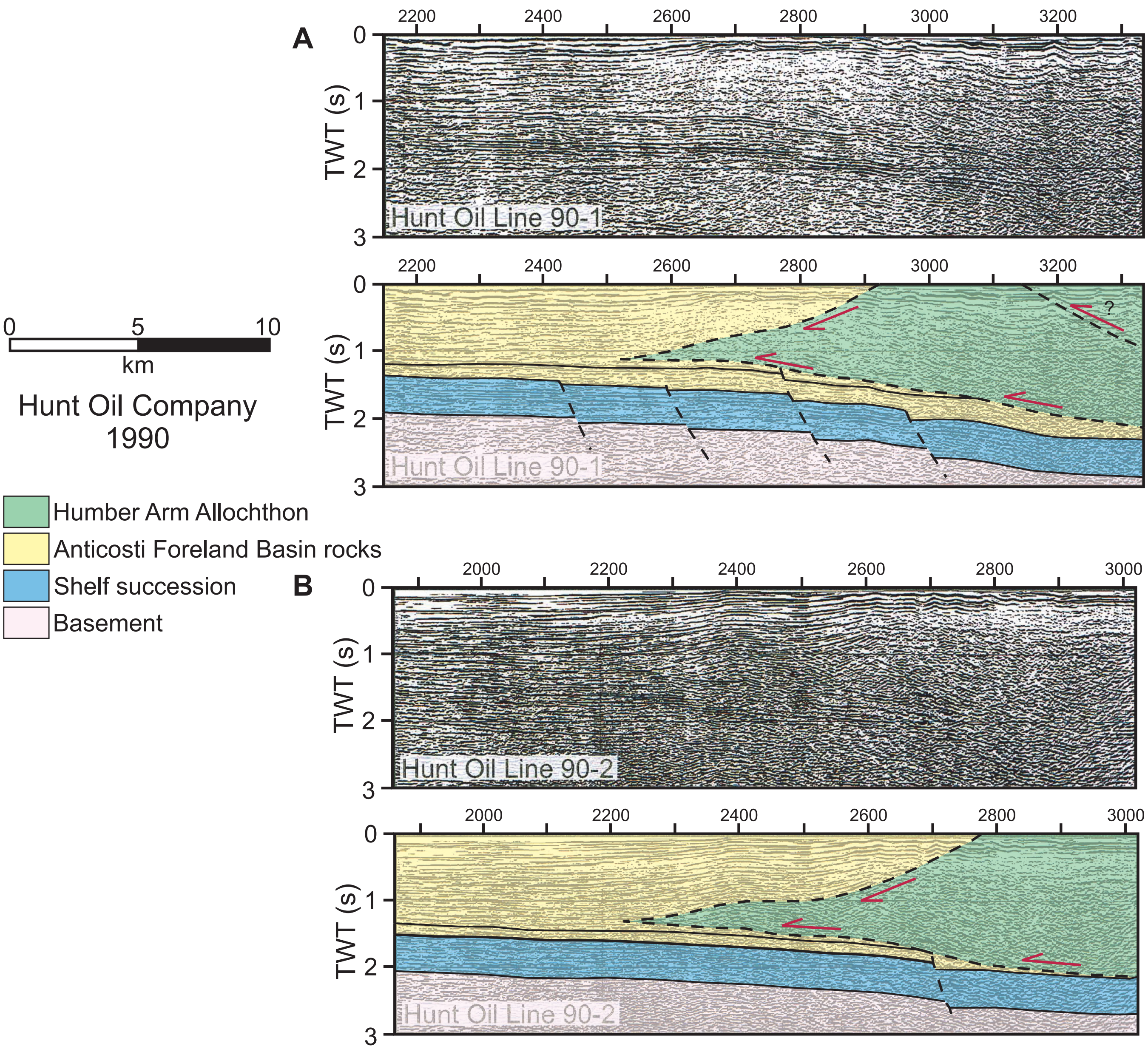

Figure 5. *Interpreted cross-sections that show the presence in western Newfoundland of a tectonic triangle zone. The locations of the seismic lines are shown in Figure 2. Seismic cross-sections of western Newfoundland, 1990 data. The upper 3 seconds of data are approximately equivalent to 6 km in depth. TWT(s), two-way travel time in seconds. Based on 1990 seismic data acquired and migrated from Hunt Oil Company. The figure is modified from Stockmal* et al. *(1998).*

In general, seismic lines within Port au Port Bay to Parson's Pond reveal very few features that can be reliably followed for any distance within the sedimentary rocks of the HAA (Figures 8 and 9). This may be due to the following factors:

1) The succession comprises alternating thin and laterally discontinuous beds of sandstone, shale and limestone and lacks good marker horizons having significant seismic contrast;
2) The complex internal structure of the HAA, reflecting its deformation and structural history within the Bay of Islands area; and
3) Steeply dipping reflectors are poorly imaged by the 2-D seismic surveys.

Because the available seismic data does not image the HAA or the Green Point shale effectively, this impedes the formulation of an effective structural model of the allochthon in the subsurface. A new seismic program in the region would greatly improve the ability to predict and

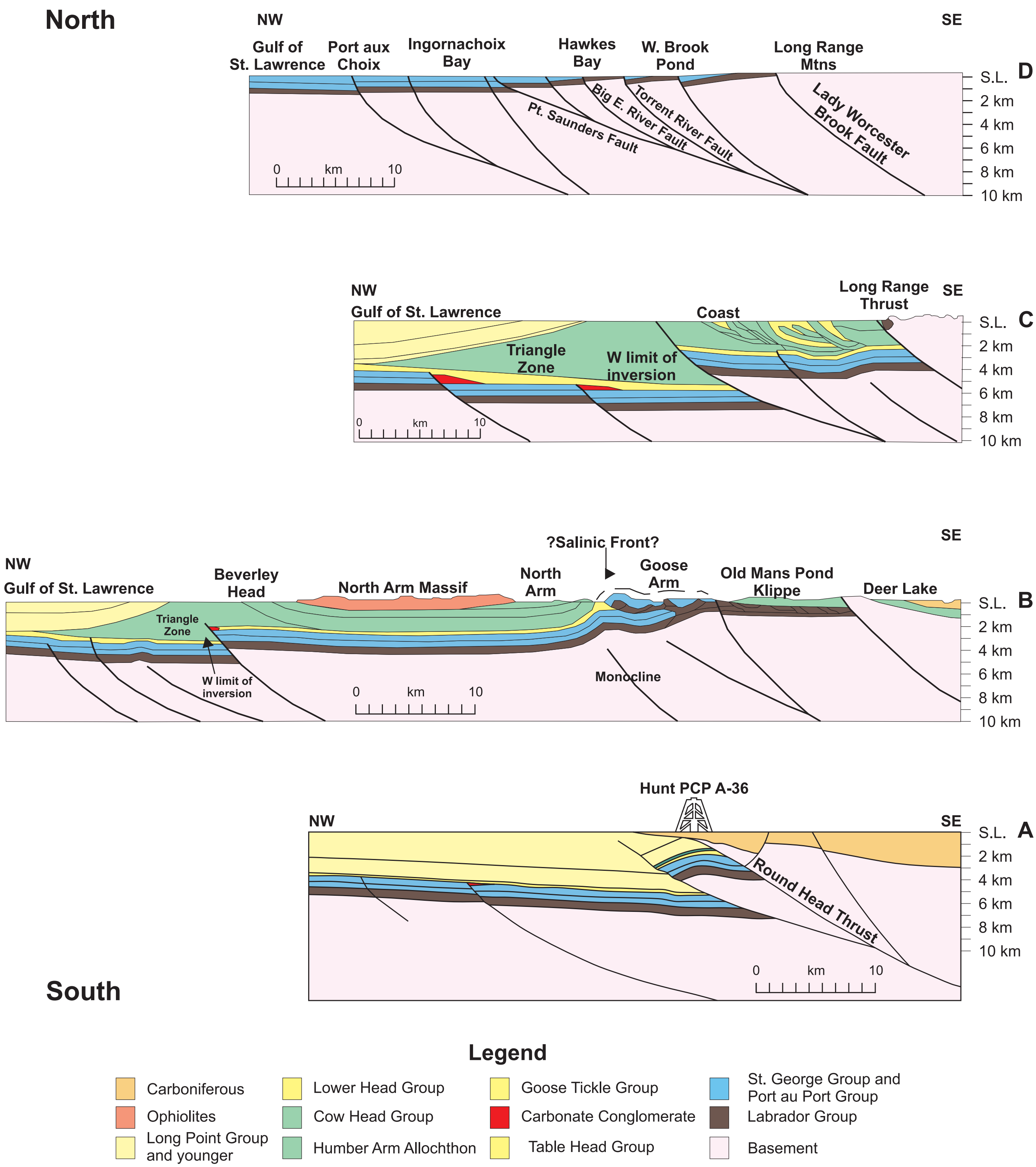

Figure 6. *Regional cross-sections through the western Newfoundland illustrating variations in structural style from north to south (from Cooper* et al.*, 2001). Location of sections is plotted in Figure 2.* A) *The southmost section, highlights the truncation of Acadian thrusts by the Carboniferous Bay St. George Basin;* B) *Cross-section shows the deformation and stacking of the main structural elements of the western part of the Humber Zone near Bay of Islands;* C) *Complex folds and imbricated thrust slices deform the Humber Arm Allochthon in the Parson's Pond area (a possible analog for the Port au Port area); and* D) *Most northerly section marked by thick-skinned faulting (*see *Cooper* et al.*, 2001 for further interpretation).*

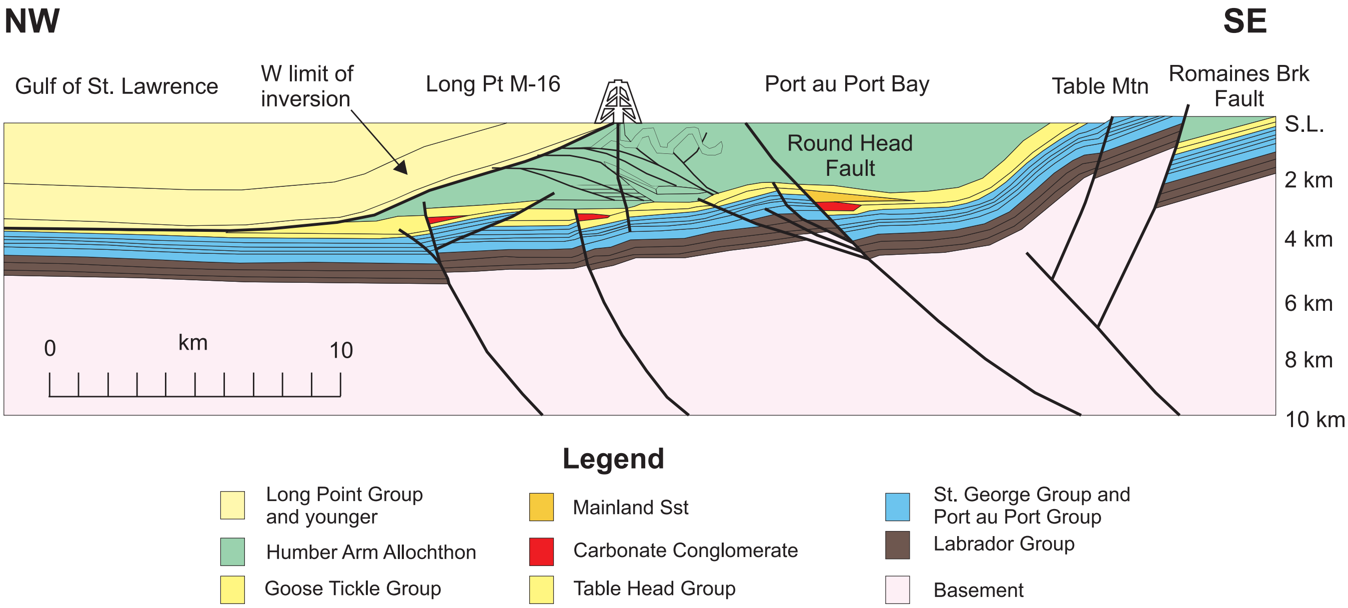

Figure 7. *Structural cross-section through Port au Port Bay, showing the location of the Long Point M-16 well. The section is based on interpretation of well data, seismic data and surface geology, line location is in Figure 2 (from Cooper* et al.*, 2001).*

model, a) location of the Green Point shale, b) internal variations in composition of the HAA, and c) regional deformation and faulting.

A grid of seismic lines over the eastern Gulf of St. Lawrence immediately west and northwest of Port au Port Peninsula (Figures 4 and 8) show a simple layering of sediment stratigraphy in the eastern Anticosti Basin (Figures 6, 7 and 9). Several, strong, nearly horizontal seismic reflectors in the shallower part of the basin can be reliably mapped from one seismic line to the next throughout the basin. The seismic data shows that the basin shallows to the north and west and that successively older sedimentary units have been eroded as they are exposed or subcrop on the seafloor.

Aeromagnetic Field Data

Recent, detailed aeromagnetic surveys, conducted in both onshore and offshore western Newfoundland in 2009 and 2012, respectively (Figures 10 and 11), provide an aeromagnetic geophysical framework to define basement and basin, and underpin new geological models for oil and gas exploration. The most obvious features on the aeromagnetic maps are several high aeromagnetic anomalies that form the southwestern extension of an arcuate belt of ophiolitic rocks mapped onshore in Bay of Islands (Figures 10 and 11); the large blocks are interpreted as the Bay of Islands ophiolites (Figure 11). Several large blocks with typical highly magnetic and variable signatures in Port au Port Bay are also interpreted as ophiolitic rocks, one of which is mapped on Fox Island in the eastern part of the bay (Figure 11). There also appear to be many smaller ophiolite blocks scattered throughout the bay and its shoreline, within rocks presently mapped as HAA sediments. From their magnetic signature, these ophiolitic rocks are probably situated near surface, at or below the seafloor. Their strong magnetic pattern indicates that there may be two ophiolite trends, separated by a distinct break. Interestingly, several seismic lines of a 1996 program crossed directly over some of the large potential ophiolite blocks, but showed little or no expression even though density and seismic velocity contrast would be expected at the interface between these crystalline rocks and encompassing HAA sediments.

Aeromagnetic data in the Port au Port Bay area imaged the subsurface in contrast to the poor-imaged seismic surveys. For example, several northeast–southwest to north–south-oriented faults, cutting carbonate platform rocks on the Port au Port Peninsula, can be traced for some distance into Port au Port Bay using the aeromagnetic data (Figure 11). Although some of these faults cannot be mapped with confidence within the overlying HAA rocks onshore, it is possible to map strong linear magnetic north–south features in East Bay, and to project the Piccadilly Bay Fault northward dissecting Port au Port Bay as proposed by Stockmal *et al.* (2004). The magnetic data, however, also suggests that the structure within the bay may be more complicated than previously shown because it reveals several, previously unrealized faults of similar orientation to the Piccadilly Bay Fault.

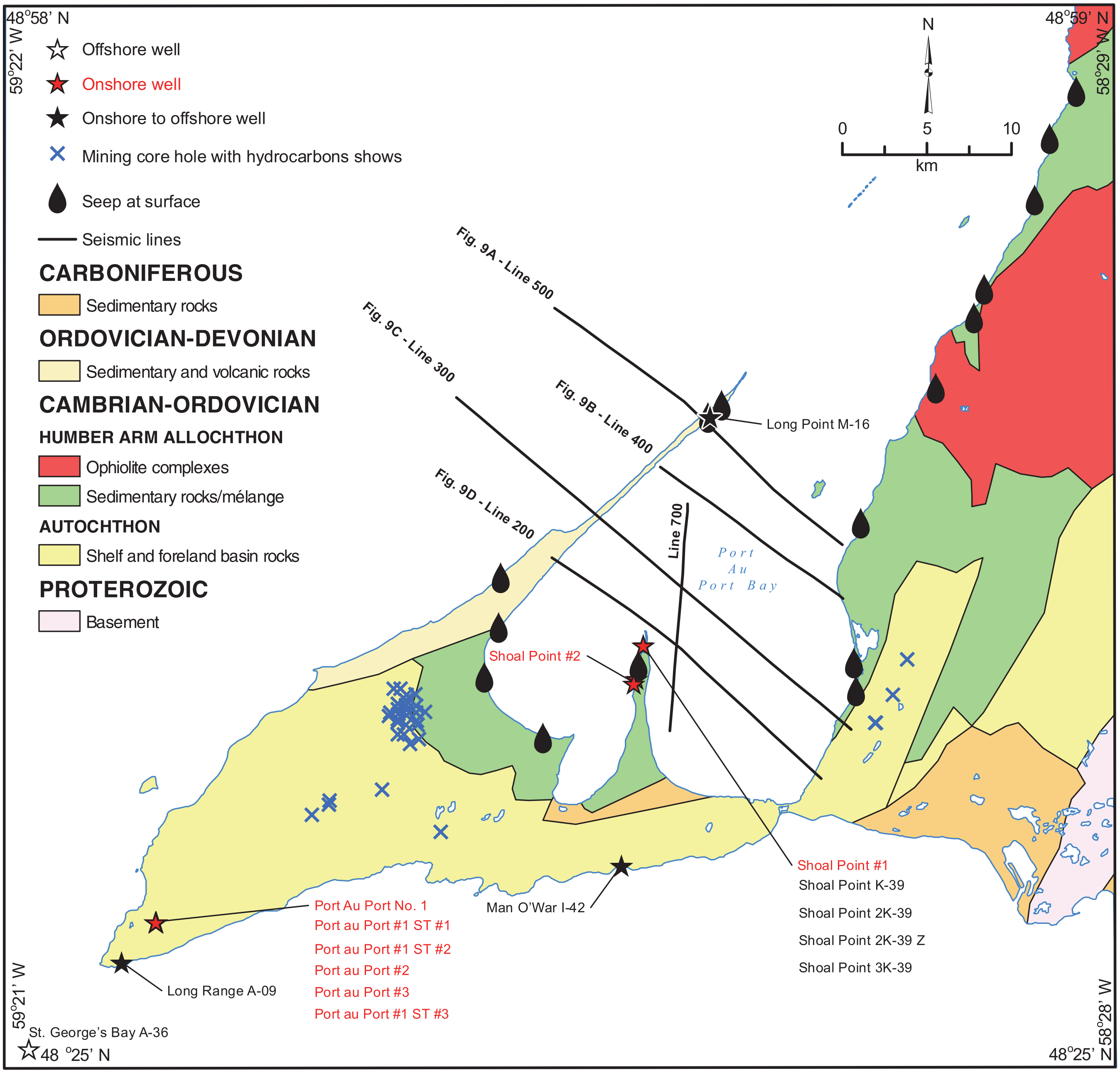

Figure 8. *Geology map of the Port au Port Peninsula showing the locations of known surface oils, seeps and shows, mining core holes with shows and petroleum wells with shows (modified after Knight, 2013). Cross-sections illustrated in Figure 9 are also shown.*

Aeromagnetic Data of the Eastern Anticosti Basin

Based on the offshore aeromagnetic surveys, the near seafloor sediments in the basin, imaged as a series of bands of low-magnetic susceptibility, alternating with ones of slightly more magnetic susceptibility, strike east–west to northeast–southwest. Only along the eastern margin of the foreland basin are the rocks deformed significantly, where they are in contact with the HAA. Approaching this contact, foreland basin sediments are warped up such that the strata strike north-northeast and dip steeply to the west-northwest as observed along Long Point, Port au Port Peninsula. Several parallel, north-northeast-trending magnetic trends can be observed in the magnetic data, from Long Point into the offshore as far north as the mouth of Bonne Bay. Two relatively strong magnetic markers named the Odd Twins Anomaly coincide with two units of sandstone, rich in magnetic mineral sand grains (Figure 10; Waldron *et al.*, 2002).

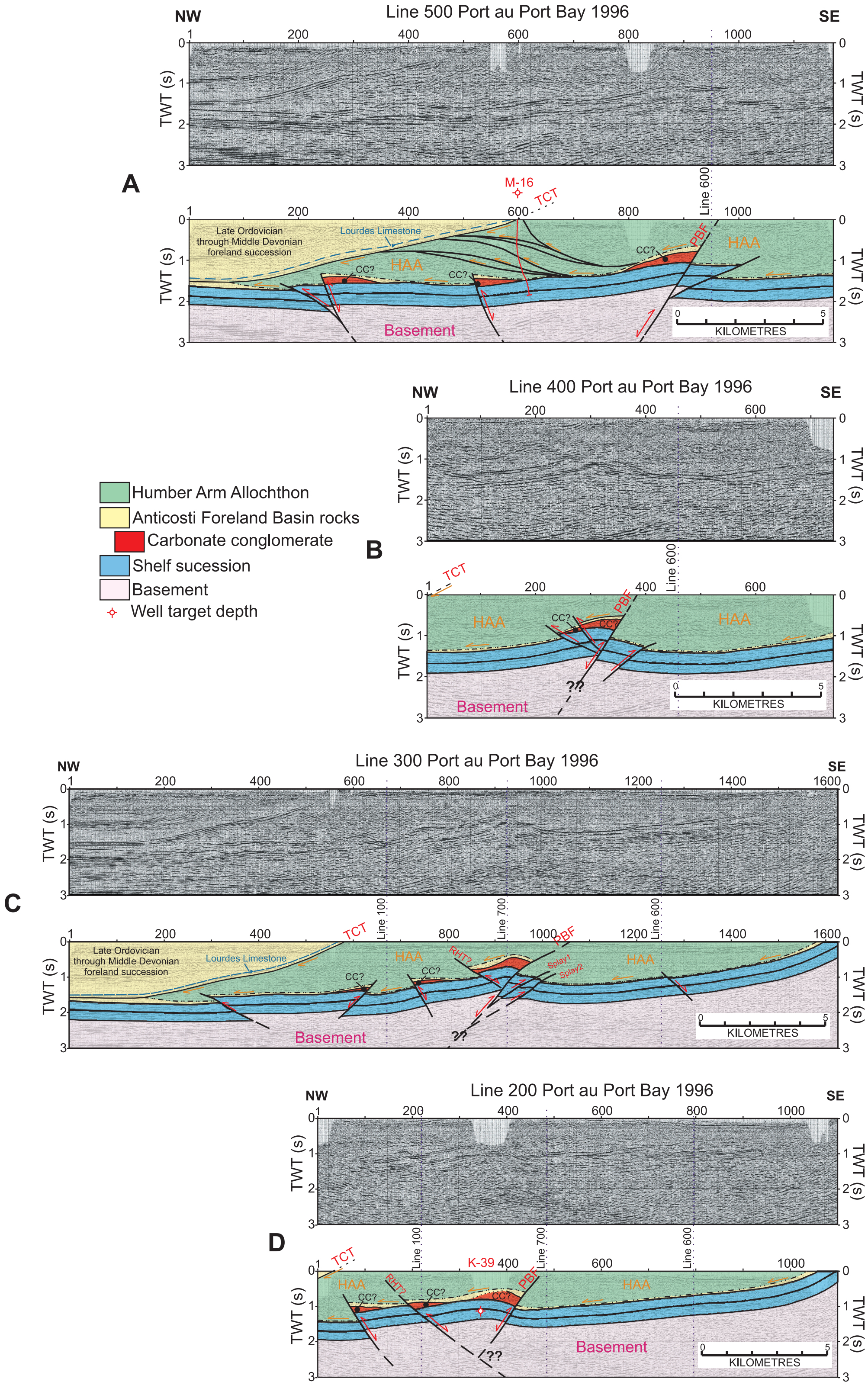

Figure 9. *Geological cross-sections based on uninterpreted 1996 seismic data in Port au Port Bay acquired and migrated from Hunt Oil of Canada Ltd (figure from Stockmal* et al., *2004); only the upper 3 s of two-way travel time (TWT) data are shown. CC – Cape Cormorant Formation; HAA – Humber Arm Allochthon; PBF – Piccadilly Bay Fault; RHT – Round Head Thrust; TCT – Tea Cove Thrust; VBF – Victors Brook Fault. The locations of the lines are plotted in Figure 8.*

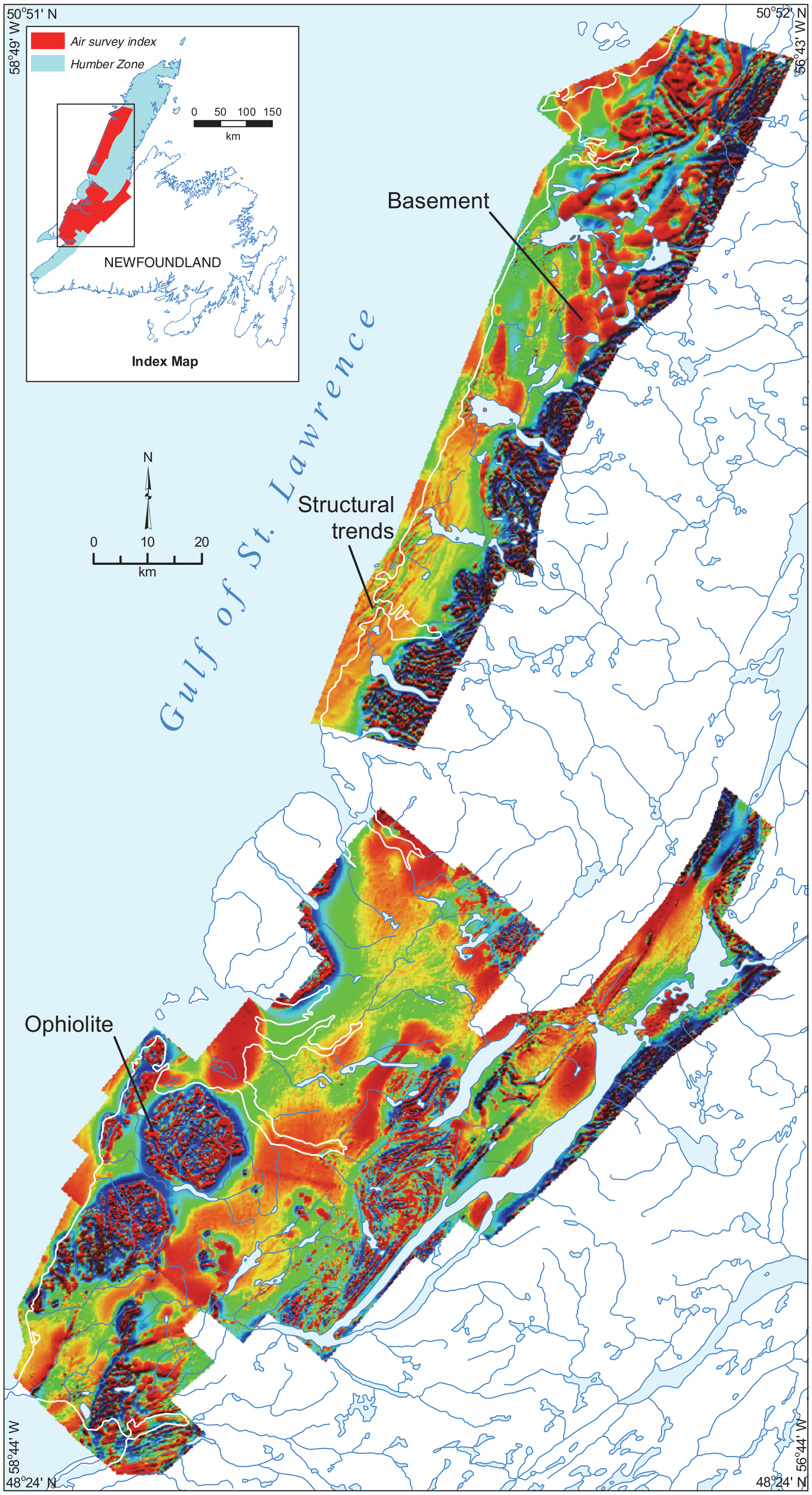

Figure 10. *Regional geophysical map of the first vertical derivative of aeromagnetic data in onshore western Newfoundland flown in 2009 and 2012.*

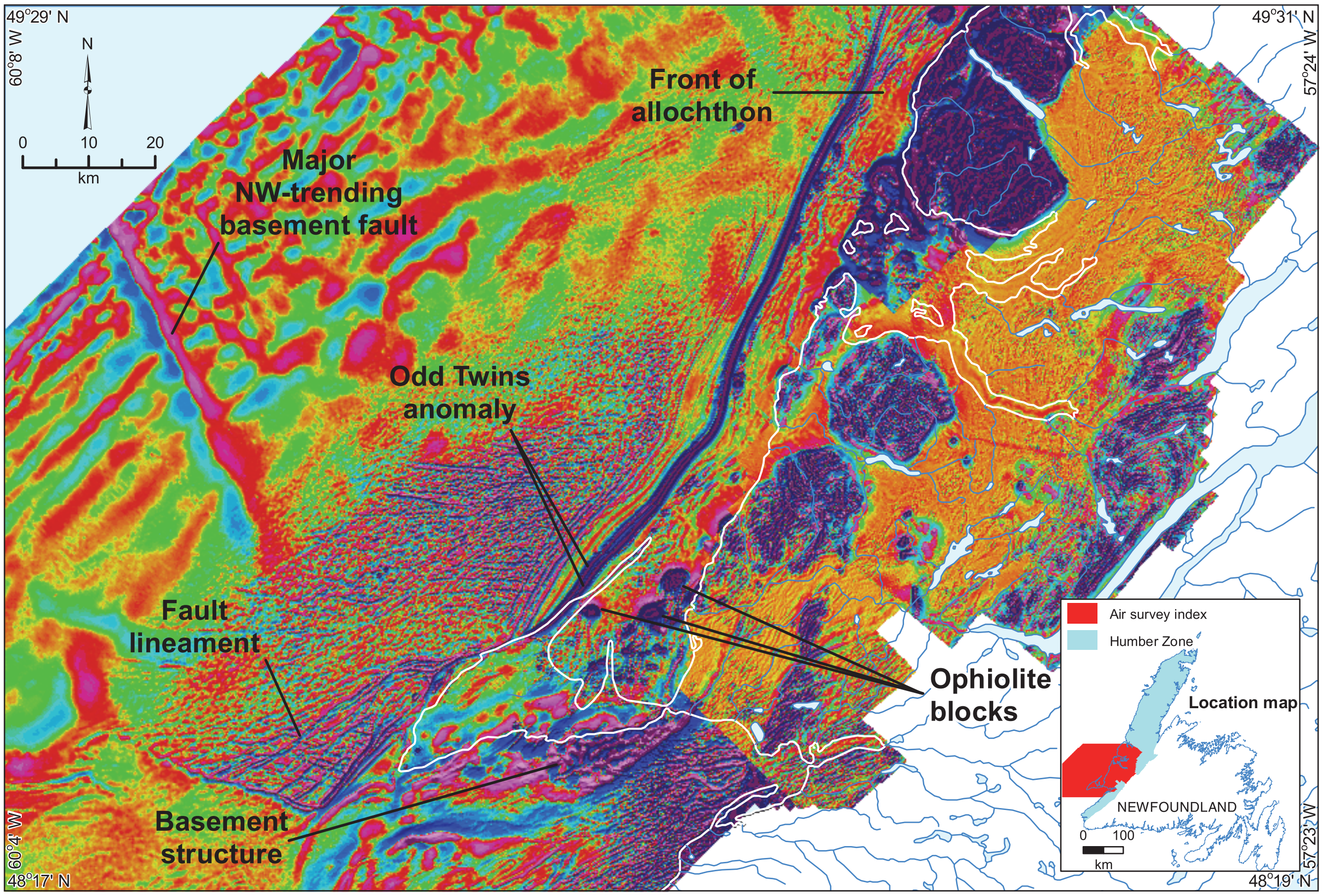

Figure 11. *Regional geophysical map of the second vertical gradient flown onshore to offshore from south and west of Port au Port Peninsula to Bay of Islands.*

The two parallel magnetic markers separate and bifurcate near Bonne Bay suggesting the deformation of the foreland basin sediments along the Appalachian Front may have a northern limit. A weaker magnetic linear parallel to, but just east of the anomaly, defines the approximate trace of the Tea Cove Thrust, which juxtaposes the deformed edge of the Anticosti Basin sediments with the HAA (Figure 11).

In summary, 2-D seismic data show that the simpler stratigraphy of the eastern Anticosti Basin and the underlying carbonate rocks of the autochthonous platform beneath and west of Port au Port Bay contrasts strongly with the opaque, essentially non-reflective rocks of the adjacent, strongly deformed HAA. However, even though the structural architecture of the HAA has been interpreted using the seismic data (Stockmal *et al.*, 2004), high-resolution aeromagnetic data can be used to better define the near-surface geology where seismic data is inadequate. Magnetic data indicate the Bay of Islands ophiolites continues beneath much of Port au Port Bay and several northeast- to north-oriented faults can be mapped from onshore into the offshore.

HYDROCARBON RESOURCES OF WESTERN NEWFOUNDLAND

EXPLORATION HISTORY

Historical Petroleum Exploration (Pre-1994)

Although hydrocarbon seeps have been noted in western Newfoundland since 1812, oil collected from seeps along the shore of Parson's Pond in the 19th century and many shallow wells drilled in rocks of the HAA at Parson's Pond, St. Paul's Inlet and Shoal Point (for a summary of this history *see* Fleming, 1970; Fowler *et al.*, 1995; Hicks, 2005), it was only in the 1990s that an exploration program was launched in western Newfoundland. The first historical documented well was drilled to 700' (213.4 m) on the south shore of Parson's Pond in 1867; it reportedly encountered oil and gas. The second successful well was drilled in 1895 and numerous additional wells followed until 1925 (Fowler *et al.*, 1995) when up to four wells were in production at one time during the 1920s.

Oil seeps were first described by J.P. Howley at Shoal Point, Port au Port Peninsula in 1874 and several wells drilled there from 1898 to 1901 are said to have produced up to 20 barrels per day (*i.e.*, 3.18 m^3). It was 40 years later before Golden Eagle drilled two wells on Shoal Point (Shoal Point #1 and 2, *see* Figure 8) in 1965. Shoal Point #1 well encountered limited porosity and cuttings exhibited only minor to trace amounts of oil staining and fluorescence (Hicks *et al.*, 2010). Shoal Point #2, however, penetrated numerous zones with live and dead oil shows (Fowler *et al.*, 1995).

Additional historical information can be found in reports by Fleming (1970), Newfoundland and Labrador Petroleum Directorate (1982), Newfoundland Department of Energy (1989), Newfoundland Department of Mines and Energy (2000), Fowler *et al.* (1995) and Hicks *et al.* (2010) and Newfoundland and Labrador Department of Natural Resources (2008).

Recent Petroleum Activity (1994–2013)

Renewed interest in the hydrocarbon potential of western Newfoundland followed the publication of vintage, poor-quality offshore seismic data by Stockmal and Waldron (1990) at the same time two comprehensive field workshops in western Newfoundland led by geologists of Memorial University and the Geological Survey of Newfoundland and Labrador (GSNL) (James *et al.*, 1988b; Knight and Cawood, 1991) showed the region to researchers and petroleum geologists. Stockmal and Waldron (1990) defined a structural triangle zone in western Newfoundland similar in character to that known in the foothills of the Rocky Mountains of Alberta. The workshops presented for the first time a comprehensive field study of the lower Paleozoic sedimentary rocks of western Newfoundland and showed that the area included all the elements favourable for an oil play, namely reservoir rocks, source rocks and suitable structures in which to trap hydrocarbons.

It was Hunt Oil of Canada who pioneered seismic surveys on the Port au Port Peninsula and in the offshore Gulf of St. Lawrence that showed the presence of large, potential structural traps. The first well, Port au Port No 1, tested a deep onshore structure at Garden Hill, north of Cape St. George, Port au Port Peninsula. The well struck oil and gas at 11 000' (3553 m) after drilling through more than 1900' (579 m) of crystalline basement rock above the Round Head Thrust and another 2200' (670 m) of barren shale and sandstone below that sealed an anticline of lower Paleozoic carbonate rocks in which hydrocarbons were trapped. Recent petroleum wells located in western Newfoundland (*see* Figure 1B) are listed in Table 1.

Exploration concentrated on the Cape St. George area, Shoal Point, and the Parson's Pond area on the Great Northern Peninsula. Additional unsuccessful exploration occurred in other parts of the Port au Port Peninsula, near Stephenville and in the Bay of Islands area. This exploration activity consisted of two phases, an early phase where large to medium-size exploration companies headquartered in Calgary and Houston participated, and a later phase that involved small, often local, exploration companies. The opening phase included Hunt Oil of Canada, PanCanadian (now Encana), BHP Petroleum Ltd, Talisman Energy, Marathon Oil, Mobile Oil of Canada, Norcen Energy (now Union Pacific Resources Group) and Encal Energy. The later phase participants were Canadian Imperial Venture Corporation (CIVC), Inglewood Resources, Tekoil, PDI Productions Inc., Enegi Inc., Ptarmigan Resources, Contact Exploration, Shoal Point Energy Ltd, Nalcor Energy and Black Spruce Resources amongst others.

PETROLEUM GEOLOGY OF WESTERN NEWFOUNDLAND

Petroleum System Overview

Cooper *et al.* (2001) described and illustrated a successful petroleum play within the western part of the Humber Zone of western Newfoundland and defined two petroleum fairways, an extensional fairway and an inversion fairway (Figure 12). Within the extensional fairway, reservoirs are in shallow-water platform carbonates and source and seal are in sequences that have been deposited upon or thrust over the ancient continental margin. Most of this extensional fairway lies in the Gulf of St Lawrence west of the Island of Newfoundland. The inversion fairway lies east of the extensional fairway. There, deep-water allochthonous rocks are deformed by folding and faulting. Source, reservoir and seal are arranged in much more complicated ways and the majority of petroleum seeps and showings in western Newfoundland are found in the allochthon in the inversion fairway.

Potential Reservoir Targets

Carbonate Shelf Reservoirs Exploration wells in western Newfoundland have targeted deep conventional carbonate reservoirs in the Early Ordovician St. George Group that hosts several potential to good reservoir intervals. Figure 13 illustrates the correlation of the Ordovician carbonate stratigraphy between wells on the Port au Port Peninsula. The cave system linked to the St. George Unconformity provides one such reservoir type but the primary target are beds and thick sequences of crystalline dolostone that replace St. George and (locally) Table Head group limestone after the carbonate shelf rocks were deeply buried.

Table 1. Hydrocarbon wells drilled in western Newfoundland since 1990

Well Name	Type	Year	Class	Status	Northing[1]	Easting[1]	Total Depth[2]	Operator
Anticosti Basin								
Big Spring #1	Onshore	1997	Exploratory	Abandoned	5663981	572180	1397	Delpet Resources Ltd.
Finnegan #1	Onshore	2010	Exploratory	Suspended	5549336	456529	3130	Nalcor Energy Oil and Gas Inc.
Indian Head #1	Onshore	2001	Exploratory	Abandoned	5384012	394845	805	Canadian Imperial Venture Corp.
Lark Harbour WW #2	Onshore	1996	Stratigraphic	Abandoned	5438801	398605	123	Mobil
Little Port WW #3	Onshore	1996	Stratigraphic	Abandoned	5439996	396468	152	Mobil
Long Point M-16	Offshore	1995	Exploratory	Abandoned	5402657	368161	3810	NL Hunt Oil Corp. and PanCanadian Petroleum
Long Range A-09	Offshore	1996	Exploratory	Abandoned	5370511	333472	3685	Talisman and others
Man O'War I-42	Offshore	1998	Exploratory	Abandoned	5376200	362950	677	Inglewood Resources Inc.
Parsons Pond #1	Onshore	2004	Exploratory	Abandoned	5536408	449723	1062	Contact Exploration Inc.
Port au Port #1	Onshore	1994	Exploratory	Abandoned	5372856	335490	4699	NL Hunt Oil Company Inc.
Port au Port #1 ST #1	Onshore	2001	Step Out	Abandoned	5372857	335491	4054	Canadian Imperial Venture Corp.
Port au Port #1 ST #2	Onshore	2002	Step Out	Abandoned	5372857	335491	3482	Canadian Imperial Venture Corp.
Port au Port #1 ST #3	Onshore	2008	Development	Completed	5372856	335491	4256	PDI Production Inc.
Port au Port #2	Onshore	2001	Exploratory	Suspended	5372863	335498	503	Canadian Imperial Venture Corp.
Port au Port #3	Onshore	2001	Exploratory	Suspended	5372869	335505	30	Canadian Imperial Venture Corp.
Seamus #1	Onshore	2010	Exploratory	Suspended	5536434	449731	3160	Nalcor Energy Oil and Gas Inc.
Shoal Point 2K-39	Offshore	2008	Exploratory	Abandoned	5389201	364249	2740	Shoal Point Energy Ltd.
Shoal Point 2K-39 Z	Offshore	2008	Step Out	Abandoned	5389201	364249	36	Shoal Point Energy Ltd.
Shoal Point 3K-39	Offshore	2001	Exploratory	Suspended	5389201	364249	1745	Dragon Lance Mng. Corp.
Shoal Point K-39	Offshore	1999	Exploratory	Abandoned	5389192	364249	3035	PanCanadian Petroleum
St. Georges's Bay A-36	Offshore	1996	Exploratory	Abandoned	5365376	327991	3240	NL Hunt Oil Corp. and PanCanadian Petroleum
York Harbour #1	Onshore	1996	Exploratory	Abandoned	5435750	406350	299	Mobil

Wells drilled since 1990, as of October 2013.
(1) Northing and Easting are UTM location coordinates using datum NAD 27. (2) Depths are in metres.

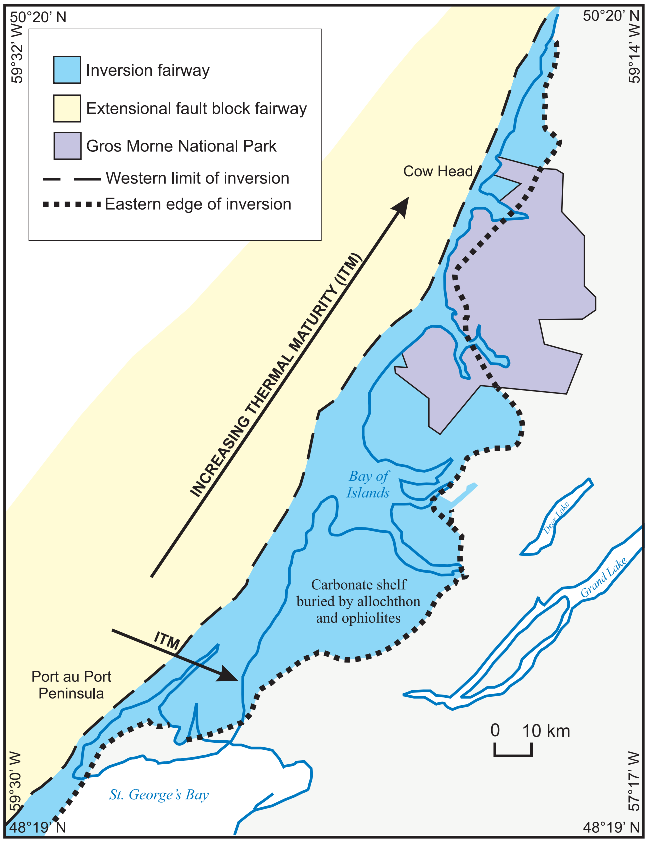

Figure 12. *Structural fairways and thermal maturity trends in the Humber Zone of western Newfoundland (after Cooper* et al. *(2001) and Fowler* et al. *(1995) respectively). The extensional fairway is thought to create conditions for large reservoirs to form due to rifting and shelf development. The inversion fairways is host to traps and seals created during tectonic inversion along faults and diagenesis of slope and basin strata. ITM = Increasing thermal maturity.*

Such dolostone, commonly rich in porosity, formed a now exhumed oil field in the Catoche Formation, St. George Group at Port au Choix, where outcrop studies and a suite of cored drillholes show the dolostone was bitumen soaked (Baker and Knight, 1993; Cooper *et al.*, 2001). The same dolostone unit is host to the zinc deposit mined in the area of Daniel's Harbour. Crystalline dolostone also replaces limestone (of any age) close to faults. An exhumed reservoir for example occurs in dolostone that replaced limestone conglomerate and carbonate sand of the Daniel's Harbour Member, American Tickle Formation at the Arches Provincial Park just north of Parson's Pond.

Unconventional Plays in the Port-au-Port Region Although exploration drilling on the Port au Port Peninsula has targeted deep conventional carbonate reservoirs, the penetration of thick sections of HAA hosting organic-rich shale (Green Point shale) above the carbonate shelf has encouraged revision of exploration targets to include unconventional shale resources in the area. Drilling of 3K39 in 2011 began this new focus of exploration of the Green Point Formation (*see* Plate 1) but evaluation of the potential of the Green Point Formation as an unconventional reservoir in the HAA is incomplete. Although basic log suites and mud gas records are available for some of the wells penetrating the allochton, no cores or sidewall cores were taken of the shale with exception of Shoal Point 3K39 well. The following is an evaluation of the shale from available well and research data.

Evaluation of Available Rock Data for the Green Point Formation Shale

Well-log data for assessing the basic reservoir characteristics of the Green Point shale, either regionally or within the Port au Port Peninsula area is sparse, in contrast to formations in lower Paleozoic carbonate platform sequence beneath the peninsula, where multiple electric-wireline logs and geological logs can be combined to correlate rock layers among a series of wells (*see* Figure 13). Some of these same wells cut through the Green Point shale en route to the platform rocks (*e.g., see* Figures 6A and 7) but electric logs were not taken for the shale section, except for a gamma-ray log in Shoal Point K-39 and Shoal Point 3K-39 wells (Stockmal *et al.*, 2004; Shoal Point Energy Ltd., 2011); a lithological log of the Shoal Point 2K-39 well is illustrated in Figure 14. Live and dead oil shows, gas emissions and petroliferous odours are common from both autochthonous and allochthonous rocks in outcrop and drillcore and cuttings (Figures 1 and 8). Nonetheless, because of the limited well data, much of the data about the Green Point shale are from surface samples and is extrapolated to depth.

Many maturity and source-rock studies have been undertaken since the mid 1980s by Stouge (1986), Macauley (1987), Nowlan and Barnes (1987), Weaver and Macko (1988), Weaver (1988), Sinclair (1990), Williams and Burden (1992), Fowler *et al.* (1995), Burden and Williams (1996), Williams *et al.* (1998) and Hamblin (2006) and to assess the source potential and thermal maturity of the region.

The Green Point shale, includes organic-rich (Type I/II) intervals with TOC contents up to 10.4%, HI (hydrogen index) up to 759 and Tmax (maximum temperature) values ranging from 434–443, indicating a thermal maturity below or within the oil window (Figure 15; Nowlan and Barnes, 1987; Weaver and Macko, 1988; Fowler *et al.*, 1995; Bertrand *et al.*, 2003). The geochemical characteristics of the oil seeps compare closely to those of the Green Point shale and the chemistry of the oils is consistent with a pre-Devonian clastic source rock containing Type BI organic

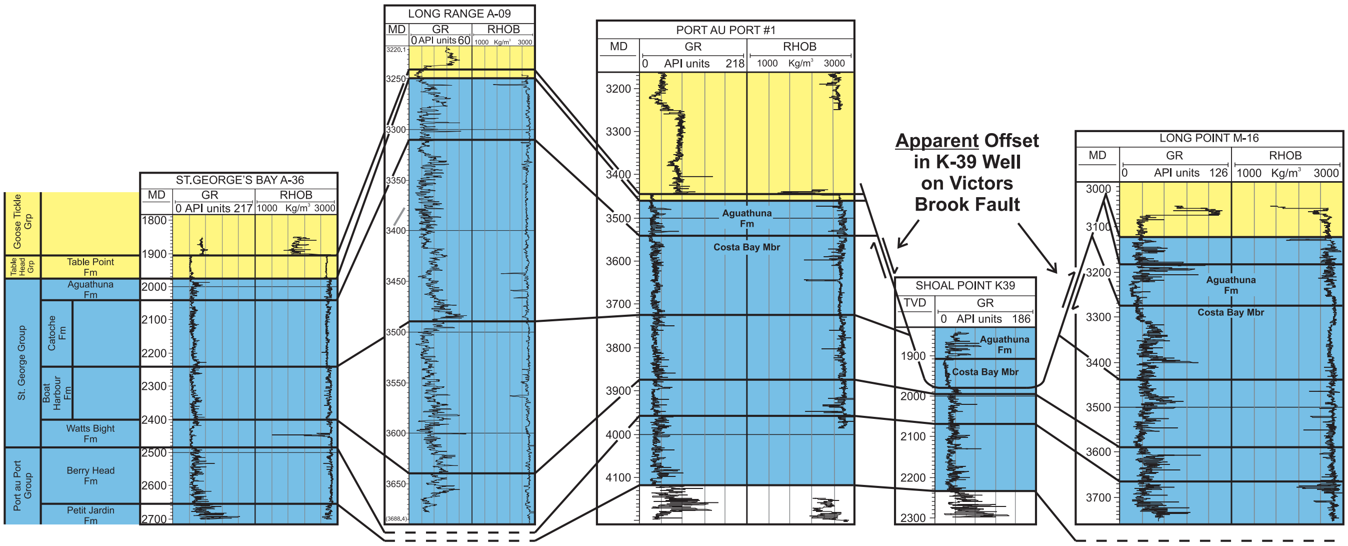

Figure 13. *Stratigraphic correlation of Lower Paleozoic carbonate shelf rocks in five wells on the Port au Port Peninsula based on lithologic and electric logs (from Stockmal* et al.*, 2004). Note no density log for K-39. MD – Measure depth, TVD – true vertical depth. K-39 depth values are in TVD, all other wells in MD. Wells are located on Figure 1B.*

matter of mostly algal (*Gloeocapsomorpha prisca*) origin (Fowler *et al.*, 1995).

The GSC Rock-Eval Database includes 12 samples of Green Point Formation with the following characteristics: TOC up to 8.37, averaging 5.86; Tmax up to 444, averaging 440; S1 up to 1.73, averaging 1.32; S2 up to 62.06, averaging 34.83; S3 up to 0.53, averaging 0.29; HI up to 753, averaging 613, and OI up to 7, averaging 5 (Hamblin, 2006; Figure 16 and Table 2).

Both Fowler *et al.* (1995) and Hamblin (2006) noted two rock maturity trends in western Newfoundland: increasing maturity from the Port au Port area northward to the Gros Morne area and increasing maturity from west to east across the Port au Port area, a trend presumed to apply regionally, particularly in the offshore (Figure 12). Williams *et al.* (1998) report Conodont Alteration Index (CAI – 1.5 to 5.0), Acritarch Alteration Index (AAI – 1.3 to 4.0) and graptolite reflectance (GR – 0.51 to 1.9) from samples of the Cow Head, Table Head and Goose Tickle groups between Bonne Bay and Table Point that support T_{max} data, and place most of these units in the oil generative window (Figure 17; Tables 2 and 3). Green Point shale occurring north of Parson's Pond may, however, reside in the gas window. The typical mineral composition of the Green Point shale is listed in Table 4.

Based on stratigraphic studies of the Cow Head Group (James and Stevens, 1986) and reconnaissance studies of the Green Point shale outcropping on the Port au Port Peninsula, it is likely the shale includes thick sequences of excellent source rocks, rich in Type I/II kerogen, that are thermally immature to mature (possibly ranging up to overmature). Hamblin (2006) suggests that good potential shale plays may range from a Style A (Antrim-like) play to a Style B (Ohio/New Albany-like) play, provided structural complications can be accommodated. Consequently, further study of the stratigraphy, sedimentology, geochemistry, maturity and mineralogy of the Green Point shale is necessary to better understand the shale petroleum potential.

Areas in western Newfoundland where shale, coeval with the Green Point shale, may be overmature include the Curling Group. A single sample from this group analyzed by Fowler *et al.* (1995) yielded TOC of 1.2% suggesting that these strata are at least organic-rich. However, because these units were caught up in the Taconian thrust stack, widespread faulting and fracturing are pervasive, and there are no continuous or flat-lying occurrences of these strata. It is probable that their structural complexity would render these rocks very difficult exploration targets (Hamblin, 2006) and that they are likely more mature than the Green Point shale.

Well-log Data of the Green Point Shale, Shoal Point

Wells drilled from the tip of Shoal Point since the late 1990s have all deviated from the vertical seeking to reach a deep carbonate shelf sequence in the offshore, northwest of the point (Figure 9). Behind-casing gamma-ray logs in Shoal Point K-39 well indicate a marked drop in signal at 943 m TVD, which was interpreted as the base of the shale-dominated HAA, or possibly the base of the Goose Tickle Group (Stockmal *et al.*, 2004). Below this depth, the

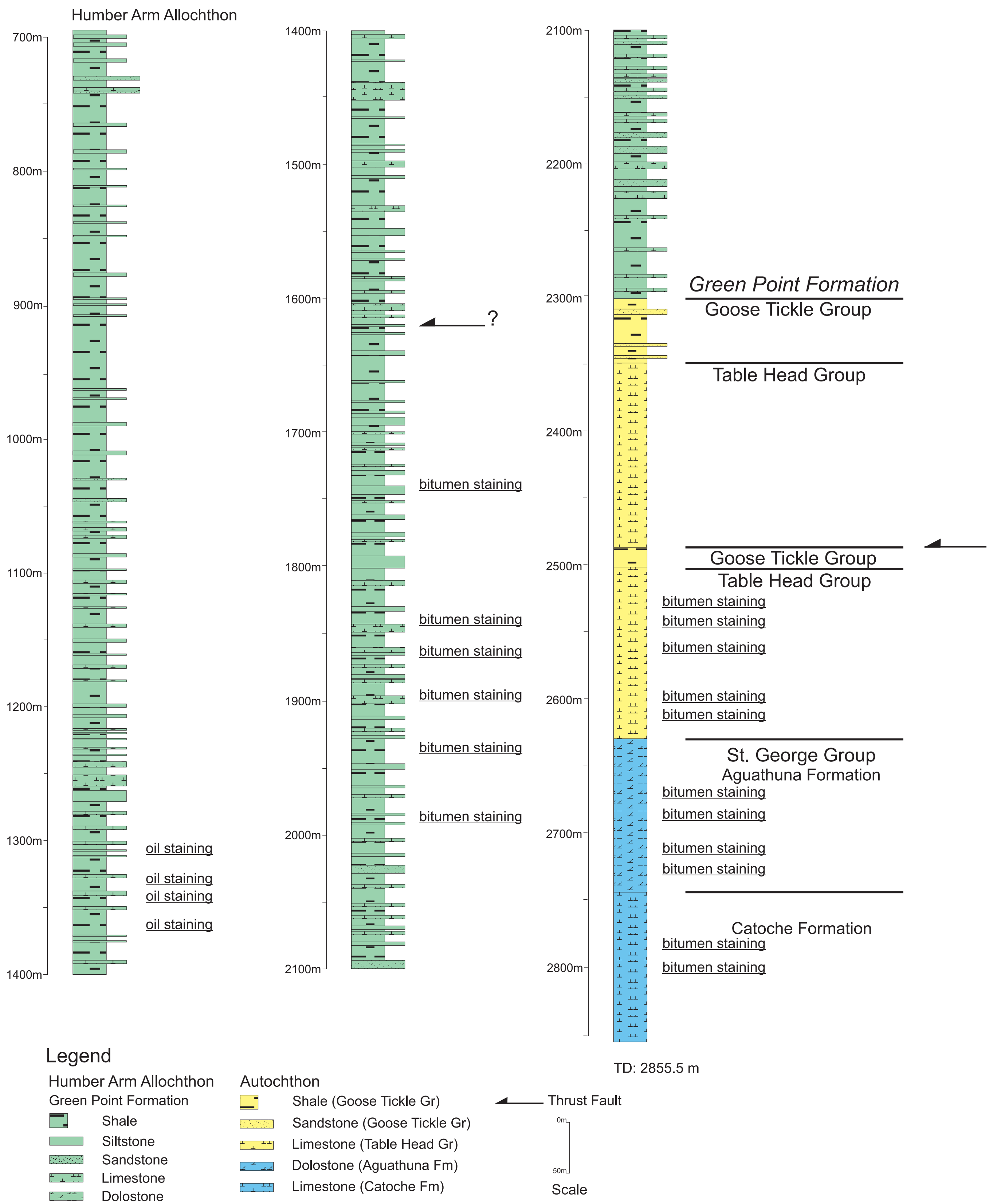

Figure 14. *Lithological log for 2K-39 well at Shoal Point (Shoal Point Energy Ltd., 2009).*

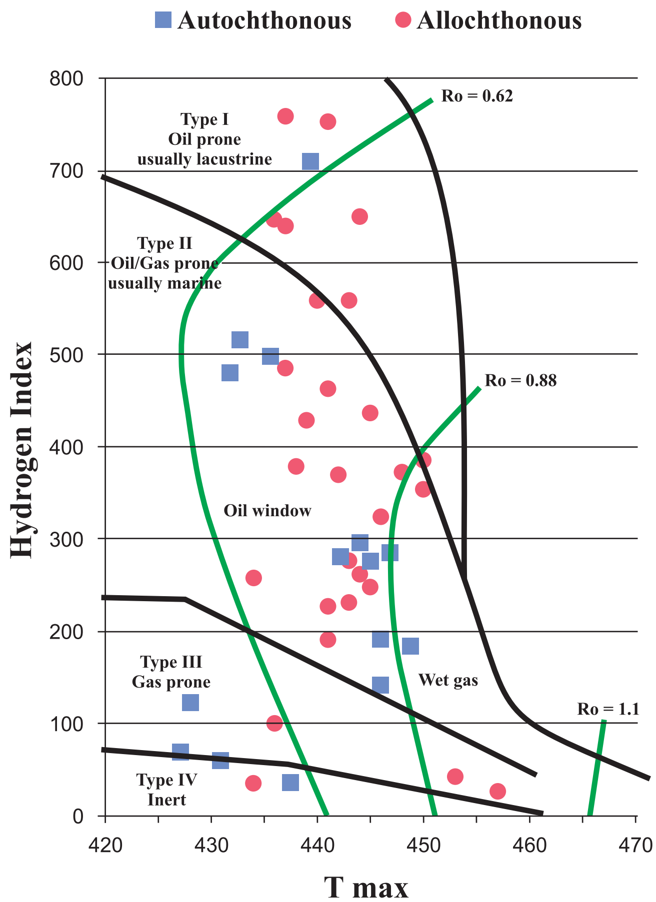

Figure 15. *Thermal maturity plot (Hydrogen Index* vs *Tmax) for authochthonous and allochthonous organic-rich shale of the eastern Anticosti Basin; all samples collected from outcrop (data from Sinclair, 1990; Weaver, 1988; Fowler* et al*., 1995).*

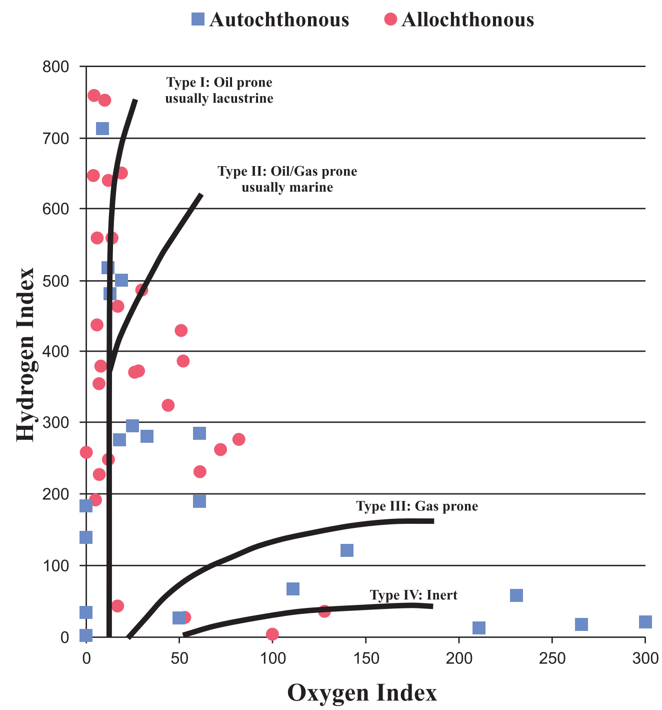

Figure 16. *Modified van Krevelen plot illustrating kerogen type in source rocks of the eastern Anticosti Basin (data from Sinclair, 1990; Weaver, 1988; Fowler* et al*., 1995).*

gamma-ray signal is consistent with a carbonate-dominated lithology even though shale cuttings were still present due to caving up hole. In the final well log, this upper section is interpreted, based on cutting samples as 'Cow Head Group' (*i.e.*, allochthonous slope facies).

The final well report for well K-39 recognized that, like at surface, rocks of the HAA at depth are structurally disturbed, and were expected to be highly contorted, folded, fractured and faulted (PanCanadian Resources, 1999). Frequent slickensides, likely represent abundant faulting with strain being distributed through the weak shale units especially in the upper cased portion of the hole. The report also noted that lower drilling rates near the base of the allochthon may relate to faulting and fracturing. The final well report for Shoal Point 2K-39 well also noted wellbore instability, and abundant slickensides in the HAA (Shoal Point Energy Ltd., 2009). It is therefore very likely that, based on surface and subsurface data, the Green Point shale will be deformed, fractured and faulted at depth, and as such a model for drilling and development would need to consider this (Shoal Point Energy Ltd, 2009).

The following details however can be distilled from the log data and final reports for Shoal Point wells K-39, 2K-39 and 3K-39. Very limited well-log reports indicate that porosity in the Green Point shale averages approximately 9%, although it does range up to 20%, locally. Water saturation ranges around 20–32% and the Green Point shale appears to be normally pressured to slightly overpressured (0.5 psi/ft;

Table 2. Geological Survey of Canada rock eval data for the Green Point shale

Measure	TOC	Tmax	S1 peak	S2 peak	S3 peak	HI	OI
Max. value	8.37	444	1.73	62.06	0.53	753	7
Ave. value	5.86	440	1.32	34.83	0.29	613	5

TOC, total organic carbon; **HI**, hydrogen index; **OI**, oxygen index. From Hamblin (2006)

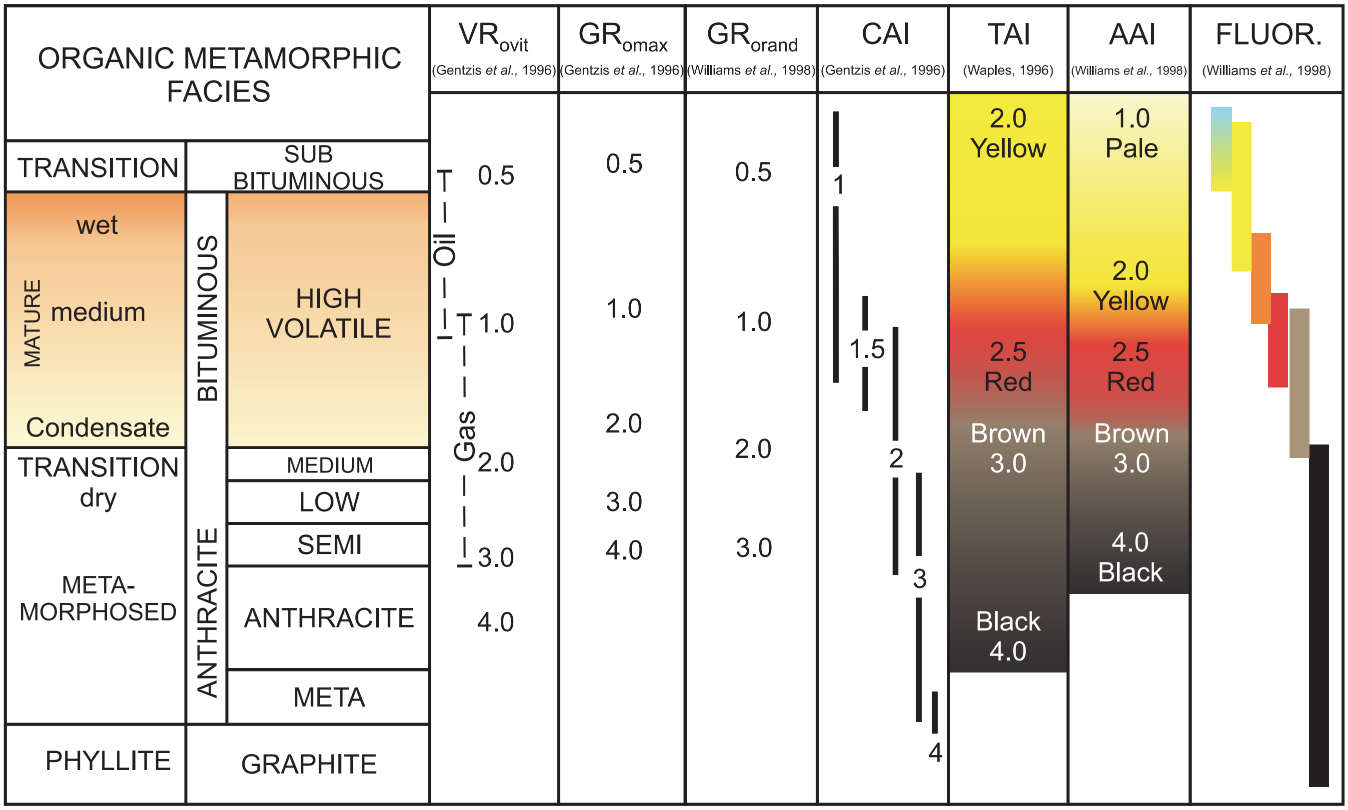

Figure 17. *Correlation chart of thermal maturation indices (from Staplin, 1977), particularly AAI and graptolite reflectance with other thermal maturation techniques (data from Waples, 1982; Bertrand, 1991; Gentzis* et al.*, 1996; Williams* et al.*, 1998; modified from Williams* et al.*, 1998). VR = Vitrinite Reflectance, GR = Graptolite Reflectance, CAI = Conodont Alteration Index, TAI = Thermal Alteration Index, AAI = Acritarch Alteration Index, and Fluor. = fluorescence.*

Table 3. Fossil-based indices of thermal maturity for western Newfoundland

Measure	Conodont Alteration Index	Acritarch Alteration Index	Graptolite Reflectance
Min. Value	1.5	1.3	0.51
Max. Value	5.0	4.0	1.9

From Williams *et al.* (1998)

Shoal Point Energy Ltd., 2011). There is no record of gas or oil production from the formation even though the shale shows excellent source rock capability in outcrop and there are oil seeps in the Shoal Point area. However, a flow test in K-39 by PanCanadian Resources Ltd (1999) recovered 14 600 cubic metres per day of dry gas during a stem test (*see* below).

In wells K-39 and 2K-39, briny water was encountered in the HAA (PanCanadian Resources, 1999; Shoal Point Energy Ltd., 2009); the fluid was encountered at depths of 869–875 m (TVD) in well K-39. Water analysis indicated

Table 4. Typical mineral composition of the Green Point shale

Mineral	% of total
Quartz	35–50%
Clays, primarily illite	10–50%
Calcite, dolomite, siderite	0–30%
Feldspars	7%
Pyrite	5%
Phosphate, gypsum	trace
Mica	<5%

Based on data from Shoal Point Energy 3K-39 well

that this fluid contains 25.8% total dissolved solids composed largely of salt (NaCl), which is substantially greater than ocean water (typically dissolved solids content of 3.5%; PanCanadian Resources, 1999). The increased salinity indicates that the water has been isolated likely from other water sources for a prolonged period of time and the isolation of this briny water at depths of ~800 m could indicate that the rock system is probably sealed at depth.

In 1999, a drillstem test was completed in the Shoal Point K-39 well at a measured depth[1] of 1251.5 m (Pan-Canadian Resources, 1999). The drillstem test results included recovery of a 375-m column of briny water (with 258 000 parts per million of sodium chloride) and a 2-m column of sand in the drillpipe before sand plugged the tool. The drillstem test showed good initial reservoir pressure (in the range of about 10 000 kilopascals), which built back up reasonably well. The initial flow test recovered 14 600 cubic m per day of dry gas that decreased to 150 cubic m per day after the third flow test and subsequent accumulation of salty water in the drillpipe. Further details on petroleum exploration in the region and on the hydraulic fracturing technique are provided in Hinchey *et al*. (2014)

CONCLUSION

Naturally occurring seeps and shows of hydrocarbon have been documented along the coast of western Newfoundland for over 150 years, leading to a long history of oil and gas exploration in the region; this exploration targeted conventional oil and gas resources. The recent interest in unconventional hydrocarbon resources has focused attention on the Green Point shale (part of the Green Point Formation of the Cow Head Group) of western Newfoundland as a potential host to shale oil and shale gas.

However, the Green Point shale is not a simple package in a consistently layered sequence but is hosted by an allochthon that has travelled at least 200 km to its present location and is known to be complexly deformed. The rocks in the allochthon are folded, locally repeated by thrusts, and thickened, or pinched out due to multiple tectonic events. Because of a scarcity of good geological data, there is currently no way to reliably and accurately depict or predict the extent, location, rock characteristics, or shape of Green Point shale layers below the surface. It is therefore, not feasible to present a model for unconventional shale gas/oil exploration in the area.

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REFERENCES

Baker, D. and Knight, I.
1993: The Catoche dolomite project, Anticosti Basin, eastern Canada. CERR Report, Memorial University of Newfoundland, St. John's, Nfld., 174 pages.

Bertrand, R.
1991: Maturation thermique des roches mères dans les bassins des basses-terres du Saint-Laurent et dans quelques buttes témoins au sud-est du Bouclier canadien. International Journal of Coal Geology, Volume 19, pages 359-383.

Bertrand, R., Lavoie, D. and Fowler, M.
2003: Cambrian-Ordovician shales in the Humber Zone: Thermal maturation and source rock potential. Bulletin of Canadian Petroleum Geology, Volume 51, pages 213-233.

Bostock, H.H., Cumming, L.M., Williams, H. and Smith, W.R.
1983: Geology of the Strait of Belle Isle area, northwestern insular Newfoundland, southern Labrador and adjacent Quebec. Geological Survey of Canada, Memoir 400, 145 pages.

Botsford, J.
1988: Stratigraphy and sedimentology of Cambro-Ordovician deep-water sediments, Bay of Islands, western Newfoundland. Unpublished Ph.D. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 534 pages.

Burden, E.T. and Williams, H.
1996: Biostratigraphy and thermal maturity of strata in NHOC-PCP Long Point M16: Well Report. Newfoundland Department of Mines and Energy, 75 pages.

CNLOPB
2010: Seismic data coverage: Offshore Newfoundland and Labrador [Report]. St. John's, NL. ISBN 978-1-897101-97-1. http://www.cnlopb.nl.ca/pdfs/seisdatacoverage.pdf

Footnote 1 'Measured depth' refers to the length in metres along the stem of the drillhole where data is collected. It may not coincide with true vertical depth (TVD) which refers to the depth measured in a straight perpendicular line from surface to the bottom of the borehole. If the well is vertical, measured depth will be the same as true vertical depth. If a well is drilled at an angle, then its measured depth will be significantly greater than TVD.

Cooper, M., Weissenberger, J., Knight, I., Hostad, D., Gillespie, D., Williams, H., Burden, E., Porter-Chaudhry, J., Rae, D. and Clark, E.
2001: Basin evolution in western Newfoundland: New insights from hydrocarbon exploration. American Association of Petroleum Geologists Bulletin, Volume 85(3), pages 393-418.

Fleming, J.M.
1970: Petroleum exploration in Newfoundland and Labrador. Newfoundland Department of Mines, Agriculture and Resources, Mineral Resources Report, No. 3, 118 pages.

Fowler, M.G., Hamblin, A.P., Hawkins, D., Stasiuk, L.D. and Knight, I.
1995: Petroleum geochemistry and hydrocarbon potential of Cambrian and Ordovician rocks of western Newfoundland. Bulletin of Canadian Petroleum Geology, Volume 43(2), pages 187-213.

Gentzis, T., de Freitas. T. and Goodarzi, F.
1996: Thermal maturity of Lower Paleozoic sedimentary successions in Arctic Canada. American Association of Petroleum Geologists Bulletin, Volume 80, pages 1065-1084.

Hamblin, A.P.
2006: The “shale gas” concept in Canada: A preliminary inventory of possibilities. Geological Survey of Canada, Open File Report 5384. 108 pages. http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/2246f370-67f8-5e43-8168-d2a8cd57e936.html

Hicks, L.G.
2005: First international symposium on oil & gas resources in western Newfoundland [Excursion guidebook]. St. John’s, Newfoundland. Department of Natural Resources, Government of Newfoundland and Labrador, 43 pages.

Hicks, L., Waldron, J. and Burden, E.
2010: An under-explored western Newfoundland slope/rise turbidite petroleum system awaits discovery [Field trip guidebook]. Western Newfoundland Oil and Gas Symposium, September 23-24, Marble Mountain, Newfoundland, 70 pages.

Hinchey, A.M., Knight, I., Kilfoil, G., Hynes, K.T., Middleton D. and Hicks, L.G.
2014: The Green Point Shale of Western Newfoundland. A review of its geological setting, it’s potential as an unconventional hydrocarbon reservoir, and its ability to be safely stimulated using the technique of hydraulic fracturing. Newfoundland and Labrador Department of Natural Resources, Energy Branch, 128 pages. http://www.nr.gov.nl.ca/nr/energy/pdf/green_point_ shale_west_nl.pdf

Hyde, R.S.
1995: Upper Paleozoic rocks, Newfoundland. *In* Geology of the Appalachian-Caledonian Orogen in Canada and Greenland, Chapter 5. *Edited by* H. Williams. Geology of Canada No. 6, pages 523-552 .

James, N.P.
1981: Megablocks of calcified algae in the Cow Head breccia, western Newfoundland; vestiges of a Lower Paleozoic continental margin. Geological Society of America Bulletin, Volume 92, pages 799-811.

James, N.P., Barnes, C.R., Boyce, W.D., Cawood, P.A., Knight, I., Stenzel, S.R., Stevens, R.K. and Williams, S.H.
1988a: Carbonates and faunas of western Newfoundland [Field trip guidebook]. Fifth International Symposium on the Ordovician System, St. John’s, Newfoundland, 123 pages.

James, N.P., Barnes, C.R., Stevens, R.K. and Knight, I.
1989: A Lower Paleozoic continental margin carbonate platform, northern Canadian Appalachians. *In* Controls on Carbonate Platforms and Basin development. *Edited by* T. Crevello, R. Sarg, J.F. Read and J.L. Wilson. Society of Economic Paleontologists and Mineralogists, Special Publication 44, pages 123-146.

James, N.P., Knight, I., Barnes, C.R. and Stevens, R.K.
1988b: Sedimentology and paleontology of an Early Paleozoic continental margin, western Newfoundland. GAC-MAC-CSPG Field trip guide B1, 121 pages.

James, N.P. and Stevens, R.K.
1986: Stratigraphy and correlation of the Cambro-Ordovician Cow Head Group, western Newfoundland [Report]. Geological Survey of Canada, Bulletin 366, 143 pages.

Knight, I.
1983: Geology of the Carboniferous Bay St. George subbasin, western Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Memoir 1, 358 pages. http://www.nr.gov.nl.ca/nr/mines/geoscience/publications/docs.html

1994: Geology of Cambrian-Ordovician platformal rocks of the Pasadena map sheet (12H/4). *In* Current Research. Newfoundland and Labrador Department of

Natural Resources, Geological Survey, Report 94-1, pages 175-186. http://www.nr.gov.nl.ca/nr/mines/geoscience/publications/ currentresearch/1994/knight_pasadena.pdf

1995: Preliminary 1:50 000 mapping of lower Paleozoic parautochthonous sedimentary rocks of the Corner Brook area. *In* Current Research. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 95-1, pages 257-265. http://www.nr.gov.nl.ca/nr/mines/geoscience/publications/currentresearch/1995/knight.pdf

1997: Geology of Cambro-Ordovician carbonate shelf and coeval off-shelf rocks, southwest of Corner Brook, western Newfoundland. *In* Current Research. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 97-1, pages 211-235. http://www.nr.gov.nl.ca/nr/mines/geoscience/ publications/currentresearch/1997/knight.pdf

2013: The Forteau Formation, Labrador Group, in Gros Morne National Park: A preliminary reassessment of its stratigraphy and lithofacies. *In* Current Research. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 13-1, pages 267-300. http://www.nr.gov.nl.ca/nr/mines/geoscience/ publications/currentresearch/2013/Knight_2013.pdf

Knight, I., Azmy, K., Greene, M.G. and Lavoie, D.
2007: Lithostratigraphic setting of diagenetic, isotopic, and geochemistry studies of Ibexian and Whiterockian carbonate rocks of the St. George and Table Head groups, western Newfoundland. *In* Current Research. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 07-1, pages 55-84. http://www.nr.gov.nl.ca/nr/mines/geoscience/publications/ currentresearch/2007/knight.pdf

2008: Tremadocian carbonate rocks of the lower St. George Group, Port au Port Peninsula, western Newfoundland: lithostratigraphic setting of diagenetic, isotopic and geochemistry studies. *In* Current Research. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 08-1, pages 115-149.

Knight, I. and Boyce, W.D.
1991: Deformed Lower Paleozoic platform carbonates, Goose Arm-Old Man's Pond. *In* Current Research. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 91-1, pages 141-153. http://www.nr.gov.nl.ca/nr/mines/geoscience/ publications/current research/1991/knight.pdf

Knight, I. and Cawood, P.A.
1991: Paleozoic geology of western Newfoundland: An exploration of a deformed Cambro-Ordovician passive margin and foreland basin and Carboniferous successor basin. A field-based short course for industry. CERR, Department of Earth Sciences, Memorial University of Newfoundland, St. John's, Newfoundland, Canada., 2 volumes, 403 pages.

Knight, I. and James, N.P.
1987: The stratigraphy of the Lower Ordovician St. George Group, western Newfoundland: The interaction between eustasy and tectonics. Canadian Journal of Earth Sciences, Volume 24, pages 1927-1951.

Knight, I., James, N.P. and Lane, T.E.
1991: The Ordovician St. George Unconformity, northern Appalachians: The relationship of plate convergence at the St. Lawrence Promontory to the Sauk/Tippecanoe sequence boundary. Geological Society of America Bulletin, Volume 103, pages 1200-1225.

Lane, T.E.
1990: Dolomitization, brecciation and zinc mineralization and their paragenetic, stratigraphic and structural relationships in the upper St. George Group (Ordovician) at Daniel's Harbour, Newfoundland. Unpublished Ph.D. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 262 pages.

Macauley, G.
1987: Organic geochemistry of some Cambro-Ordovician outcrop samples, western Newfoundland. Geological Survey of Canada, Open File OF1503, 15 pages.

Newfoundland and Labrador Petroleum Directorate
1982: Onshore/offshore western Newfoundland, prospects for petroleum. Resource Assessment Division Special Report PD 82-1. 85 pp. http://www.nr.gov.nl.ca/ nr/publications/energy/onoffshore.pdf

Newfoundland Department of Energy
1989: Hydrocarbon potential of the western Newfoundland onshore area, 20 pages. http://www.nr.gov.nl.ca/ mines&en/publications/onshore/hydrocarbon.pdf

Newfoundland Department of Mines and Energy
2000: Sedimentary basins and hydrocarbon potential of Newfoundland and Labrador. Energy Branch Report 2000-01, 71 pages. http://www.nr.gov.nl.ca/nr/publications/energy/sedimentary basins.pdf

Newfoundland and Labrador Department of Natural Resources
2008: Oil and gas report (Feb. 2008). St. John's, Newfoundland, 40 pages. http://www.nr.gov. nl.ca/nr/publications/energy/oilgasreport08.pdf

Nowlan, G.S. and Barnes, C.R.
1987: Thermal maturation of Paleozoic strata in eastern Canada from conodont colour alteration index (CAI) data with implications for burial history, tectonic evolution, hotspot tracks and mineral and hydrocarbon exploration. Geological Survey of Canada, Bulletin 367, 47 pages.

PanCanadian Resources
1999: Final Well Report for PanCanadian Resources *et al.* Shoal Point K-39, 1999. Prepared by for PanCanadian Resources, 554 pages.

Quinn, L.
1996: Middle Ordovician foredeep fill in western Newfoundland. *In* Current Perspectives in the Appalachian-Caledonian Orogen. Geological Association of Canada, Special Paper 41, pages 43-64.

Quinn, L., Bashforth, A.R., Burden, E.T., Gillespie, H., Springer, R.K. and Williams, S.H.
2004: The Red Island Road Formation: Early Devonian terrestrial fill in the Anticosti Foreland Basin, western Newfoundland. Canadian Journal of Earth Sciences, Volume 41(5), pages 587-602, 10.1139/e04-021

Rodgers, J. and Neale, E.R.W.
1963: Possible tectonic klippen in western Newfoundland. American Journal of Science, Volume 261, pages 713-730.

Rowe, C.
2003: Novel 3D transition zone seismic survey, Shoal Point, Port au Port Peninsula, Newfoundland: Seismic data processing and interpretation. Unpublished M.Sc. thesis, Memorial University, St. John's, Newfoundland, 310 pages.

Shoal Point Energy Ltd.
2009: Final Well Report for Shoal Point Energy Ltd. SPE 2K-39 & SPE 2K-39-Z, 2009, Prepared by Dragon Lance Management Corporation & Shoal Point Energy Ltd, 654 pages.

2011: Shoal Point 3K-39 - Geological Well Report, Shoal Point, Port au Port Bay Newfoundland. Prepared for Dragon Lance Management Corp. Prepared by W. Wright, Landsend Holding Ltd., 152 pages.

Sinclair, I.K.
1990: A review of the Upper Precambrian and Lower Paleozoic geology of western Newfoundland and the hydrocarbon potential of the adjacent offshore area in the Gulf of St. Lawrence. Canada–Newfoundland Offshore Petroleum Board, GL-CNLOPB-90-01, 79 pages.

Staplin, F.L.
1977: Interpretation of thermal history from colour of particulate organic matter - a review. Palynology, Volume 1, pages 9-18.

Stenzel, S.R., Knight, I. and James, N.P.
1990: Carbonate platform to foreland basin: Revised stratigraphy of the Table Head Group (Middle Ordovician), western Newfoundland. Canadian Journal of Earth Sciences, Volume 27, pages 14-26.

Stevens, R.K.
1970: Cambro-Ordovician flysch sedimentation and tectonics in west Newfoundland and their possible bearing on a Proto-Atlantic Ocean. *In* Flysch Sedimentation in North America. *Edited by* J. Lajoie. Geological Association of Canada, Special Paper 7, pages 165-177.

Stockmal, G.S., Slingsby, A. and Waldron, J.W.F.
1998: Deformation styles at the Appalachian structural front, western Newfoundland: Implications of new industry seismic reflection data. Canadian Journal of Earth Sciences, Volume 35, pages 1288-1306.

2004: Basement-involved inversion at the Appalachian structural front, western Newfoundland: An interpretation of seismic reflection data with implications for petroleum prospectivity. Bulletin of Canadian Petroleum Geology, Volume 52(3), pages 215-233.

Stockmal, G.S. and Waldron, J.W.F.
1990: Structure of the Appalachian deformation front in western Newfoundland: Implications of multichannel seismic reflection data. Geology, Volume 18, pages 765-768.

Stouge, S.
1986: Conodont colour variation in the lower/middle Ordovician strata of western Newfoundland. *In* Current Research. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 86-1, pages 177-178. http://www.nr.gov.nl.ca/nr/mines/ geoscience/publications/research.html

U.S. Department of Energy
2009: Modern shale gas development in the United States: A primer. National Energy Technology Labora-

tory, Strategic Center for Natural Gas and Oil, 116 pages. http://www.netl. doe.gov/technologies/oilgas/publications/EPreports/Shale_Gas_Primer_2009.pdf

2013: Modern shale gas development in the United States: An update. National Energy Technology Laboratory, Strategic Center for Natural Gas and Oil, 79 pages. http://www.netl. doe.gov/technologies/oil-gas/publications/brochures/shale-gas-primer-update-2013.pdf

van de Poll, H. W., Gibling, M. R., and Hyde, R. S.
1995: Upper Paleozoic rocks. In Geology of the Appalachian-Caledonian orogen in Canada and Greenland, Edited by H. Williams. Chapter 5. Geological Survey of Canada, Geology of Canada Series no. 6, p. 449–566. http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=205242

van Staal, C.R. and Barr, S.M.
2012: Lithospheric architecture and tectonic evolution of the Canadian Appalachians and associated Atlantic margin. Chapter 2 *In* Tectonic Styles in Canada: the LITHOPROBE Perspective. *Edited by* J.A. Percival, F.A. Cook and R.M. Clowes. Geological Association of Canada, Special Paper 49, pages 41-95.

van Staal, C.R.
2007: Pre-Caroniferous tectonic evolution and metallogeny of the Canadian Appalachians. *In* Mineral Deposits of Canada:ASynthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods. *Edited by* W.D. Goodfellow. Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 793-818.

Waldron, J.W.F., DeWolfe, J., Courtney, R. and Fox, D.
2002: Origin of the Odd-Twins anomaly: Magnetic effect of a unique stratigraphic marker in the Appalachian foreland basin, Gulf of St. Lawrence. Canadian Journal of Earth Sciences, Volume 39, pages 1675-1687.

Waldron, J.W.F., Hicks, L. and White, S.E.
2012: Stratigraphy, tectonics and petroleum potential of the deformed Laurentian margin and foreland basins in western Newfoundland [Field trip guidebook 3B]. Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, 28-30 May, St. John's, Newfoundland, 155 pages.

Waldron, J.W.F. and Palmer, S.E.
2000: Lithostratigraphy and structure of the Humber Arm Allochthon in the type area, Bay of Islands, Newfoundland. *In* Current Research. Newfoundland and Labrador Department of Natural Resources, Geological Survey, Report 2000-1, pages 279-290. http://www.nr.gov.nl.ca/nr/mines/geoscience/publications/research.html

Waldron, J.W.F., Scott, D.A., Cawood, P.A., Goodwin, L.B., Hall, J., Jamieson, R.A., Palmer, S.E., Stockmal, G.S. and Williams, P.F.
1998: Evolution of the Appalachian Laurentian margin: Lithoprobe results in western Newfoundland. Canadian Journal of Earth Sciences, Volume 35, pages 1271-1287.

Waldron, J.W.F. and Stockmal, G.S.
1991: Mid-Paleozoic thrusting at the Appalachian deformation front: Port au Port Peninsula, western Newfoundland. Canadian Journal of Earth Sciences, Volume 28, pages 1992-2002.

Waples, D.
1982: Organic geochemistry for exploration geologists. International Human Resources Development Corporation, Boston, Mass.

Weaver, E.J.
1988: Source rock studies of natural seep oils near Parson's Pond on the west coast of Newfoundland. Unpublished M.Sc. thesis, Memorial University, St. John's, Newfoundland, 178 pages.

Weaver, F.J. and Macko, S.A.
1988: Source rocks of western Newfoundland. Organic Geochemistry, Volume 13, pages 411-421.

Williams, H. and Cawood, P.
1989: Geology, Humber Arm Allochthon, Newfoundland, Map 1678A, Scale: 1:250 000. Geological Survey of Canada.

Williams, H. and Stevens, R.K.
1969: Geology of Belle Isle-northern extremity of the deformed Appalachian miogeosynclinal belt. Canadian Journal of Earth Sciences, Volume 6, pages 1145-1157.

Williams, S.H. and Burden, E.T.
1992: Thermal maturity of potential Paleozoic source rocks in western Newfoundland: A report to Mobil Canada [Released 1997], 34 pages. http://www.nr.gov.nl.ca/nr/publications/energy/report4.pdf

Williams, S.H., Burden, E.T. and Mukhopadhyay, P.K.
1998: Thermal maturity and burial history of Paleozoic rocks in western Newfoundland. Canadian Journal of Earth Sciences, Volume 35, pages 1307-1322.

Williams, S.H., Nowlan, G.S. and Boyce, D.W.
2001: Trip B4: Stratotype sections and hydrocarbon potential of western Newfoundland. Geological Association of Canada and Mineralogical Association of Canada, Joint Annual Meeting (2001), St. John's, Newfoundland, Field Trip B4 Guidebook, 110 pages.