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P. Durling

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Canada

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Abstract

A composite stratigraphic section of the Codroy Group in the St. George's Bay lowlands was assembled from published stratigraphic sections and borehole data, in concert with published biostratigraphic data. The relative placement of stratigraphic sections in the composite section was guided by a form line contour map, which was constructed using bedding attitudes compiled from published geological maps. The composite section comprises a thick (~1000m), evaporite dominated, lower interval; a medial interval characterised by clastic, carbonate and evaporite rocks; and an upper clastic dominated interval. The lower evaporite interval correlates with Subzone A of the Windsor Group, the middle carbonate interval with Subzone B, and the upper interval with Windsor Subzones D and E. Average rock properties were assigned to the various strata in the composite section and a synthetic seismic trace was computed. The synthetic seismic trace provides insight into the nature and thickness of the Codroy Group imaged on seismic reflection data in the immediately adjacent offshore area beneath St. George's Bay.

Introduction

St. George's Bay is a large embayment in southwestern Newfoundland in the eastern part of the Gulf of St. Lawrence (Fig. 1). The bay is underlain by an asymmetric, sedimentary basin, the Bay St. George Subbasin (Knight, 1983), which contains up to 5000 m of interpreted Carboniferous strata (based on an average seismic velocity of 4500 m/s from surface). The offshore basin is thickest in the south and thins gradually to the north; however, the stratigraphy within this basin is poorly constrained. Dafoe et al. (2016) concluded that the basin fill includes the Visean Codroy Group, and potentially younger rocks, on the basis of seismic correlation to one petroleum industry well drilled in the shallow, northern part of the basin. Snyder (2019) used synthetic seismograms from a number of wells across eastern Canada to assess the seismic stratigraphy of the offshore Bay St. George Subbasin. Complicated structure such as salt walls, thrust faults (Durling and Marillier, 1993), and tectonic wedges (Snyder, 2019) precludes direct correlation of the basin fill to onshore exposures to the south. Further, poor seismic data quality and salt structures limit reliable correlation to seismic data interpreted at the entrance to St. George's Bay in the eastern Gulf of St. Lawrence, where Upper Carboniferous rocks are mapped (Grant, 1994; Atkinson et al., 2020). In the absence of borehole data from the thick sedimentary column, the stratigraphy of the offshore Bay St. George Subbasin remains uncertain.

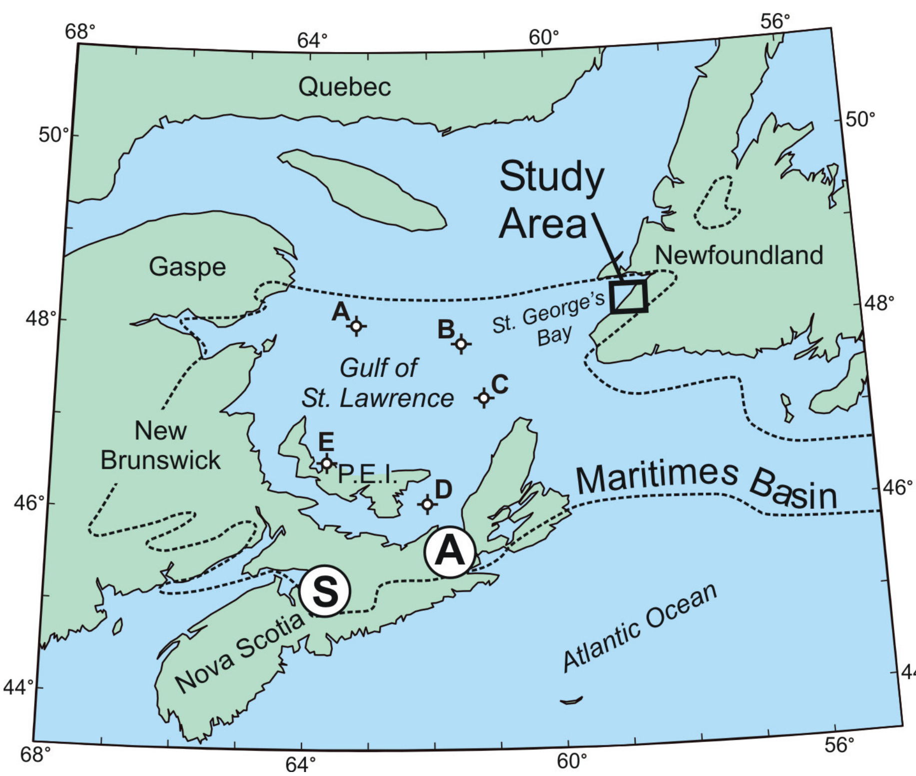

Figure 1: Location map showing the study area and St. George's Bay, Newfoundland, in the context of the Maritimes Basin (extent shown by dotted line). Subbasins are indicated by circled letters: S – Shubenacadie Basin; A – Antigonish Basin. Offshore wells presented in Table 1: A – Bradelle L-49; B – Brion Island No.1; C – Cap Rouge F-52; D – Northumberland Strait F-25; E – Irishtown No.1.

The Bay St. George Subbasin forms part of the Maritimes Basin (Fig. 1), an assemblage of structural basins with similar sedimentary fill. Terrigenous clastic rocks, ranging in age from Middle-Late Devonian to Permian, dominate the basin fill (Bell and Howie, 1990). Within this succession occurs an interval characterized by marine rocks assigned to the Visean age Windsor and Codroy groups, which comprise carbonate, sulphate, evaporite, and clastic rocks (von Bitter et al., 2006).

The objective of this work was twofold: to construct a composite stratigraphic section of the Codroy Group from the onshore St. George's Bay lowlands; and to calculate a synthetic seismic trace (synthetic) of the Codroy Group for comparison to offshore seismic data in St. George's Bay. Further, the composite section from the St. George's Bay lowlands, and the resultant seismic trace, may prove useful to compare with the Windsor Group elsewhere in the Maritimes basin.

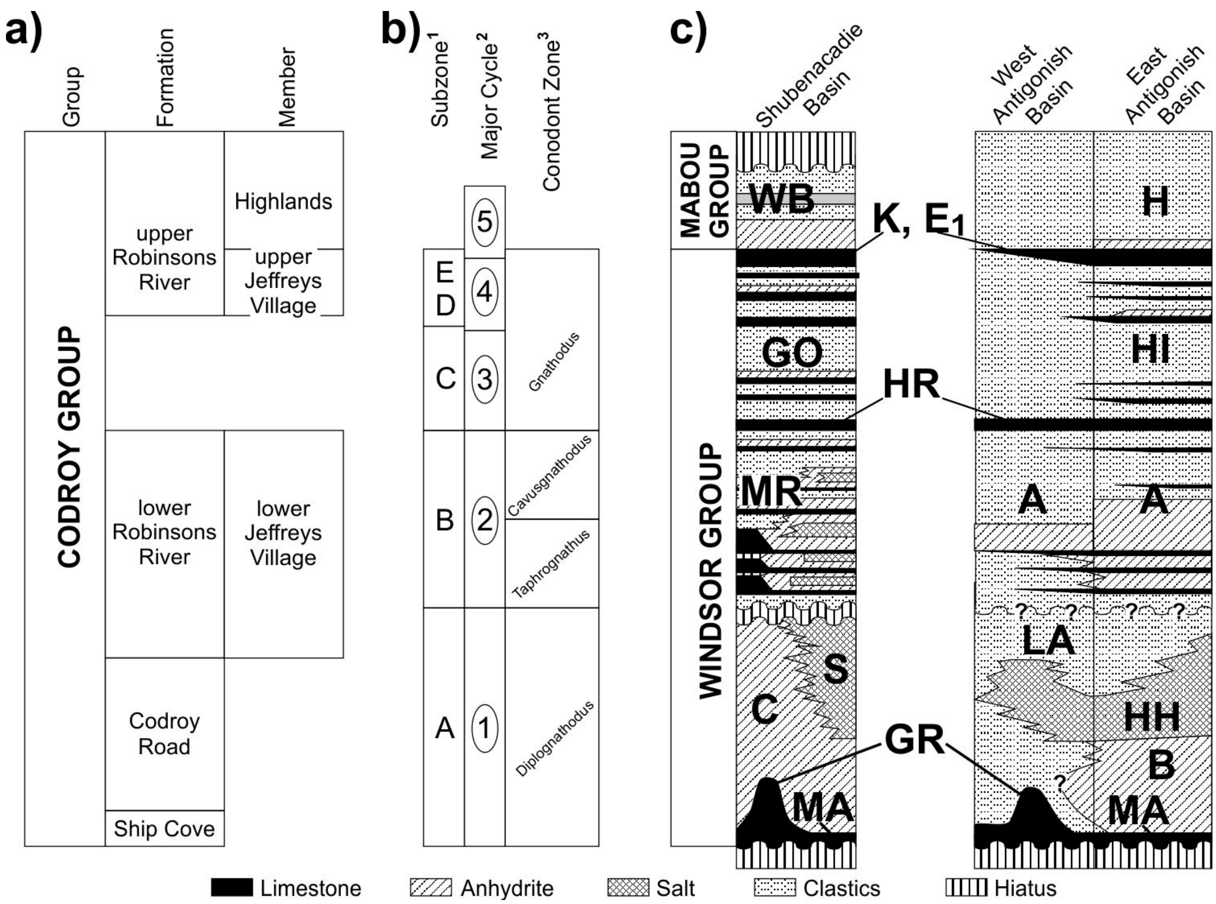

Figure 2: Stratigraphy of the Codroy and Windsor groups. See figure 1 for location of the Shubenacadie and Antigonish basins. a) Stratigraphy of the Codroy Group (Knight, 1983; Utting and Giles, 2004). b) Macrofaunal subzones[(1)] based on Bell (1929); Major Cycles[(2)] defined by Giles (1981); and conodont zonations[(3)] from von Bitter and Plint-Geberl (1982). c) Windsor stratigraphy for the Shubenacadie and Antigonish basins (from Boehner and Prime, 1993). Formation abbreviations: A – Addington; B – Bridgeville; C – Carrolls Corner; E1 – E1 Limestone Member; GO – Green Oaks; GR – Gays River; H – Hastings; HI – Hood Island; HH – Hartshorn; HR – Herbert River Member; K – Kennetcook Member; LA – Lakevale; MA – Macumber; MR – MacDonald Road; S – Stewiake; WB – Watering Brook.

Visean Marine Rocks in Eastern Canada

Rocks assigned to the Codroy (Fig. 2a) and Windsor (Fig. 2c) groups comprise Visean marine and minor terrestrial rocks in eastern Canada. Their general stratigraphy is known through extensive study of the Windsor Group (Bell, 1929; Giles, 1981; von Bitter et al., 2006). The Windsor Group consists of mainly carbonate and evaporite rocks with varying amounts of terrigenous clastic rocks (Fig. 2c); there is a tendency toward increasing clastic abundance in younger strata (Giles, 1981). The Windsor Group was deposited in a series of up to 30 transgressive-regressive (TR) events (von Bitter et al., 2006) that commonly comprise (in ascending order) carbonate, anhydrite, halite and clastic rocks. In the upper parts of the Windsor Group the TR cycles may be represented locally by carbonate overlain by thick clastic rocks.

The Codroy Group contains all the same rock constituents as the Windsor Group; however, the stratigraphic nomenclature of the former (Knight, 1983) obscures the stratigraphic similarities with the latter (Utting and Giles, 2004). For example, the Codroy Road and Robinsons River formations (Knight, 1983) describe a thick succession of strata that may be subdivided into four or more formations in the Windsor Group (Fig. 2). The following discussion describes the major cycles of the Windsor Group (Giles, 1981) with reference to the stratigraphy of the Codroy Group (Knight, 1983).

Giles (1981) subdivided the Windsor Group into five major cycles (Fig. 2b). The selection of cycle boundaries is based in part on the first appearance of fauna and/or microfossils. A fulsome discussion of biostratigraphic studies of the Windsor Group is beyond the scope of this report and the reader is referred to von Bitter et al. (2006) for a thorough review. The early work of Bell (1929) should be noted, since this work established a biostratigraphic framework that continues to be widely used. Bell (1929) used macro fauna (cephalopods, brachiopods, pelecypods, gastropods, corals and bryozoa) to subdivide the Windsor Group into Lower and Upper zones, which were further subdivided into 5 subzones (A through E, in ascending order; Fig. 2b). The subzones of Bell (1929) broadly compare to the major cycles of Giles (1981), although some subzone boundaries may not correspond exactly to major cycle boundaries (Fig. 2b).

Major Cycle 1 is generally characterized by a basal carbonate unit overlain by thick anhydrite and halite, which may be locally overlain by a thin clastic interval. Cycle 1 may exhibit very thick evaporite rocks, especially halite, which locally flowed into salt structures (Howie, 1988). In the Windsor Group type area (Giles, 1981), Cycle 1 is approximately 400 m thick. The Ship Cove and Codroy Road formations broadly correlate with Major Cycle 1 (Fig. 2a and 2b). Note that the lowermost part of the Robinsons River Formation is time equivalent to Major Cycle 1 (Utting and Giles, 2004).

A marked change to numerous repeated TR cycles occurs in Major Cycle 2, which is approximately 150 m thick in the type section (Giles, 1981). The lower part of Cycle 2 generally exhibits an abundance of evaporite rocks relative to clastic rocks, whereas the upper part comprises thinner marine intervals and increased abundance of clastic rocks relative to evaporite rocks. The upper part of the lower Jeffreys Village member (Fig. 2a) broadly correlates with Major Cycle 2 (Utting and Giles, 2004).

Cycles 3 and 4 record continued cyclic deposition (Giles, 1981); however, the TR events in cycles 3 and 4 commonly comprise marine carbonate overlain by thick terrigenous clastic rocks, and typically exhibit fewer evaporite intervals as compared to cycles 1 and 2. Utting and Giles (2004) note that rocks correlative with Major Cycle 3 have not been identified in the St. George’s Bay lowlands.

Major Cycle 5 begins at the base of the youngest marine carbonate band in the Windsor Group (Giles, 1981) and records the transition from cyclic marine-terrestrial depositional setting to a continental depositional setting. The top of the Windsor Group is defined as the top of the youngest limestone interval (Kennetcook limestone in the Windsor type area; Giles, 1981). Therefore, Major Cycle 5 includes the boundary between the Windsor Group and the overlying Mabou Group.

The Codroy Group is exposed on the southern coast of St. George's Bay and along brooks and rivers of the adjacent onshore area (Fig. 3). The area known as the St. George's Bay lowlands extends north-easterly from Ship Cove and is underlain by Carboniferous rocks assigned to the Anguille, Codroy and Barachois groups. Knight (1983) subdivided the Codroy Group (Fig. 2a) into the Ship Cove, Codroy Road, Woody Cape, and Robinsons River formations. The Woody Cape Formation does not occur within the study area; discussion of this unit is limited in this report.

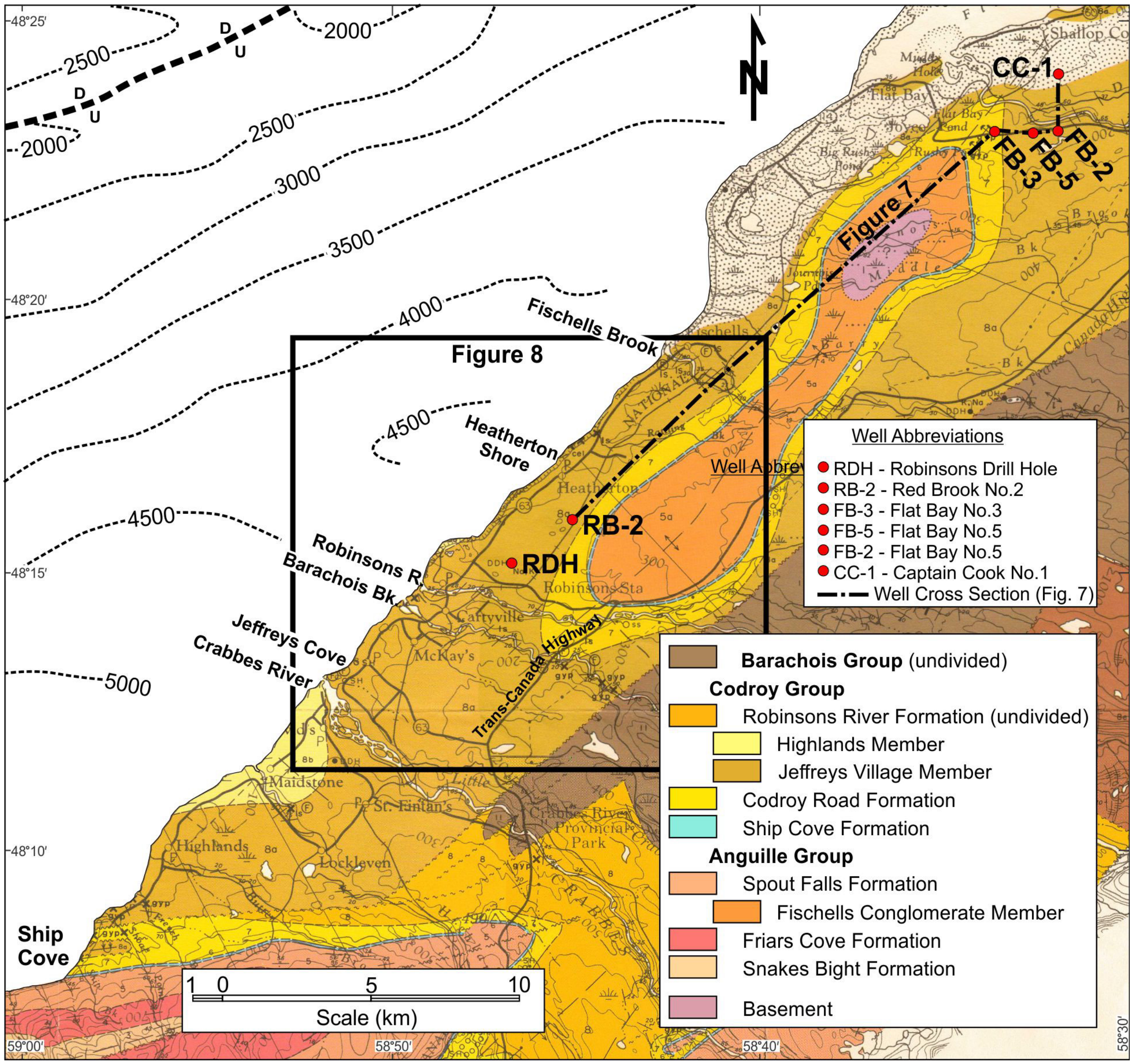

Figure 3: Geology of the St. George's Bay lowlands reproduced from Map 82-1 (Knight, 1983). Dashed lines in St. George's Bay represent approximate depth in metres based on time structure contours from Snyder (2019) and Durling and Marillier (1993) and depth conversion using an average seismic velocity 4500 m/s from surface.

The basal Ship Cove Formation (Fig. 2a) comprises mainly laminated grey limestone, which may become shaley limestone up-section. Knight (1983) reports that this unit is relatively uniform in thickness averaging 18-20 m and generally lies conformably on older rocks. It is considered correlative to the Macumber Formation of the Windsor Group (Utting and Giles, 2004).

A mixed assemblage of clastic, carbonate and evaporite rocks assigned to the Codroy Road Formation (Knight, 1983) overlies the Ship Cove Formation. The lower contact of the Codroy Road Formation is conformable or gradational whereas the definition of the upper contact is variable (Knight, 1983). The upper contact at Fischells Brook (Fig. 3) is placed at the top of the highest gypsum unit within a succession assigned to Subzone A (Knight, 1983; Utting and Giles, 2004). In contrast, at Ship Cove (Fig. 3), the upper contact is placed above the gypsum unit that overlies the Cormorant Limestone (Knight, 1983), which was assigned by Bell (1948) to Subzone B (Fig. 2b). Von Bitter and Plint-Geberl (1982) correlate the Cormorant Limestone at Ship Cove with rocks stratigraphically higher than the Codroy Road Formation at Fischells Brook. Although carbonate beds are included in the Codroy Road Formation at Ship Cove there are no carbonates in the formation at Fischells Brook. Utting and Giles (2004) suggest that the correlation of Knight (1983) may need to be reassessed. In this study, the author follows Utting and Giles (2004) and restricts the Codroy Road Formation to those strata interbedded with the anhydrite units stratigraphically overlying the Ship Cove Formation. Within the context of the stratigraphic uncertainties for the Codroy Road Formation, estimates of thickness range from 120 m to 300 m (Knight, 1983).

The upper Codroy Group in the St. George’s Bay lowlands comprises mainly terrigenous clastic rocks with subordinate carbonate and evaporite rocks assigned to the Robinsons River Formation (Knight, 1983). Utting and Giles (2004) subdivided the Robinsons River Formation into informal lower and upper units (Fig. 2a) on the basis of biostratigraphic data and lithologic differences. The key feature of the lower Robinsons River formation is interbedded limestone beds within a succession of coarse- to fine-grained siliciclastic rocks, whereas the upper Robinsons River formation comprises mainly terrigenous clastic rocks with a minor marine interval described as the Crabbes-Jeffreys Limestone (Utting and Giles, 2004). The top of the latter unit defines the contact between the informal upper Jeffreys Village (Utting and Giles, 2004) and Highlands (Knight, 1983) members (Fig. 2a).

Utting and Giles (2004) correlate the upper Robinsons River formation with Subzones D and E (Fig. 2b) and suggest that the Crabbes-Jeffreys Limestone is a probable correlative to the Kennetcook (or E1) Limestone in the Shubenacadie Basin. The clastic dominated upper Robinsons River formation appears similar to the clastic dominated upper part of the Windsor Group in the west Antigonish Basin (Fig. 2c).

Stratigraphic Sections from Field Studies

Lithostratigraphic and biostratigraphic control for the Codroy Group is provided by limited outcrop and measured stratigraphic sections compiled by various workers in the St. George's Bay lowlands. The following paragraphs summarize the results of previous work.

Fischells Brook Sections

The outcrops on Fischells Brook on the northwest limb of the Flat Bay Anticline (Fig. 3) expose strata from the Ship Cove, Codroy Road and Robinsons River (Jeffreys Village Member, lower part) formations (Fig. 4a and b). The Ship Cove Formation comprises approximately 24 m of laminated limestone and associated black shale with minor sandstone (Knight, 1983). Von Bitter and Plint-Geberl (1982) and

Utting and Giles (2004) correlate these rocks with Subzone A (Bell, 1929; Major Cycle 1 of Giles, 1981) on the basis of conodonts and palynomorphs, respectively. The Ship Cove Formation is described as a widespread and uniform laminated limestone deposit (Knight, 1983). The unit bears strong resemblance to the Macumber Formation of the Windsor Group in Nova Scotia (Fig. 2c) and is generally considered a correlative unit to the Macumber Formation (von Bitter and Plint-Geberl, 1982; Waldron et al., 2017).

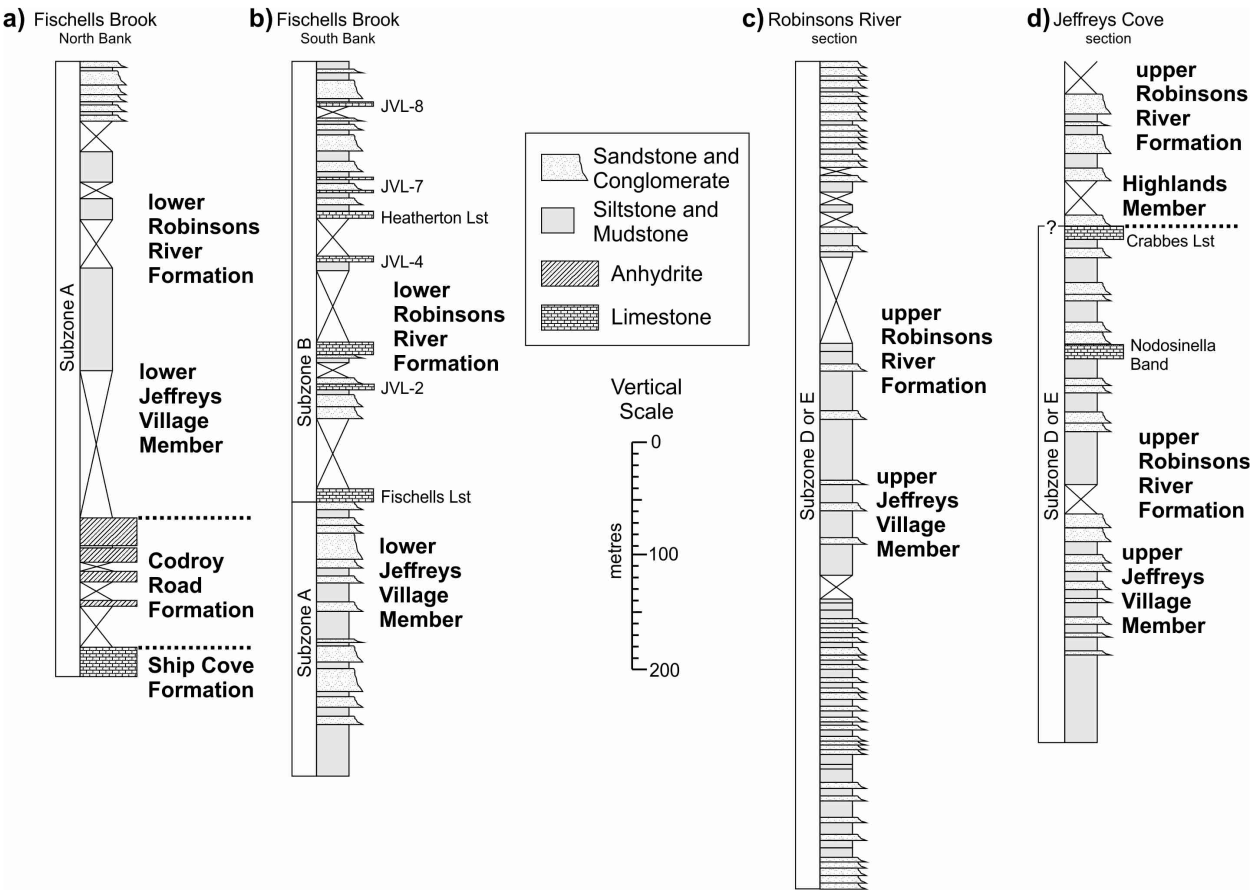

Figure 4: Stratigraphic sections described in the text and used to construct the Bay St. George composite section. Figures a) and b) redrawn from Knight (1983) and figures c) and d) redrawn from Utting and Giles (2004).

Overlying the Ship Cove Formation at Fischells Brook is approximately 112 m of gypsum and unknown rock beneath several concealed intervals (Fig. 4a), which is assigned to the Codroy Road Formation (Knight, 1983). The upper contact is placed at the top of the highest exposed gypsum unit (Knight, 1983). The gypsum dominated Codroy Road Formation at Fischells Brook (Fig. 4a) is comparable to the Carrolls Corner Formation of the Windsor Group in the Shubenacadie Basin (Fig. 2c) in Nova Scotia (Giles, 1981). However, elsewhere in southwestern Newfoundland (e.g. Ship Cove) Subzone B carbonate rocks (von Bitter and Plint-Geberl, 1982) may be included in the Codroy Road Formation (Knight, 1983) making comparison to the Windsor Group difficult.

Rocks assigned to the lower Jeffreys Village member of the lower Robinsons River formation (Utting and Giles, 2004) overlie the Codroy Road Formation (Fig. 2a). The section above the Codroy Road Formation and below the Fischells Limestone (Fig. 4a and 4b) comprises 350 m of mainly mudstone overlain by approximately 200 m of sandstone with interbedded mudstone. Knight (1983) correlates the sandstone beds in the upper part of figure 4a with the lowermost sandstone beds in figure 4b. These rocks correlate with Subzone A (note the side-bars next to the lithology columns in figure 4) on the basis of spore assemblages typical of the *pusilla-columbaris* Zone (Utting and Giles, 2004).

The upper part of the section on the south bank of Fischells Brook section (Fig. 4b) consists of up to 8 limestone units interbedded with clastic rocks, the lowermost limestone being the Fischells Limestone. This interval is approximately 380 m thick and is assigned to Subzone B (von Bitter and Plint-Geberl, 1982; Utting and Giles, 2004), and may be interpreted as numerous repeated TR cycles characteristic of Major Cycle 2 (Giles, 1981).

Note that the lower Jeffreys Village member comprises strata assigned to Subzones A and B (Utting and Giles, 2004).

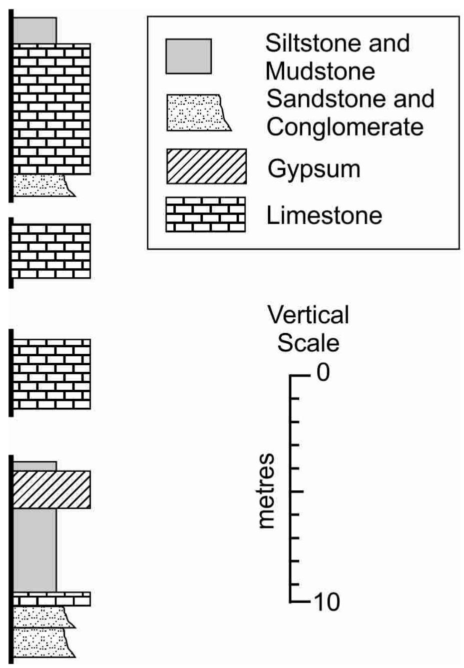

Figure 5: Four isolated carbonate intervals identified on Barachois Brook by Knight (1983) and von Bitter and Plint-Geberl. Redrawn from Knight (1983).

Barachois Brook section

Fine-grained clastic rocks interbedded with limestone and gypsum are located on Barachois Brook (Fig. 5) in the vicinity of the Trans-Canada Highway (Fig. 3). Von Bitter and Plint-Geberl (1982) studied conodont macrofossils from these outcrops, as well as outcrops to the west of the Trans-Canada Highway; they tentatively assigned these rocks to Subzone B. Knight (1983) correlated two fossiliferous dolomitic limestones on Barachois Brook with the Fischells Limestone and JVL-2 of the Fischells Brook sections, although specific limestones on Barachois Brook were not identified in this correlation. Knight's (1983) correlation, combined with the Subzone B assignment by Von Bitter and Plint-Geberl (1982), suggests that the limestones on Barachois Brook are correlative with the Subzone B limestones on Fischells Brook (Fig. 4b).

No evaporite rocks were identified in the Fischells Brook south bank section (Fig. 4b); however, concealed intervals commonly occur stratigraphically above limestone units. Gypsum occurrences were noted at Barachois Brook (Fig. 5), where Knight (1983) mapped gypsum at three different localities. Evaporite rocks may be better exposed at Barachois Brook than at Fischells Brook, where they may be represented by concealed intervals at Fischells Brook. Or, perhaps the proportion of evaporite rocks in Subzone B of the Codroy Group increases toward the southwest. Thick, strongly deformed gypsum and limestone beds assigned to Subzone B are observed at Ship Cove (Knight, 1983; Von Bitter and Plint-Geberl, 1982; Snyder and Waldron, 2021).

Robinsons River and Jeffreys Cove sections

Utting and Giles (2004) compiled stratigraphic sections totalling an estimated 2200 m comprising the upper part of the Robinsons River Formation (Fig. 2a). The Robinsons River (Fig. 4c) and Jeffreys Cove (Fig. 4d) sections describe strata from the upper Jeffreys Village (Utting and Giles, 2004) and Highlands members. The succession consists of mainly red sandstone and siltstone with minor grey shale, which Knight (1983) interprets as alluvial deposits. Thin (< 10 m) marine limestone beds occur in the upper 100 m of the Jeffreys Village Member and the top of the highest carbonate unit, described as the Crabbes-Jeffreys limestone, marks the contact with the overlying Highlands Member (Utting and Giles, 2004). Utting and Giles (2004) correlate these rocks with Subzones D and E (Fig. 2a).

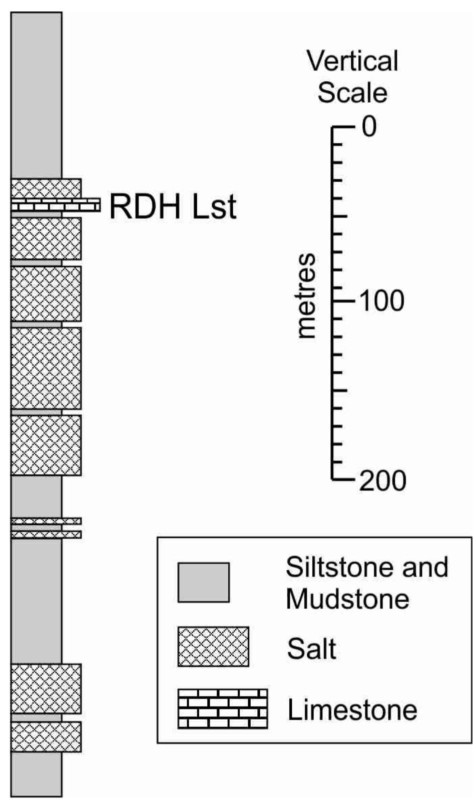

Figure 6: Lithological log of the Robinsons drill hole, redrawn from Knight (1983).

Borehole Data

Several deep boreholes were drilled within the study area. The westernmost borehole used in this study was the Robinsons drill hole (see "RDH" in Fig. 3 for location). Lithologic information on this borehole was based on the work of Knight (1983). Strata intersected by the borehole comprise roughly 450 m of interbedded salt and mudstone (Fig.6). A single, uncorrelated limestone bed is noted near the upper part of the borehole, which is identified in this report as the RDH Limestone. There is no known biostratigraphic data from this borehole.

The Red Brook No.1 borehole (Vulcan Minerals Inc., 2007) was drilled to 186 m total depth (see RB-2 in figure 3 for location). The upper part of the borehole encountered overburden underlain by 37 m of sandstone. At a depth of 123 m, gypsum and anhydrite measuring 42 m thick were intersected. These rocks were underlain by a 21 m thick sandstone interval before reaching total depth.

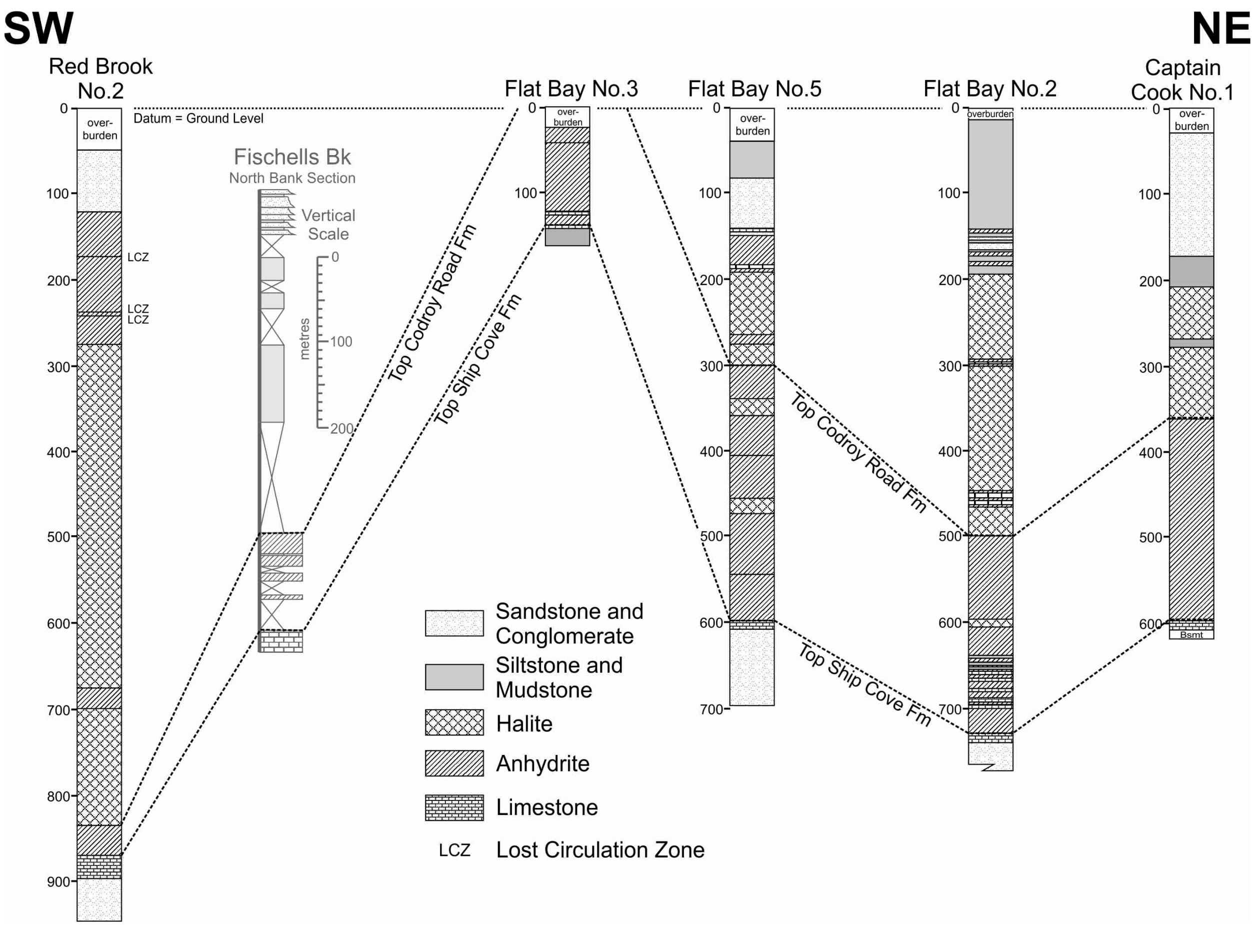

Figure 7: Lithological logs for selected boreholes described in the text. All depths are in metres. See figure 3 for cross section location. The lower part of the Codroy Group from the Fischells Brook section (Fig. 4a) is also shown.

A second borehole drilled at an immediately adjacent location (Red Brook No.2, Fig. 7) also intersected gypsum at 123 m depth (Vulcan Minerals Inc., 2010); however, the thickness of the gypsum interval in Red Brook No.2 was reported to be thicker (160 m). Lost circulation zones (LCZ in Fig. 7) at multiple depths were encountered in within this gypsum interval. A probable sandstone interval was noted at

173 m (as compared to 165 m in Red Brook No.1). The lost circulation zones in Red Brook No.2 are interpreted by the author of this report as thin (1-2 m) salt intervals on the basis that lost circulation problems were resolved once the drilling mud was replaced with a salt-saturated drilling mud.

Massive salt was intersected at 283 m in Red Brook No.2. The salt interval was greater than 500 m thick and contained minor interbeds of anhydrite. The salt was underlain by 49 m of anhydrite assigned to the Codroy Road Formation and 12 m of Ship Cove Formation (Vulcan Minerals Inc., 2010). The base of the Codroy Group was logged at 987 m. The stratigraphy reported in the Red Brook No.2 well, particularly at depths below 283 m, is characteristic of Major Cycle 1 (Giles, 1981).

Given that evaporitic rocks are generally poorly represented in outcrop, a number of boreholes were reviewed for this report to assess the variability of evaporite rocks in the subsurface (Fig. 7). In general, the Codroy Road Formation thickens from about 30 m in the southwest to 240 m thickness in the northeast. The Fischells Brook section (Fig. 4a) is shown in figure 7 for comparison to the borehole logs, which further supports the general trend of the increased thickness of the Codroy Road Formation toward the northeast, or conversely, decreasing thickness to the southwest. Therefore, the implied uniform thickness of the Codroy Road Formation shown on the geology map of Knight (1983) is not likely an accurate representation of formation thickness (Fig. 3).

Form Line Contouring

Form line contouring was employed to develop a structure contour map for the northwest limb of the Flat Bay Anticline (Fig. 8). The form line map was used to guide the stratigraphic placement of borehole data and measured sections during assembly of the composite stratigraphic section.

A form line contour map is a structure contour map constructed from bedding attitudes alone (Badgley, 1959; Ragan, 1985). The general structure is represented the spacing and pattern of form line contours; contour spacing is a function of bedding dip and contour lines are drawn parallel to bedding strike. Since bedding attitudes may be derived from outcrops representing multiple stratigraphic horizons on a geologic map (e.g. Fig. 3), the structure contours do not represent any one surface and, as such, cannot be assigned absolute values (Badgley, 1959; Ragan, 1985).

Figure 8 shows the form line map constructed using a 500 m contour interval. Contours were constrained by bedding attitude measurements compiled from Knight (1983) and Von Bitter and Plint-Geberl (1982). The pattern of the form line contours honours the interpreted distribution of the Ship Cove Formation from Knight (1983), as well as the bedding strike from outcrop measurements. The form line contours represent increasing depth down-dip toward the north and west away from the core of the Flat Bay Anticline (note the tick marks on the upper contact of the Ship Cove Formation showing dip direction).

The strike of beds in the study area is generally northeast, with some southeast and east striking beds located near the axis of the Flat Bay Anticline in the southwestern part of figure 8. In general, the strata of the Codroy Group dip more gently inland than at the coast, and bedding dips are generally lower in the southwestern part of the map area the than in the northeast. For example, bedding attitudes recorded on the coast are in the range of 50° to 80° whereas on Barachois Brook (see locality “A” in Fig. 8) bedding dips were reported in the range of 20° to 30°. Small-scale folds identified on Fischells Brook

(Knight, 1983) in the northeastern part of the map area were not represented in the construction of the form line map. Outcrop distribution is sparse throughout the study area and no outcrops were observed in a large area in the southwestern part of figure 8. The contours were truncated at the location of the Barachois Fault (Fig. 8). Note that Knight (1983) mapped no faults on the northwest limb of the Flat Bay Anticline.

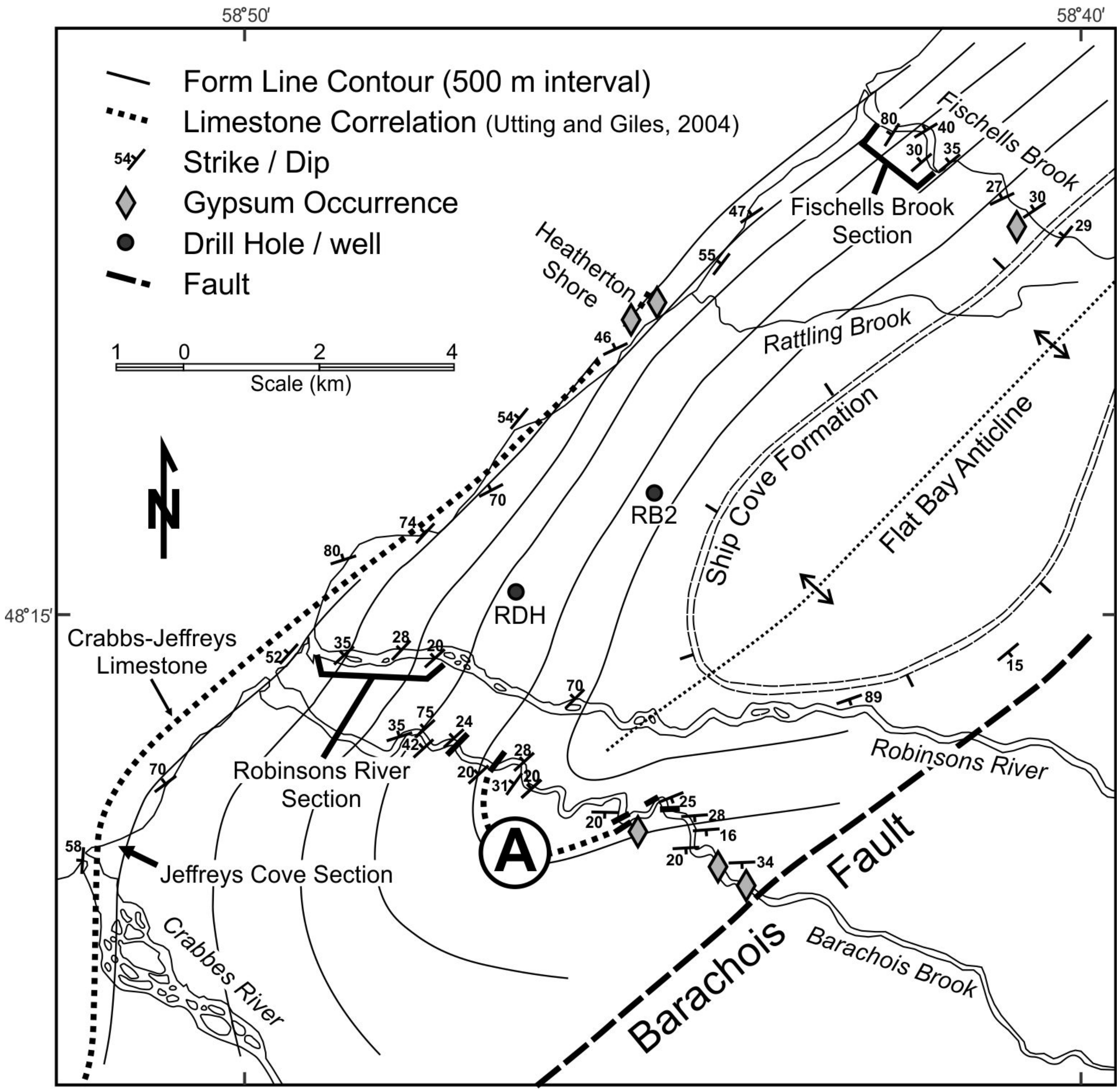

Figure 8: Form line map of the St. George's Bay lowlands. Strike and dip data were compiled from Knight (1983) and Von Bitter and Plint-Geberl (1982). See text for discussion.

The Crabbes-Jeffreys Limestone was mapped on the coast from Heatherton Shore to Crabbes River (Knight, 1983; Utting and Giles, 2004), approximately 12km. This stratigraphic marker was used to guide form line contouring. The Crabbes-Jeffreys Limestone and the Ship Cove Formation converge slightly in map pattern from southwest to northeast. Bedding dips are somewhat stepper in the northeast (35^o to 50^o on Fischells Brook) than in the southwest (20^o to 30^o), which is reflected in the spacing of the form line contours (Fig. 8). However, the relative difference in bedding dip does not fully account for the northeastward convergence between the Ship Cove Formation and the Crabbes-Jeffreys Limestone. The contour spacing calculated using the principles of form line contouring suggests approximately 2500 m of strata in the vicinity of Rattling Brook and greater than 3000 m of strata in the area of Robinsons River and Barachois Brook, suggesting that the Codroy Group may be thicker in the southwest than in the northeast.

Composite Section

A composite section is presented in figures 9 and 10 that was compiled from the stratigraphic sections and borehole data included in this report. Column "a" in each figure identifies the stratigraphic section or well bore used in the construction of the composite section and column "b" shows the lithology. The rationale used for relative placement the various stratigraphic sections and boreholes in the assembly of the composite section is described below, starting at the base.

The Fischells Brook (north bank) section (Fig. 4a) and the Red Brook No.2 well (Fig. 7) demonstrate the nature of the Ship Cove and Codroy Road formations in St. George's Bay lowlands. The Fischells Brook section is incomplete due to concealed intervals, which may be indicative of dissolved evaporite beds.

Since the Red Brook No.2 well documents an apparently complete lower Codroy Group interval, including halite intervals, it was selected to represent the basal portion of the composite section. The lithologies encountered in the Red Brook No.2 well are representative of those observed in a typical Major Cycle 1 setting (Giles, 1981); that is, a basal carbonate overlain by anhydrite and thick salt (see Fig. 2c for examples). No biostratigraphic information is available for the Red Brook No.2 well; however, given the similarity of the succession to Major Cycle 1 strata, the assignment appears reasonable. Note that the surface location of the Red Brook No.2 well is located approximately 1000 m down-dip from the Ship Cove Formation (Fig. 8) on the form line map (assuming the outcrop of the Ship Cove Formation represents 0 m). This compares favourably to the 987 m depth for the base of the Ship Cove Formation in the well, suggesting that the stratigraphic thickness estimated by form line contouring is consistent with the stratigraphic thickness drilled in the well.

Gypsum and anhydrite, with minor sandstone and halite interbeds, were intersected in the upper part of the Red Brook No.2 well between 123 m and 283 m (Fig. 7). The gypsum and anhydrite are likely part of Major Cycle 1 because, by definition, the base of Major Cycle 2 is a carbonate unit (Giles, 1981); no limestone beds were reported above the Codroy Road Formation the Red Brook No.2 well (Vulcan Minerals, 2010). Therefore, the base of Major Cycle 2 must occur stratigraphically above the succession drilled in the Red Brook No.2 well.

The stratigraphy in the Robinsons drill hole was placed immediately above the Red Brook No.2 well in the composite section. The thickness of rock drilled in the Robinsons drill hole (450 m) is roughly equivalent to the structural elevation difference (500 m) between the surface locations of the two boreholes on the form line map (Fig.8). The strata at the bottom of the Robinsons drill hole may correlate approximately with the upper most strata in the Red Brook No.2 well. Alternatively, there may be an unknown thickness of strata not sampled be either borehole. Correlation of the RDH limestone (Fig. 6) to the limestone units on Fischells Brook (Fig. 4b) is unknown. If the RDH limestone were to correlate to the Fischells limestone it would denote the base of Major Cycle 2. If it were to correlate to

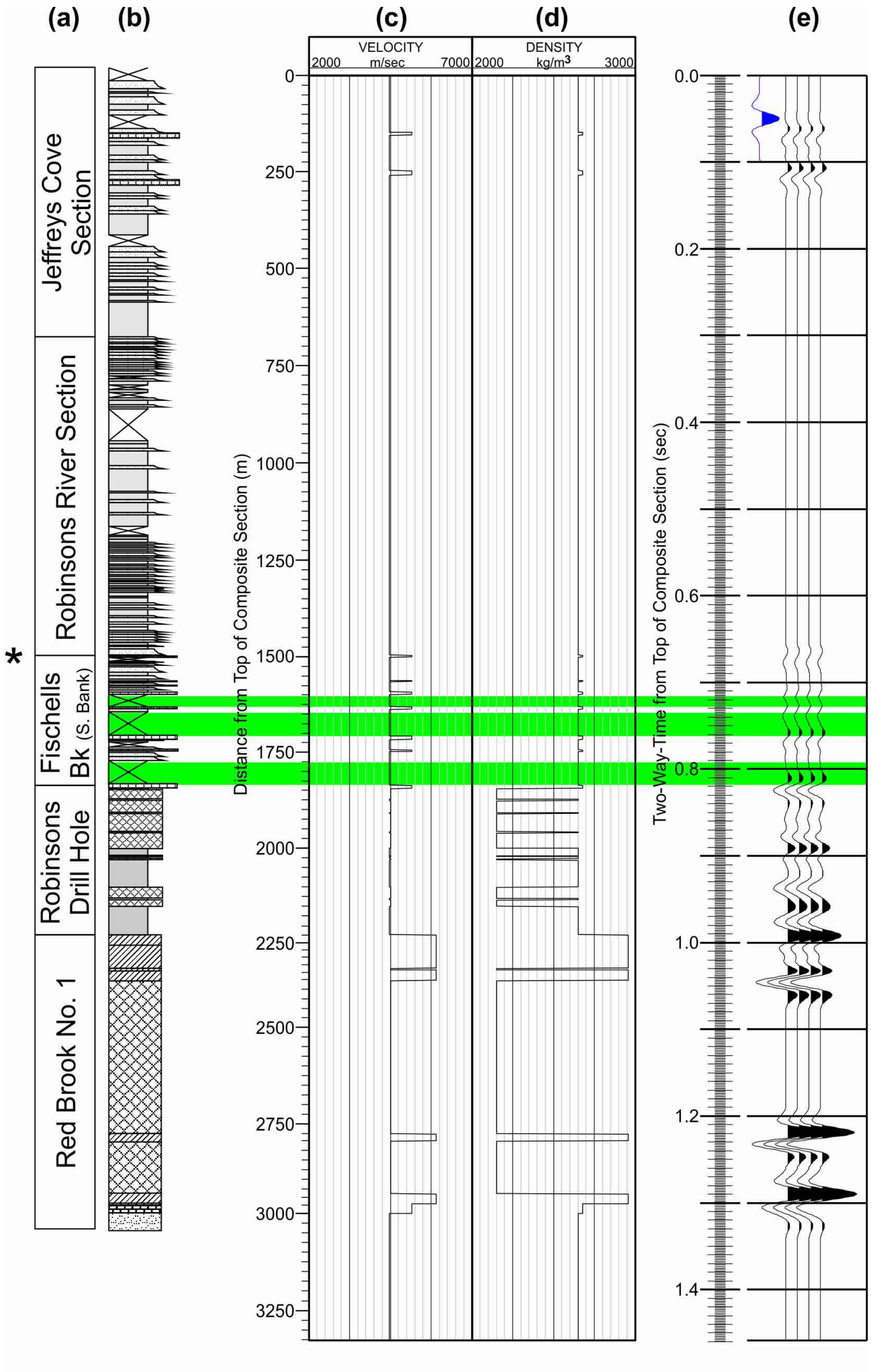

Figure 9: Composite section for the St. George's Bay lowlands. The green bands highlight concealed intervals that were replaced with clastic rocks for calculation of the synthetic. The asterisk beside column (a) denotes a contact which is not supported by field evidence. See text for discussion.

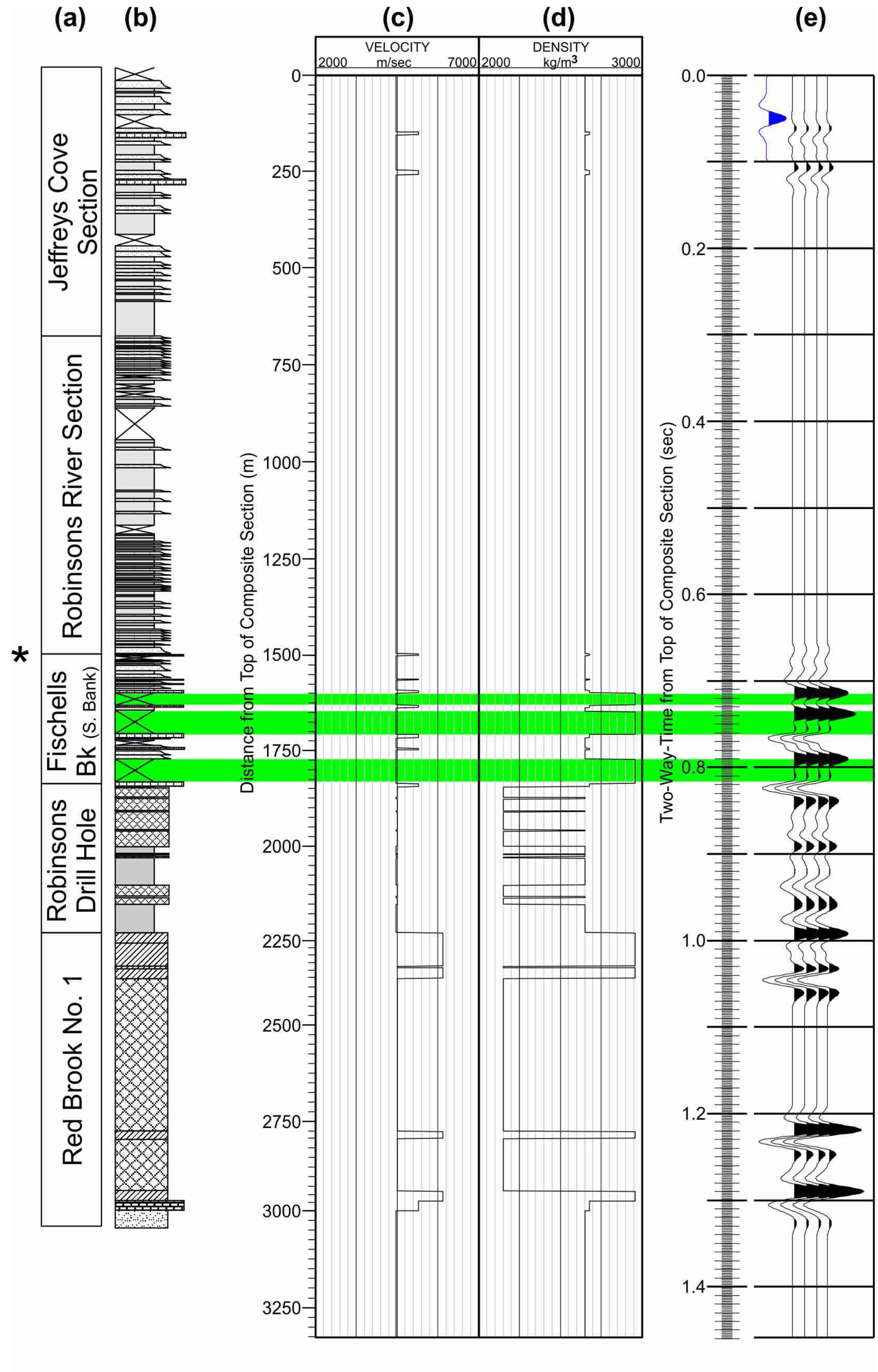

Figure 10: Composite section for the St. George's Bay lowlands. The green bands highlight concealed intervals that were replaced with anhydrite for calculation of the synthetic. The asterisk beside column (a) denotes a contact which is not supported by field evidence. See text for discussion.

a stratigraphically higher carbonate unit at Fischells Brook, the strata in the lower part of the Robinsons drill hole would be assigned to Major Cycle 2. In either case, the placement of the Robinsons drill hole immediately above strata in the Red Brook No.2 well appears reasonable.

The strata overlying the Fischells limestone from the Fischells Brook (south bank) section (Fig. 4b) were placed above the RDH limestone (Fig. 6) in the composite section. Therefore, the RDH limestone (Fig. 6) is correlated with the Fischells Limestone in this report. This correlation is admittedly conjectural but is based on comparison with the Windsor Group in Nova Scotia (Bell, 1929; Giles, 1981) where the first occurrence of carbonate above Cycle 1 marks the beginning of Cycle 2 (Fig. 2c). Further, correlation of the upper most strata in the Robinsons drill hole with the lowermost Subzone B strata on Fischells Brook is consistent with form line mapping (Fig. 8).

Regional studies of the Windsor Group (Bell, 1929; Giles, 1981) document the occurrence of Subzone C strata overlying strata of Subzone B (Fig. 2). Although Subzone C strata (Woody Cape Formation) occur in the Codroy lowlands (Knight, 1983; Utting and Giles, 2004; von Bitter et al., 2006), no such strata have been identified in the St. George's Bay lowlands (Utting and Giles, 2004). Marine carbonates at Fischells Brook (Heatherton limestone, for example; Fig. 4b) were correlated by Knight (1983) with similar carbonate units at Rattling Brook and Heatherton (Fig. 8). Utting and Giles (2004) traced the Crabbes-Jeffreys limestone (the youngest marine limestone in the upper Robinsons River formation; Fig. 4d) from Crabbes River to Heatherton Shore (Fig. 8), not far from Rattling Brook. Subzone C strata have not been recognized between Heatherton Shore and Rattling Brook, or even at Fischells Brook. That these strata have not been identified in the St. George's Bay lowlands does not preclude their presence and complicates the construction of the composite section. However, if Subzone C strata were to be included in the composite section, questions arise regarding thickness and lithologic composition.

The most likely proxy for Subzone C strata would be the Woody Cape Formation in the Codroy lowlands, which comprises interbedded sandstone, siltstone and shale with as many as six thin limestone intervals (Knight, 1983). Given that the composition of the Woody Cape Formation is mainly clastics and thin carbonate, its composition is similar to the upper Robinsons River formation (Figs. 4c and 4d; Utting and Giles, 2004). The presence or absence of a few hundred metres of clastic rocks, within a section approximately 1500 m thick, is likely inconsequential for the calculation of a synthetic seismic trace. Therefore, the upper part of the composite section is represented by the Robinsons River and Jeffreys Cove measured sections (Figs. 4c and 4d), even though there is no evidence to support a contact between the Fischells Brook section and the Robinsons River section (see asterisk beside column a in figures 9 and 10).

Synthetic Seismogram

A synthetic seismic trace was computed using average rock properties calculated from five petroleum wells in the Gulf of St. Lawrence (Table 1). Values for velocity (Fig. 9c and 10c) and density (Fig. 9d and 10d) were assigned to each lithology compiled for the composite section. The synthetic seismic trace was computed using a 20 Hz Ricker wavelet as an input to the GeoSyn software developed by Kingdom Suite (Figs. 9e and 10e).

The key features of the seismogram are (in ascending order): high amplitude reflections associated with the Codroy Road and Ship Cove formations at the base; a low amplitude interval related to the Cycle 1 salt; a series of high amplitude reflections resulting from interbedded halite and clastic rocks from the Robinsons Drill Hole and interbedded carbonate and clastic rocks from the Fischells Brook sections; and an upper low amplitude interval capped by weak reflections from the Crabbes-Jeffreys Limestone. The green bands in figures 9 and 10 highlight concealed intervals in the Fischells Brook south bank section above the Fischells Limestone (Fig. 4b). Figures 9 and 10 show replacement of the green highlighted concealed intervals with clastic rocks and anhydrite, respectively. Concealed intervals in the Robinsons River and Jeffreys Cove sections were replaced with clastic rocks only. Note that higher amplitude reflections are observed where the concealed intervals are replaced by anhydrite (Fig. 10).

The justification for replacing concealed intervals with anhydrite in the Subzone B interval is based on field observations. Knight (1983) identified a gypsum bed approximately 2 m thick at Barachois Brook (Fig. 5) in addition to at least two other gypsum occurrences mapped in the area (Fig. 8). Carbonate rocks associated with these gypsum beds were assigned to Subzone B by Von Bitter and Plint-Geberl (1982). Gypsum correlated to Subzone B also occurs at Ship Cove (Von Bitter and Plint-Geberl, 1982, Snyder and Waldron, 2021). These widely separated gypsum occurrences may suggest that Windsor Subzone B (Major Cycle 2) evaporite rocks may be widely distributed in the subsurface.

Well Name	Clastics		Salt		Anhydrite		Limestone	
	Density (g/cm^3)	Velocity (km/s)	Density (g/cm^3)	Velocity (km/s)	Density (g/cm^3)	Velocity (km/s)	Density (g/cm^3)	Velocity (km/s)
Northumberland Strait F-25	**2.65**	**4096**	**2.15**	**4509**	**2.95**	**6097**	**2.68**	**5440**
	2.60-2.70	3846-4347	2.00-2.20	4504-4587	2.90-3.0	5714-6369	2.65-2.70	4878-5882
Cap Rouge F-52	-	**4326**	-	**4524**	-	**5814**	-	**4797**
	-	3773-4878	-	4347-4587	-	5714-5882	-	4587-4878
Bradelle L-49	**2.65**	**4347**	-	-	-	-	**2.69**	**5405**
	2.60-2.70	4000-5000	-	-	-	-	2.65-2.71	5208-5586
Brion Island No.1	-	**4651**	-	**4504**	-	**5714**	-	**5248**
	-	3802-5291	-	4464-4587	-	5263-6211	-	5000-5405
Irishtown No.1	**2.65**	**4751**	**2.15**	**4484**	**2.96**	**5988**	**2.68**	**5137**
	2.60-2.70	4444-5494	2.10-2.20	4347-4545	2.93-3.00	5618-6134	2.65-2.74	5020-5350
Average Values	**2.65**	**4456**	**2.15**	**4505**	**2.96**	**5903**	**2.68**	**5156**

Table 1: Rock property values for density and velocity estimated from well logs from various wells in the Gulf of St. Lawrence (see Fig. 1 for well locations). For each well, the upper number is the estimated value and the lower number denotes the range of values from the well logs. The bottom row shows "Average Values" assigned to each lithology for computation of the synthetic seismic trace.

The vertical distribution of seismic reflections in the synthetic seismogram is dependent on the relative order of the input geologic sections and borehole data. Some discussion is warranted to assess whether a different stratigraphic order would significantly impact the final synthetic seismic trace.

It is clear that the Robinsons River and Jeffreys Cove measured sections should be placed at the top of the composite section. Similarly, the Red Brook No.2 well is appropriately placed at the bottom. The more subjective decisions made in the construction of the composite section regard the relative placement of the Robinsons Drill Hole and the Fischells Brook sections. However, if the order of these two intervals were to be reversed (or combined by correlating the RDH Limestone with an arbitrary Windsor 'B' limestone), the overall character of the seismogram would be unchanged; that is, the central portion of the seismogram would comprise higher amplitude reflections than the thick clastic rocks above and the thick halite unit below. Only the details of the reflections within the high amplitude central part of the seismogram would change.

Similarly, the presence or absence of Subzone C rocks is unlikely to affect the overall appearance of the synthetic seismogram. The rocks closest to the study area assigned to Subzone C comprise sandstone, siltstone and mud rock intercalated with thin (~ 1 m; Knight, 1983) carbonate beds of the Woody Cape Formation. Its composition, being similar to the upper Robinsons River formation (Utting and Giles, 2004) and devoid of thick evaporite rocks, is likely to yield low amplitude reflections. Therefore, the seismic reflections in the upper Codroy Group above the Subzone B interval are likely to be uniformly low amplitude.

Note that the objective of this work is not to study small scale variations in reflection amplitude from one bed to another, but to develop an understanding of the seismic response from the major cycles (Giles, 1981) in the Codroy Group. From this perspective, the composite section compiled for this report, and the resulting synthetic seismogram, appears reasonable.

Implications for Offshore Seismic Interpretation

The synthetic seismogram calculated from the Bay St. George composite section (Figs. 9 and 10) was compared to figure 10 of Dafoe et al. (2016), which is presented here in Figure 11. The asymmetry of the offshore basin is apparent, being shallow in the north and deep in the south. A salt structure is observed in the north-central part of the line. The northward dipping reflections at the south end of the line are interpreted as a tectonic wedge (Snyder, 2019), consistent with the thrust interpretation of Durling and Marillier (1993). Southerly dipping, high amplitude reflections are highlighted by a blue dashed line, interpreted as the base of the Ship Cove Formation (Dafoe et al., 2016; Snyder, 2019). This event was previously mapped by Durling and Marillier (1993) as the base Windsor Group and was correlated with similar reflections further west in the Gulf of St. Lawrence (Atkinson et al., 2020). A green dashed line on the seismic line denotes the top of a package of high amplitude reflections, which are folded in broad synclines to the north and south of the salt structure. A black dashed line marks the boundary between high and low frequency seismic units (Fig. 11).

The synthetic correlation point was located in the south-central part of the seismic line, on structural strike with the study area (Fig. 11, inset). This location avoids the structural complications of the tectonic wedge (Snyder, 2019) and yet allows comparison of the synthetic to thick Carboniferous stratigraphy in the offshore.

The pair of peak reflections, interpreted as Ship Cove Formation (blue dashed line), compare favourably to similar reflections at the base of the synthetic. These reflections can be traced up-dip beyond the salt structure, suggesting widespread distribution (Durling and Marillier, 1993; Atkinson et al., 2020). The reflections on the seismic profile are approximately 0.100 seconds apart, which is comparable to the time separation (0.080 seconds) of the reflections at the base of the synthetic. This correlation suggests that the basal Codroy Group reflections in St. George's Bay may represent anhydrite beds approximately 150 m apart, similar to the stratigraphy encountered in the Red Brook No.2 well (Fig. 7).

The package of high amplitude reflections below the green dashed line (Fig. 11) resemble the reflections on the synthetic seismogram at the correlation point. That the comparison is in some ways deficient may be attributed to deformation associated with tectonic wedge emplacement (Snyder, 2019). Further north, in the vicinity of the salt structure, the reflections appear to be much less deformed. This reflection package thins northward (Fig. 11). Comparable reflections on the synthetic correspond to interbedded limestone, evaporite and clastic rocks from the Robinsons drill hole and the Fischells Brook section (Figs. 9 and 10). This correlation suggests assignment to Subzone 'B', or the middle Codroy Group. The stratigraphic position of the high amplitude reflections above interpreted salt (Dafoe et al., 2016) is consistent with this correlation.

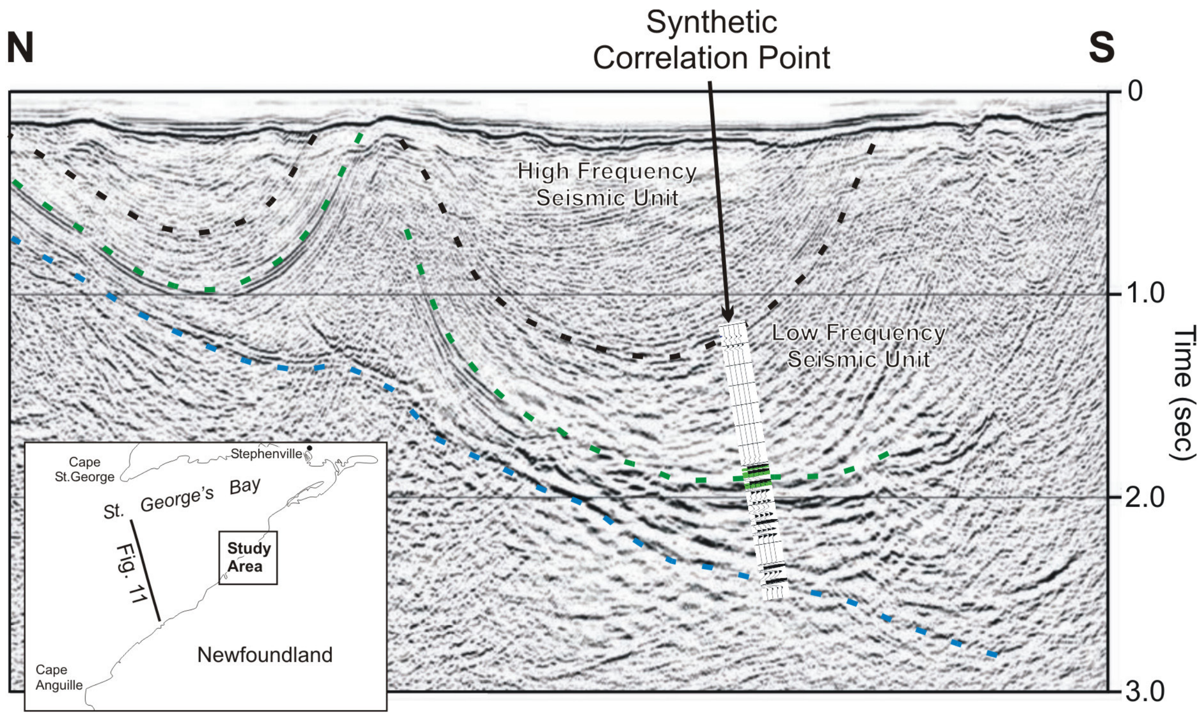

Figure 11: Seismic line (Fig. 10a of Dafoe et al., 2016) from offshore Bay St. George Subbasin with synthetic seismic trace from figure 10e superimposed. See text for discussion. CSPG© 2016, seismic image reprinted by permission of CSPG whose permission is required for further use.

Overlying the green dashed line (Fig. 11) is a low frequency seismic unit. At the synthetic correlation point, it is approximately the same time-thickness (0.600 seconds; Figs. 9 and 10) as the clastic rocks of the upper Jeffreys Village member. The absence of reflections on the synthetic results from the use of a constant acoustic impedance value for clastic rocks in this study (Table 1). No attempt was made in this study to model acoustic impedance variations in clastic rocks.

A black dashed line on the seismic data marks the boundary between the low and high frequency seismic units. Since no synthetic modeling of acoustic impedance variations in clastic rocks was conducted in this study, stratigraphic assignment of the low frequency and high frequency seismic units may only be suggested on a speculative basis. The difference in peak-to-peak time separation between reflections indicates a difference in bed thickness. Generally, thicker beds should be expected in the low frequency unit than the high frequency unit.

The upper Jeffreys Village member comprises mainly red sandstone and siltstone with minor grey shale (Knight, 1983; Utting and Giles, 2004). Multi-storied sandstone intervals up to 25 m thick are common (Fig. 4). In contrast, rocks assigned to the younger Barachois Group in Barachois Synclinorium comprise green-grey and red sandstones, pebbly sandstones, red siltstones, dark grey to black shales and mudstones, and coal beds (Knight, 1983; Utting and Giles, 2004). Sandstone beds in the Barachois Synclinorium are generally 5-6 m in thickness with occasional multi-storied sandstones up to 15 m thick in the lower parts of the Barachois Group (Utting and Giles, 2007). On the basis of sandstone bed thickness, the author speculatively correlates the low frequency seismic unit to the upper Jeffreys Village member. Similarly, the high frequency seismic unit is correlated with undivided Barachois Group. Coincidentally, the time-thickness of the low frequency seismic unit at the synthetic correlation point is approximately the same as the time-thickness of the upper Jeffreys Village member on the synthetic.

The different seismic reflection character of the low and high frequency seismic units suggests a different depositional environment from one to the other. Knight (1983) interprets a significant change in paleoenvironment from arid and semiarid alluvial plain in the upper part of the Codroy Group to humid alluvial fan deposition in the Barachois Group. This interpreted change in paleoenvironment may support the correlation of the low frequency and high frequency seismic units to the upper Jeffreys Village member (Codroy Group) and the undivided Barachois Group, respectively.

The discussion presented in the previous paragraphs suggests that the black dashed line in figure 11 may represent the approximate stratigraphic position of the Crabbes-Jeffreys limestones (Utting and Giles, 2004). However, it is unclear whether the youngest unit of the Codroy Group in the Bay St. George lowlands, the Highlands Member (Knight, 1983), is represented in the offshore seismic data.

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