Deformation and kinematic history of the Sackville and Moncton Subbasins, southeastern New Brunswick, Maritimes Basin of Atlantic Canada

by

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Abstract

The Maritimes Basin of Atlantic Canada is a structurally and stratigraphically complex basin filled from the Late Devonian to the Permian; it contains smaller subbasins with common stratigraphy separated by fault-controlled basement uplifts. The Sackville and eastern Moncton Subbasins are located in southeastern New Brunswick. Seismic data show localized unconformities within the Horton Group that indicate a complex history of movement. Basement faults controlled sedimentation and deformation during the late Devonian and early Tournaisian. In the Tournaisian and Visean, the region was shortened in association with dextral strike-slip, and normal listric faults were inverted. Low-angle faults intersect to form tectonic wedges that controlled local stratigraphy as they were inserted southward into Visean evaporites and initiated salt expulsion in the subbasins. When the seismic data are artificially flattened, restoring pre-Visean geometry, faults are seen to define a positive flower structure. The flower structure collapsed into the evaporites during the late Serpukhovian, rotating the associated tectonic wedges and producing a "wilted" flower structure with low-angle faults.

To the tune of Ob-La-Di, Ob-La-Da:

Prepping for our field work out on the east coast,
Trying to decide what gear to pack,
Maybe just some MEC pants and a flannel shirt,
And a satchel we can sling across our backs.

written in the field, 2014

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Chapter 1. Introduction

The Maritimes Basin of Atlantic Canada (Fig. 1.1) is a large (148,000 km^2) and deep (~12 km) basin filled from the Late Devonian to the Permian (Wilson and White, 2006; Gibling et al, 2008; Hibbard and Waldron, 2009). Approximately two-thirds of the Basin is offshore (Wilson and White 2006). The Maritimes Basin is structurally complex; geophysical data show a deep sedimentary basin with uplifted basement blocks separating smaller subbasins (Hibbard & Waldron, 2009). Subbasins have common stratigraphy, indicating that tectonic events happened on a basin-wide scale (Martel, 1987; van de Poll, 1993; Calder, 1998; St. Peter and Johnson, 2009; Waldron et al., 2015). Deformation within the Maritimes Basin included folding, faulting, uplift, salt expulsion, erosion, and subsidence (Calder, 1998, Wilson et al 2006, Waldron et al 2014).

Basin development is a source of debate. (van de Poll 1995; Barr and White 1996; Hibbard & Waldron, 2009)In southeastern New Brunswick, a thrust-belt was favored by Gussow (1953), oblique extension by Webb (1963, 1969), strike-slip by Martel (1987), and a rift model by McCutcheon and Robinson (1987). Authors have documented evidence that shows significant strike-slip motion (Waldron, 2004; Waldron et al, 2007; Hibbard and Waldron, 2009; Murphy et al 2011; Waldron et al 2013, Waldron et al. 2015), though these models invoke both transtensional and transpressional movement throughout basin development. Waldron et al (2015) demonstrates that major dextral movement began in the late Devonian, amounting to 200 – 300 km movement along faults on the Appalachian trend.

Major northeast-trending faults have had a significant influence on the history of the Maritimes Basin. During the Permian, basement blocks were tilted and uplifted along reactivated faults. Activity on these faults may have been prolonged by the migration of an evaporite-rich succession of the Windsor Group (Waldron et al, 2012). Regional salt expulsion was followed by erosion of uplifted strata, resulting in large

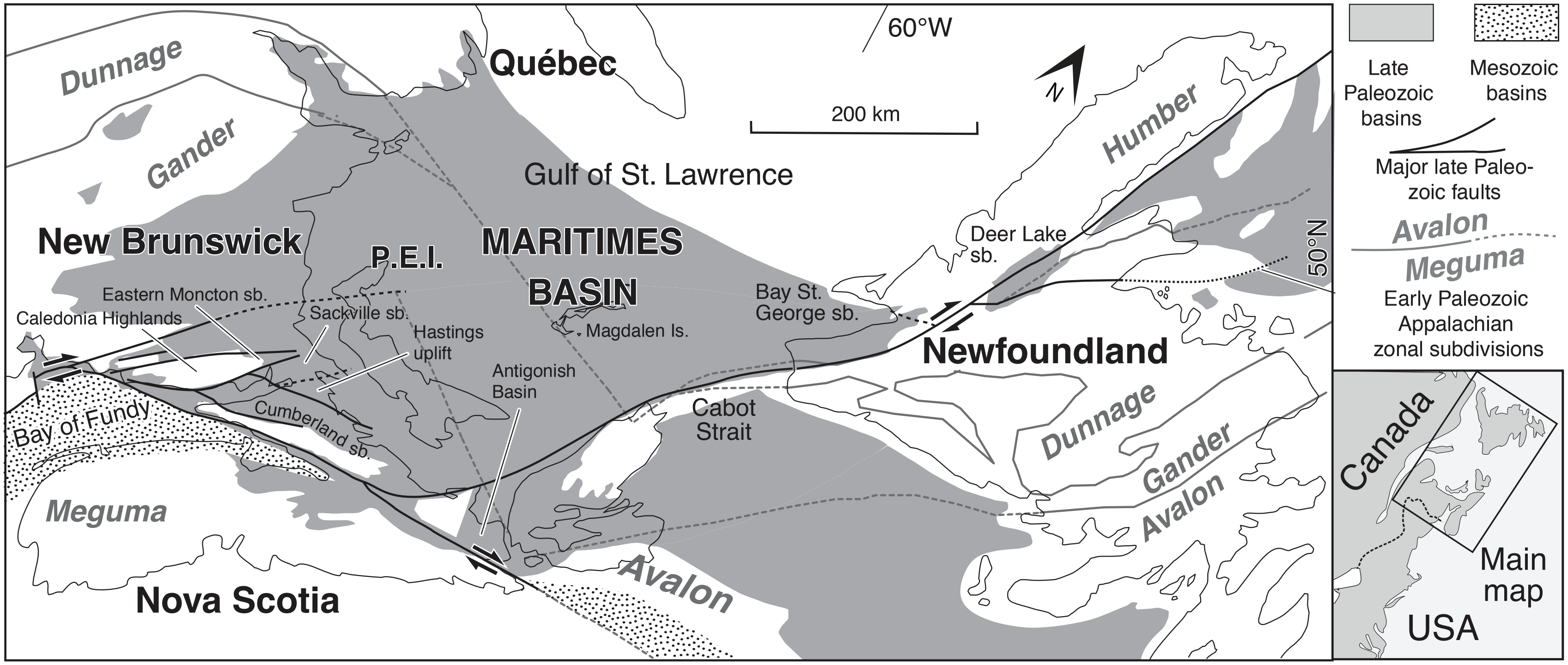

Figure 1.1. Location of the Maritimes Basin of Atlantic Canada

Location of the Maritimes Basin of Atlantic Canada, the locations of selected subbasins (sb.), and structural features. After Waldron et al. (2013) and Gibling et al (2008).

amounts of Windsor and lower Mabou strata being removed (van de Poll 1995).

1.1. Previous Work

In 1849, the first evidence of oil in New Brunswick was discovered; the solid bitumen Albertite was mined and shipped for production (St. Peter and Spady, 2003). One of the first oil exploration wells in North America was drilled ten years later; the Stoney Creek Field was discovered fifty years after that, in 1909 (St. Peter and Spady, 2003). Oil and natural gas were produced from the Stoney Creek Field from 1910 to 1991 and intermittently thereafter; the McCully Field, discovered in 2000, has been producing since 2003 (St. Peter and Spady, 2003; Wilson and White, 2006; St. Peter and Johnson, 2009).

Research spurred by industry interest was first initiated by Wright (1922) and Gussow (1953). Gussow interpreted southeastern New Brunswick by combining geological mapping, early seismic, gravity, magnetic surveys, and drilling; his primary goal was to create a "geologic picture" and gain understanding of the faults in the subsurface. Webb (1969), Bradley (1982), and Ruitenberg & McCutcheon (1982), all proposed models for basin development. Webb and Bradley proposed dextral strike-slip movement in the Maritimes Basin, which was followed up by Martel (1987), who related compressional faulting in the Sackville Subbasin to a strike-slip setting. Hibbard and Waldron (2009) interpreted dextral strike-slip displacement of ~250 km along the eastern Laurentian margin. Waldron et al (2015) expanded this interpretation, showing estimates of motion on selected major faults throughout the Maritimes Basin.

Park and St. Peter (2005) sought to constrain large regional faults in southeastern New Brunswick. The Dorchester Fault was interpreted to have the most complex history, with both dip-slip and strike-slip components (Park and St. Peter, 2005). Pre-existing Devonian-Tournaisian thrust faults were interpreted by Park et al. (2010) to control early Carboniferous deposition. St. Peter and Johnson (2009) wrote a comprehensive memoir on southeastern New Brunswick, changing stratigraphic interpretations, adding new formations and reassigning some older formations to different groups. Deep exploration wells in the Sackville Subbasin were reinterpreted by Stewart (2011, 2014), leading to more precisely defined contacts and better understanding of the distribution of the oil- and gas-bearing Horton Group.

Greater understanding about the movement of salt renewed industry interest in the Maritimes Basin, as salt domes, diapirs, walls, and canopies are significant to petroleum exploration (Hudec and Jackson, 2007). Dramatic thickness changes in the Cumberland Group in northern Nova Scotia were attributed to evaporite expulsion during the Carboniferous (Waldron and Rygel, 2005; Waldron et al, 2013). Craggs et al. (2015) proposed that diapir growth followed by collapse is associated with strike-slip and transpressional settings.

1.2. Methods

Eight weeks of fieldwork were completed between September 2013 and September 2014. Southeastern New Brunswick has a lot of forests, marshes, and farmland, so field mapping was done primarily on the coast of the Petitcodiac and Memramcook estuaries, along stream traverses and road cuts, where there were exposed rocks. At each outcrop location, GPS coordinates were logged, field observations recorded, and orientation measurements for bedding, joints, and faults taken (if possible).

Field observations were used to create a revised interpretation for the geologic map, which was loaded into Petrel software.

1.2.1. Seismic Interpretation

Raw seismic data are collected by firing an energy source, usually explosive. The wave generated by this source travels though subsurface, and is both reflected and refracted upward when it meets a change in rock properties or lithology. The reflected waves are recorded by geophones, which are laid out in an array to capture the data via a recording computer. Once a shot is completed, the geophones are moved, and the source triggered again. Each subsurface reflection point is recorded multiple times. This allows for a common depth point (CDP) to be established, and the seismic traces with that point are called CDP gathers. Once the raw data are collected, the seismic traces are corrected so that they may be interpreted. The first step is to dynamically correct the trace so that shot point and receiver coincide. A stacked trace uses the dynamic correction, and adds in the CDP gathers. Multiple corrected stacked traces side-by-side create the seismic section. The seismic section is then migrated, either by time or depth migration. Migration uses algorithms to place features in the correct location and improve resolution, creating the seismic image of the subsurface (Yilmaz, 2000). Additional corrections may be applied to further refine the image and remove noise.

Industry-generated migrated seismic profiles were provided by Corridor Resources, Inc., Contact Exploration, and First Sahara Energy, Inc. The data were corrected and migrated when received, no corrections or migration was done for this project. Corridor Resources, Inc. provided eight seismic reflection profiles. Contact Exploration provided nine profiles and one 3D volume. First Sahara Energy, Inc. provided six profiles. Additional profiles were acquired by the New Brunswick Department of Natural Resources (NBDNR) to aid interpretation. Twelve profiles trend approximately north-south and eleven trend approximately east-west (Fig. 1.2). All profiles are SEG-Y files, loaded into Petrel software, and displayed in two-way travel time (TWT).

1.2.2. Wells

Well-log correlations were interpreted from deep petroleum exploration holes and more shallow petroleum and mineral resource exploration holes. Eleven wells were initially selected for the project, based on their proximity to seismic lines. Of these, three wells (331, 333, and 711/716) were prioritized because they had both sonic and density logs, needed to create synthetic well ties for this project. Wells 331 and 333 are located

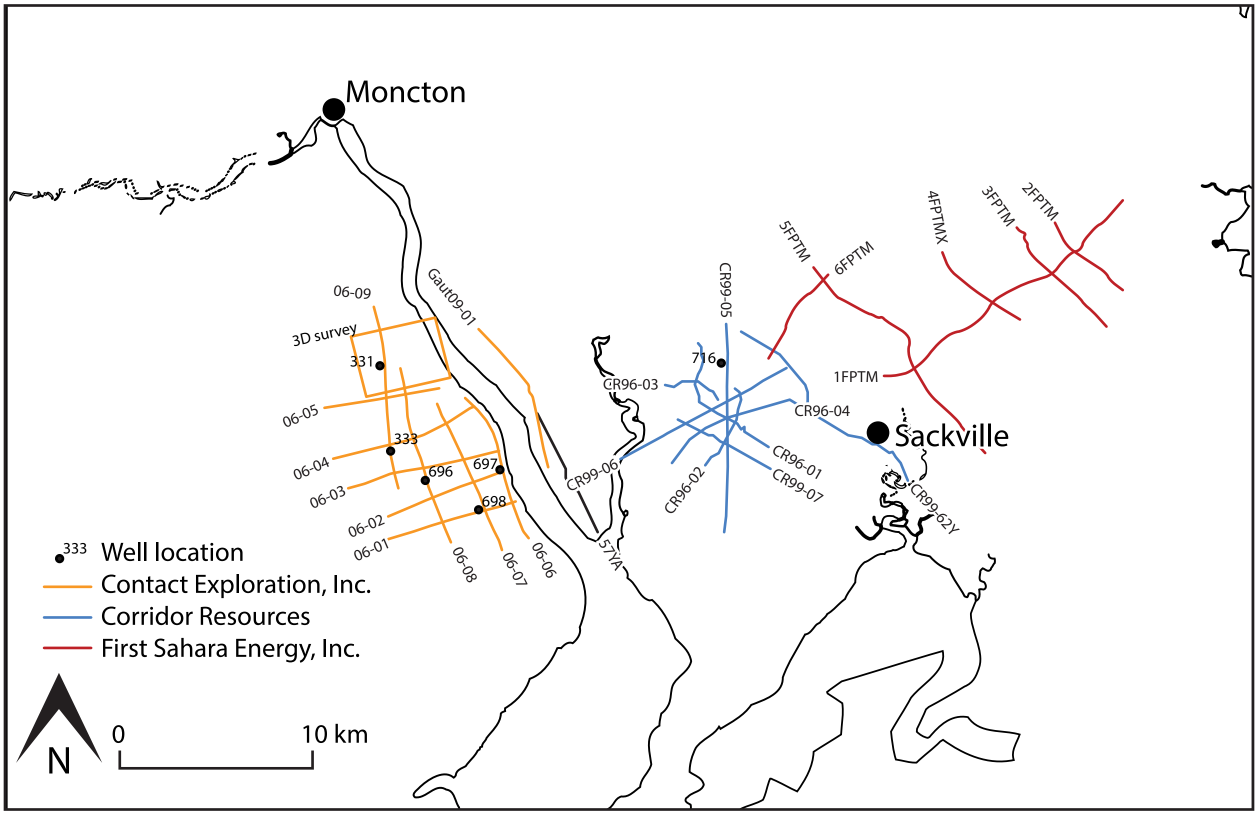

Figure 1.2. Location of seismic profiles in the eastern Moncton Subbasin and the Sackville Subbasin.

in the eastern Moncton Subbasin; Well 711/716 is located in the Sackville Subbasin (Fig. 1.2).

Location, total depth (TD), and Kelly Bushing (KB) elevation are the first data loaded into Petrel, followed by deviation (if available) and well logs. Ideally, there should be a combination of resistivity, geophysical, density/porosity, and lithology data in the well logs. The next step is to import well tops; this indicates where drilling encountered the tops of formations.

Tying the well to the seismic data requires a synthetic seismogram. Creating a synthetic seismogram requires sonic logs (DT), and density logs (DENS, DRHO). Sonic logs are collected using a sonic tool; this tool transmits p-waves through the formation, receives the p-waves, and sends back the data to the surface. At the surface, a computer calculates transit time or slowness, from which interval velocities can be calculated. Sonic tools are not used close to the surface because of interference, so a check-shot survey is used for up to the first 500 m of the well.

Check-shot surveys are created by lowering a seismometer into the well, sending a p-wave from a known location to the known depth of the seismometer. The checkshot data are calibrated to the sonic log. After this calibration is made, a time-depth relationship (TDR) is calculated, which shows the relationship between the depth of a horizon to the time the signal took to get to that horizon. Wells in this project often did not have check-shot data. Using well 711/716 as an example, an artificial check shot was created because there were no check-shot data available. The check shot for 711/716 used an assumed standard velocity of 2 km/s (for sandstone) and 4 km/s (for limestone) for the artificial log (Cordier, 1985). Transit time and velocity have an inverse relationship; in an artificial check shot, the sonic log can therefore be used to find velocities. The average velocity is then calculated for 50 m intervals.

A synthetic seismogram is generated in Petrel based on data from the well. Once this synthetic has been created the best location on the seismic profile is determined;

this process aims to match prominent reflectors between the synthetic and the seismic profile. Bulk shifting the seismogram gets it approximately positioned in place, minimal stretching and shortening of the seismogram helps to match the peaks and troughs precisely, allowing the best possible correlation between the known stratigraphy and the seismic profiles.

1.3. Presentation and Main Objectives

A paper-based format was selected to aid in the publication of the thesis in peer-reviewed journals. This thesis contains two manuscripts that describe the deformation history of the Sackville and Eastern Moncton Subbasins in southeastern New Brunswick. Repetition occurs between chapters so that they can each function as an independent paper.

Chapter 2 attempts to determine the deformation history of the Sackville Subbasin, which was last researched in the 1980s by Martel (1987). Using 2D seismic profiles, well data, and field observations, a revised subsurface model is presented. This model is used to determine the structures and constrain the kinematic history in the Subbasin. The model constrains the emplacement of two tectonic wedges, salt expulsion, and movement along the major faults in the Sackville Subbasin. Research goals of this chapter are to resolve the conflicting interpretations of the Dorchester Fault (Gussow, 1953; Martel, 1987), and to see if evidence for salt expulsion exists, similar to that seen in the adjacent Cumberland Subbasin (Waldron and Rygel, 2005).

Chapter 3 determines the deformation history of the eastern Moncton Subbasin, where the Stoney Creek oil and gas field is hosted. Understanding the deformation history of this subbasin may lead to new reservoirs. This model shows basin development from an extensional basin-and-range setting to a large-scale positive flower structure formed by transpression. Research goals for this chapter are to find evidence proving or disproving strike-slip motion in southeastern New Brunswick (Waldron et al, 2015). Chapter 3 also connects the two geometrically complex subbasins.

Chapter 4 summarizes the major research conclusions.

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Chapter 2. Salt expulsion, tectonic wedges, strike-slip, and basin development: The Sackville Subbasin of southeastern New Brunswick, Atlantic Canada

2.1. Introduction

The Maritimes Basin of Atlantic Canada (Fig. 2.1) is a large and complex basin filled from the Late Devonian to the Permian. The Basin has a known depth of 12 km (Marillier and Verhoef, 1989; Durling and Marillier, 1993) beneath the Magdalen Islands (Fig. 2.1), and covers approximately 148,000 km^2, two-thirds of which is offshore (Wilson and White 2006). Within the Maritimes Basin are smaller depocenters, or subbasins, separated by basin-bounding faults or uplifts. Deformation caused folding, faulting, uplift, and widespread erosion throughout basin history (Gibling et al., 2008).

In southeastern New Brunswick, Carboniferous sedimentary rocks lie unconformably on Avalonian and Ganderian terranes of the Appalachians (Barr and White 1996). The distribution of uplifts and subbasins is shown in Figure 2.2. Several conflicting interpretations of the structural evolution exist in southeastern New Brunswick. Gussow (1953) favored a thrust-belt origin, whereas Webb (1963, 1969) favored oblique extension as the main control on basin formation; Bradley (1982) and Martel (1987) highlighted strike-slip movement, while McCutcheon and Robinson (1987) favored a rift model. Since these papers, other authors have documented evidence for significant strike-slip motion in the Maritimes Basin (Waldron 2004; Waldron et al. 2007; Hibbard and Waldron 2009; Murphy et al. 2011; Waldron et al. 2013), although the models of these authors invoke both transtensional and transpressional movements at various times in basin development.

Subsurface data, combined with better understanding of rapid salt withdrawal (Waldron and Rygel 2005; Waldron et al. 2013), in the adjacent Cumberland subbasin

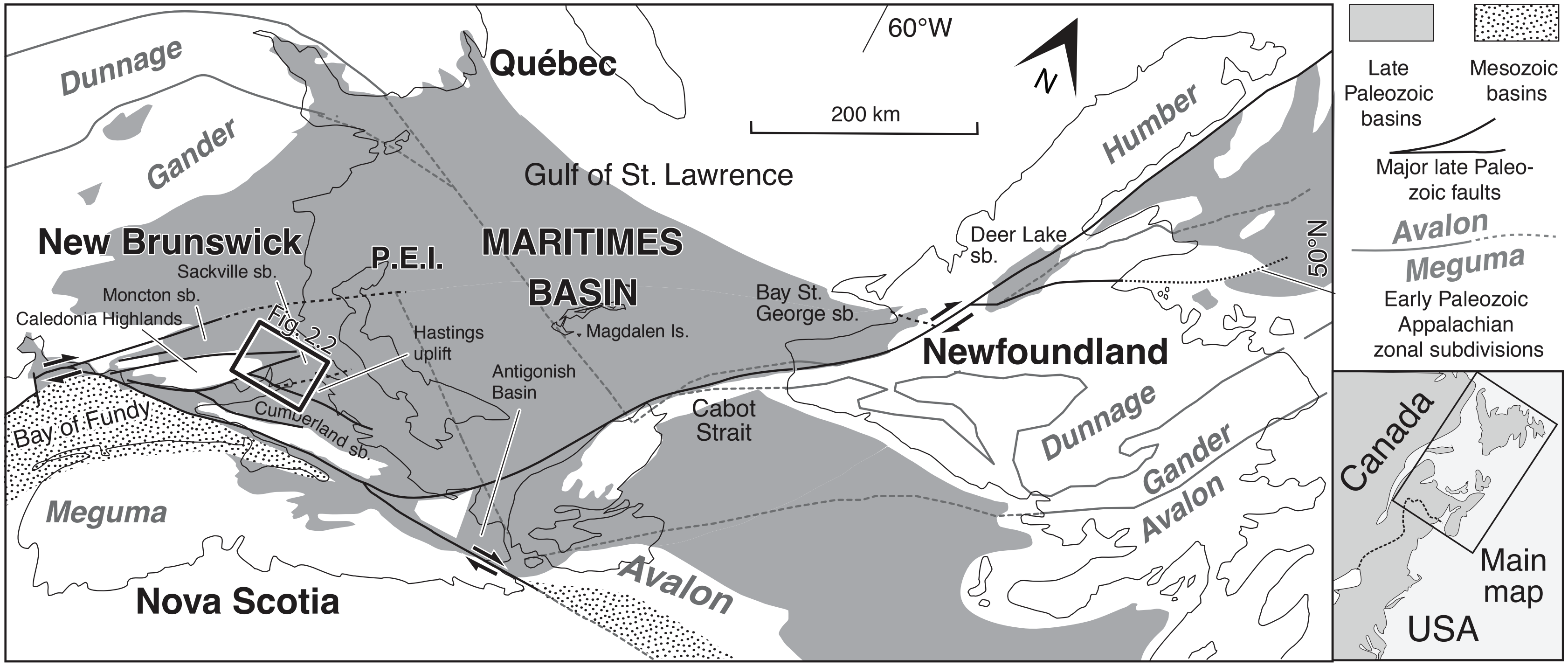


Figure 2.1. Location of the Maritimes Basin of Atlantic Canada,
showing the locations of select subbasins (sb.), and structural features. After Waldron et al. (2013) and Gibling et al (2008).

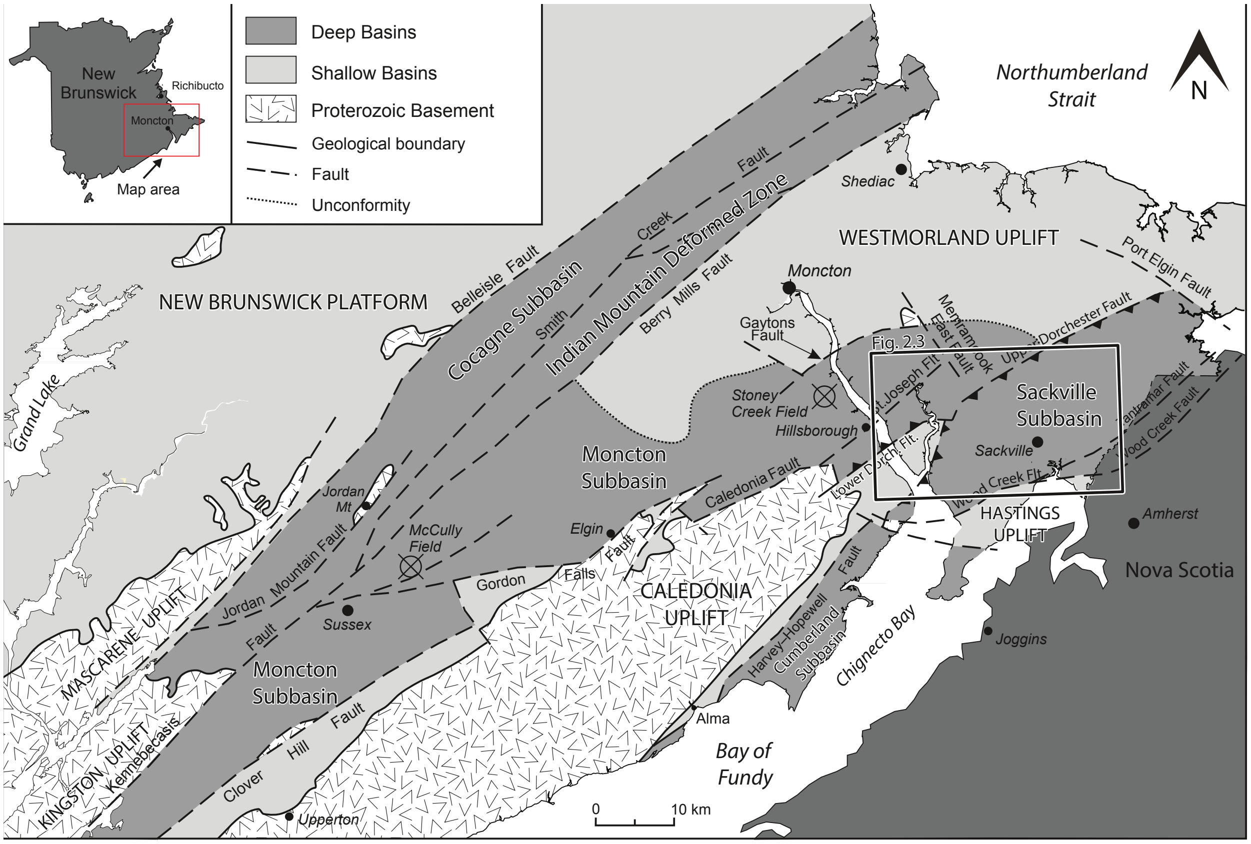


Figure 2.2. Distribution of subbasins and basement uplifts in southeastern New Brunswick.

Fault traces are projected to surface. Modified from St. Peter and Johnson, 2009.

suggest new interpretations of subbasin formation within the Maritimes Basin as a whole. The Sackville Subbasin is an ideal location to assess how salt tectonics and strike-slip movement interact in basin development.

2.2. Data Acquisition and Interpretation Methodology

To aid in the interpretation of the tectonic history of the Sackville Subbasin, we have combined structural and stratigraphic data from fieldwork with subsurface well log and seismic data. Industry-generated seismic profiles provided by Corridor Resources, Inc. and First Sahara Inc. were interpreted for this paper (Fig. 2.3). Eight seismic reflection profiles were provided by Corridor Resources, Inc.; six additional profiles were provided by First Sahara Inc. Additional profiles were provided by the New Brunswick Department of Natural Resources (NBDNR) to aid interpretation. All profiles interpreted are SEG-Y files of migrated data, loaded into Schlumberger's Petrel software. The profiles cover a roughly triangular area (Fig. 2.3). Eight trend approximately north-south and six trend approximately east-west. All profiles are displayed in two-way travel time (TWT), in milliseconds (ms). Well-log correlations were provided by deep petroleum exploration holes and more shallow petroleum and mineral resource exploration holes. Positions of stratigraphic contacts on seismic profiles were determined through well ties when possible, but also through reflectors tied to outcrop and mapped boundaries, geometric relationships, and seismic characteristics of main reflectors.

2.3. Stratigraphy

The Maritimes Basin hosts a complex and challenging stratigraphy. The Basin fill ranges from late Devonian to Kasimovian in age and is divided into six groups in southeastern New Brunswick (Fig. 2.4). From oldest to youngest, these are the Horton, Sussex, Windsor, Mabou, Cumberland, and Pictou Groups. Most of the basin fill is non-marine clastic rocks, but a marine incursion produced carbonates and thick evaporites in the Windsor Group, the mobility of which strongly impact the development of the Maritimes Basin.

Due to the complex nature of the stratigraphy in the Sackville Subbasin, the following account starts with least structurally complicated younger units and proceeds to more complicated older formations. Horizons are labeled according to the interpreted group (uppercase) and formation (lowercase); e.g. Pr represents the Richibucto Formation of the Pictou Group. However, because of the number of unconformities, where a reflection is identified close to a formation boundary, it is labeled according to the base of the overlying unit, not the top of the underlying unit as is common practice in the petroleum industry.

2.3.1. Pictou Group

The Moscovian to Kasimovian Pictou Group (St. Peter and Johnson 2009) in the Sackville Subbasin contains the Richibucto and Salisbury Formations. These formations are predominantly red sandstone, with some mudstone in the Salisbury Formation.

2.3.1.1 Richibucto Formation

The Richibucto Formation is present in the northeastern part of the Sackville Subbasin (Fig. 2.3). It consists mainly of grey and red sandstone, with an estimated thickness of ~300 m (St. Peter and Johnson 2009). Ryan and Boehner (1994), interpreted the depositional environment of the Formation to be a meandering or anastomosing stream deposit. True thickness is unknown because the upper boundary has been removed by erosion everywhere. The lower boundary of the Richibucto Formation is interpreted by Gussow (1953) as a conformable contact with the underlying Salisbury Formation. The Richibucto Fm. has relatively little deformation, but is cut by the major Wood Creek Fault System, including the Tantramar Fault (Fig. 2.3), on the southeastern side of the Sackville Subbasin.

There are no well intersections of the base of the Richibucto Formation near

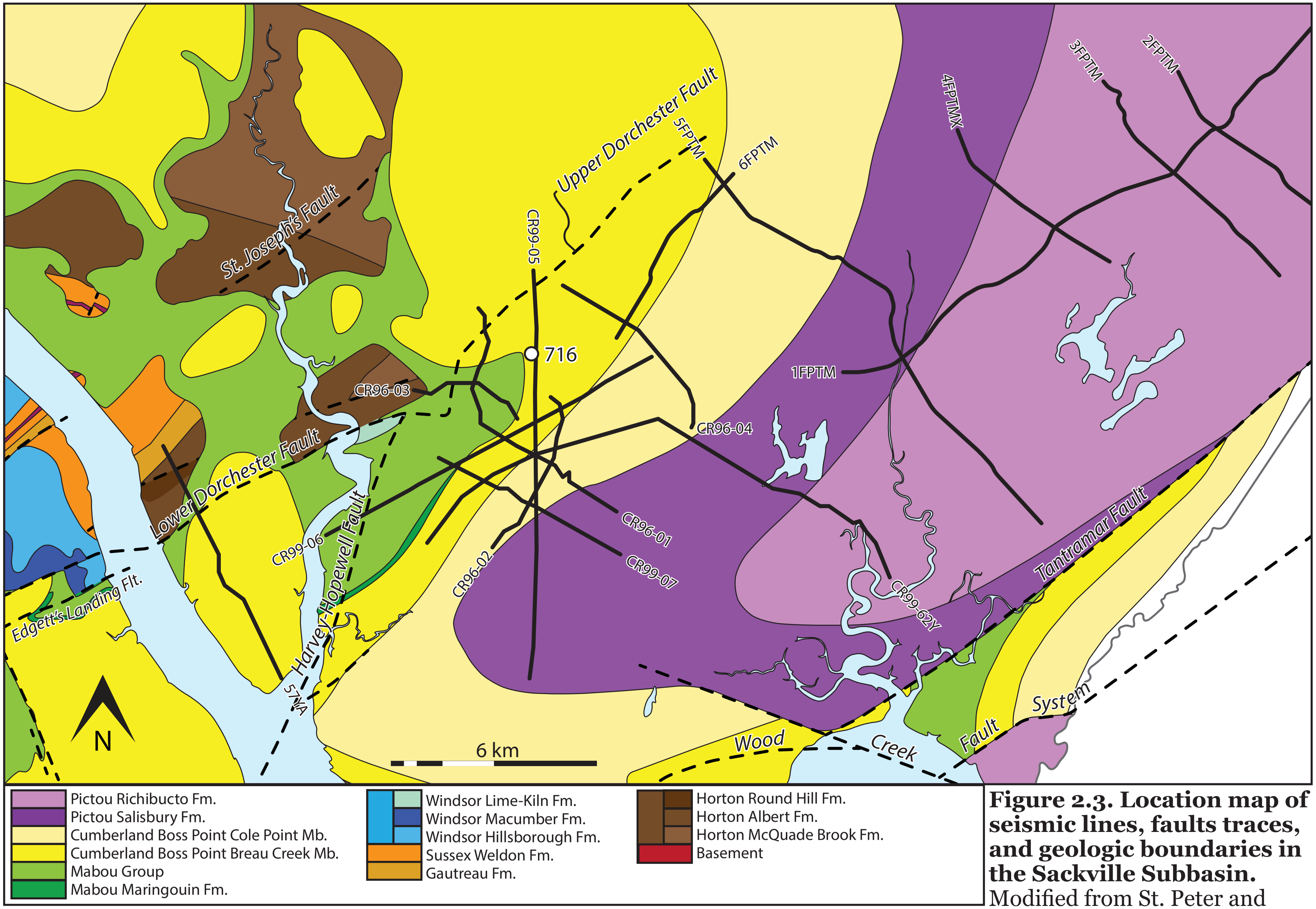


Figure 2.3. Location map of seismic lines, faults traces, and geologic boundaries in the Sackville Subbasin. Modified from St. Peter and Johnson, 2009.

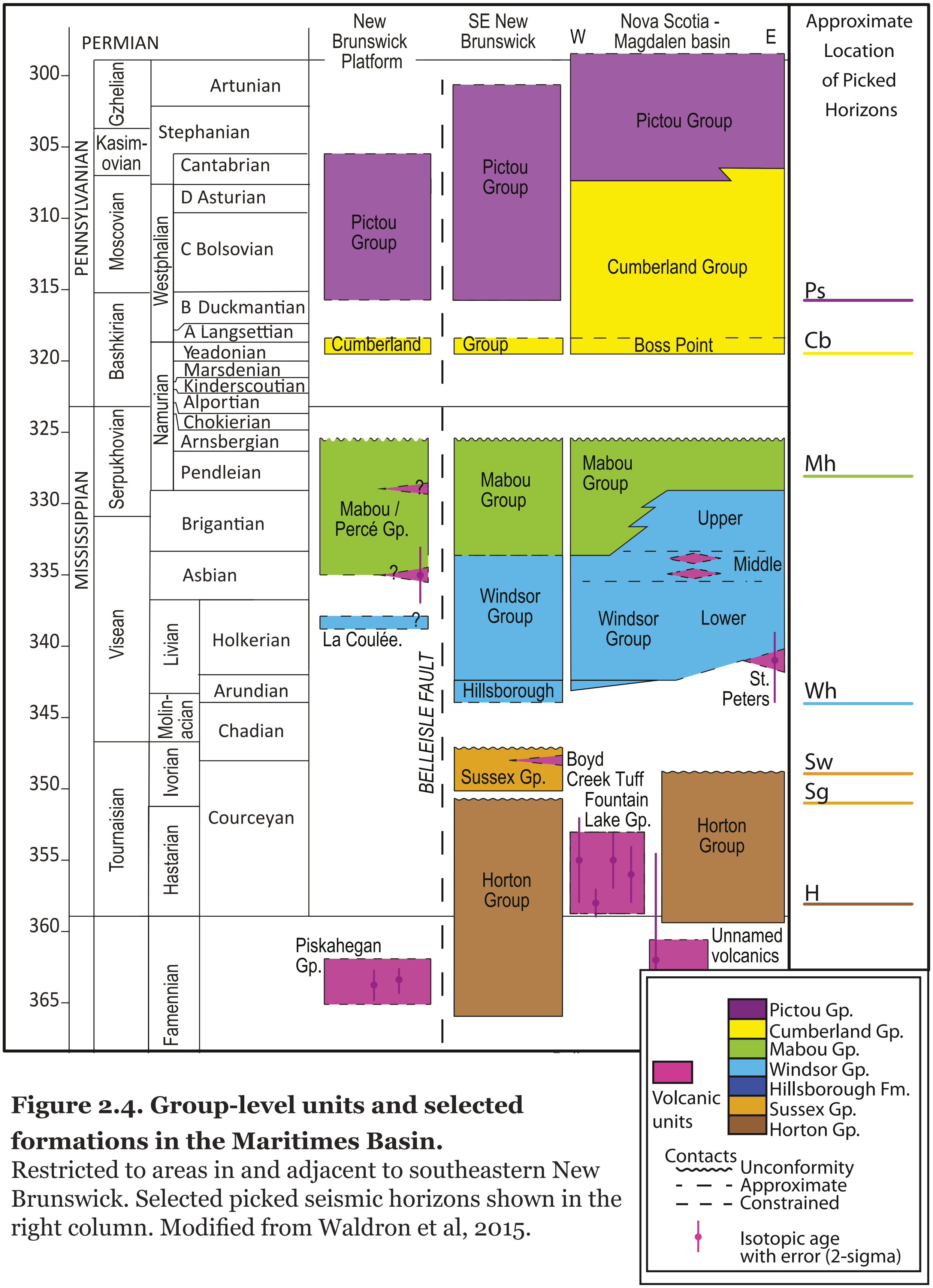


Figure 2.4. Group-level units and selected formations in the Maritimes Basin. Restricted to areas in and adjacent to southeastern New Brunswick. Selected picked seismic horizons shown in the right column. Modified from Waldron et al, 2015.

seismic lines examined for this research. The near-surface region that underlies mapped Richibucto Formation shows discontinuous near-horizontal reflections with poor coherence on line 1FPTM (Fig. 2.5), with numerous artifacts (possibly resulting from diffraction by near-surface glacial features), whereas the interval below, interpreted to represent the Salisbury Formation, shows more continuous reflectivity. Reflection Pr is chosen at a trough at the top of a trough-peak-trough group of reflections, associated with a horizon slightly below the base of the Richibucto Formation, based on correlation with limited mapped outcrop on seismic lines 1FPTM, 5FPTM, 4FPTMX, and CR99-62Y (Fig. 2.6). At the southeast end of 2FPTM, where Pr descends below 350 ms TWT, several coherent reflections are resolved in the overlying Richibucto Formation.

2.3.1.2 Salisbury Formation

Quartz-rich red sandstone and mudstone of the Salisbury Formation lie conformably beneath the Richibucto Formation. This represents the lower part of the Pictou Group in the Sackville Syncline and is exposed in the northeast part of the subbasin. St. Peter and Johnson (2009) interpreted the depositional environment as an overbank succession next to a river system. Poor outcrop contributes to poor constraint for the exact location of the boundary with the Cumberland Group below. The most complete information on the Salisbury Formation comes from boreholes. Well 402 (Port Elgin #1, Fig. 2.2) shows that the Salisbury Fm. is less than 500 m thick in the Port Elgin area and thickens to an estimated 800 m in the Sackville Syncline (St. Peter and Johnson 2009).

There are no well intersections of the base of the Salisbury Formation near seismic lines. Reflection Ps, close to the base of the Formation, is identified in seismic profiles based on correlation with mapped outcrop on lines 5FPTM, CR99-62Y, CR96-01, CR99-07, and CR99-05 (Fig. 2.6, 2.7). Ps correlates to a weak trough above a peak, which likely represents the boundary between the Pictou and Cumberland Groups. On line 5FPTM the underlying Boss Point Formation appears to thin dramatically NW.

Much of the thinning is accounted for by convergence of reflections within the Boss Point Formation (Fig. 2.6), and no clear truncations are observed at or near surface Ps. There is no visible discordance at this boundary, though it has been interpreted as an unconformity (Dolby 1999).

2.3.2. Cumberland Group: Boss Point Formation

The Bashkirian Cumberland Group has been interpreted as unconformity-bounded (Ryan and Boehner 1994; Dolby 1999). In the Sackville Subbasin it contains only the coal-bearing, sandstone-rich Boss Point Formation, whereas in the adjacent Cumberland Subbasin to the south (Fig. 2.1) it contains the thick succession of Boss Point, Little River, Joggins, Springhill Mines, Ragged Reef, and Malagash Formations (Rygel et al. 2014).

The Boss Point Formation consists of grey to red sandstone, mudstone, and conglomerate. Grey sandstone in the formation weathers to a distinctive yellow. Coalified fossil logs and plants are common. Browne and Plint (1994) interpreted the depositional environment as a braided river system. True thickness in the Port Elgin #1 well (402) is 280 m (St. Peter and Johnson 2009). Thickness at the Dorchester Cape reference section is approximately 1000 m, whereas the Boss Point Formation is estimated by St. Peter and Johnson (2009) to be 2000 m thick in the southern limb of the Sackville Syncline. The Boss Point Formation is divided into two members; the Cole Point Member, the base of which is represented by reflector Cb_c, and the Breau Creek Member, the base of which is also the base of the formation, represented by reflector Cb_b.

Three well intersections of the base of the Boss Point Formation occur near seismic lines in this data set, in wells 330 (Imperial-NBO Dorchester #1), 709 (Columbia-Corridor TransCanada Highway), and 716 (Columbia-Corridor Coppermine Hill). Well 716 sits almost on line CR99-05 and has been used as the primary control for contacts seen on the line (Fig. 2.3).

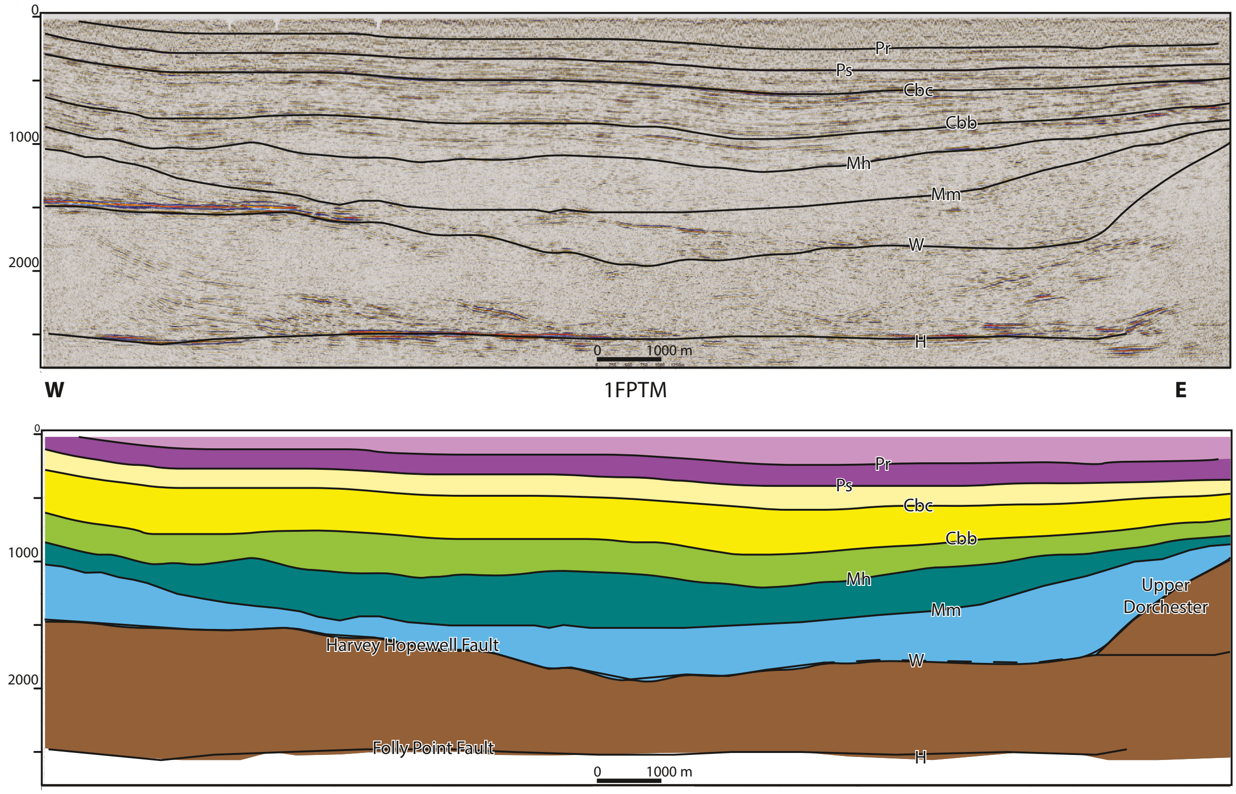


Figure 2.5. Seismic line 1FPTM showing interpreted horizons and faults. This line shows mostly parallel layers along the trough of the Sackville Syncline. Note package above Mh thinning to the east. Vertical scale milliseconds two-way-travel. For shadings and location: fig. 2.3.

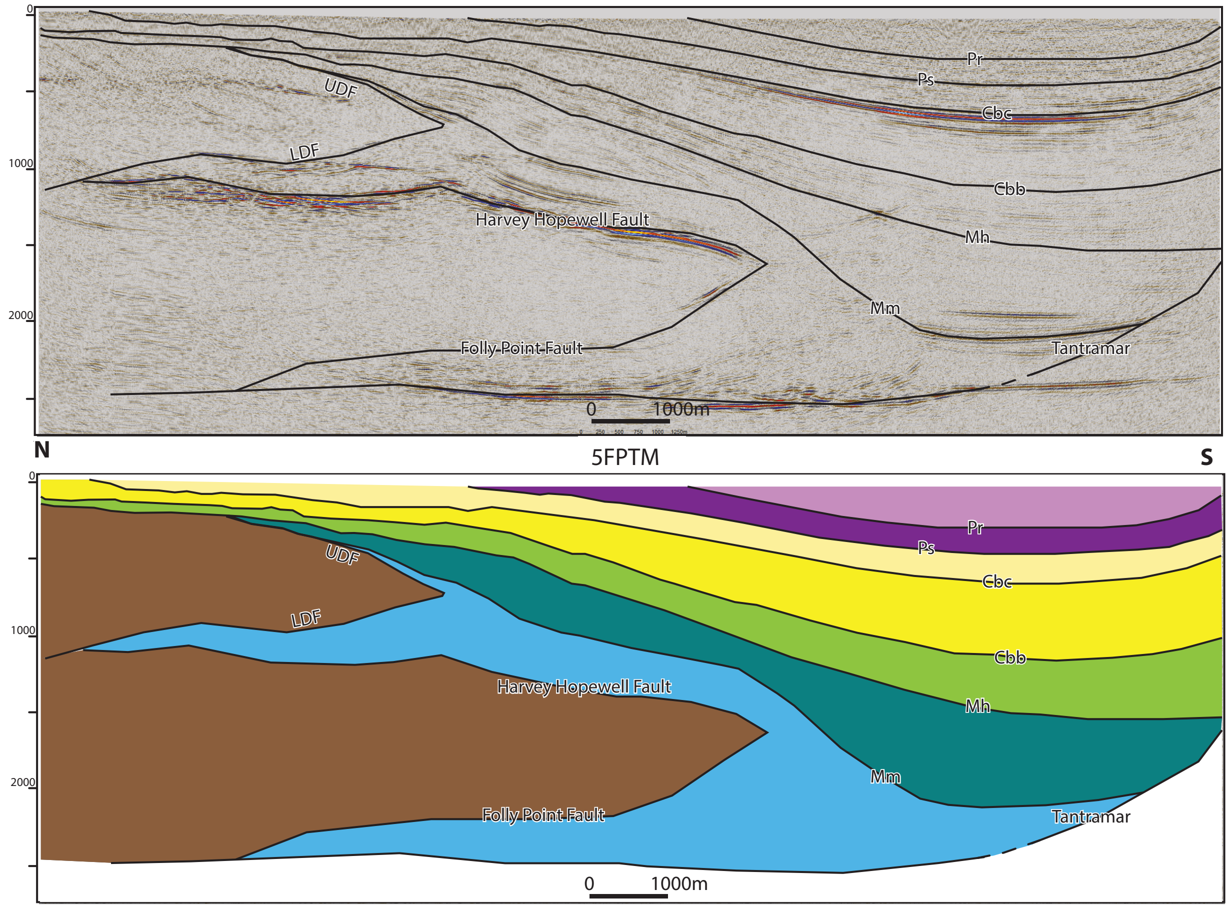


Figure 2.6. Seismic line 5FPTM showing interpreted horizons and faults
N-S profile that clearly shows the upper and lower tectonic wedges of the Sackville Subbasin. Note package above Mh thinning to the north, and convergence of reflectors within the Hopewell Cape Fm. UDF – Upper Dorchester Fault. LDF – Lower Dorchester Fault. Vertical scale milliseconds two-way-travel. For shadings and location: fig. 2.3.

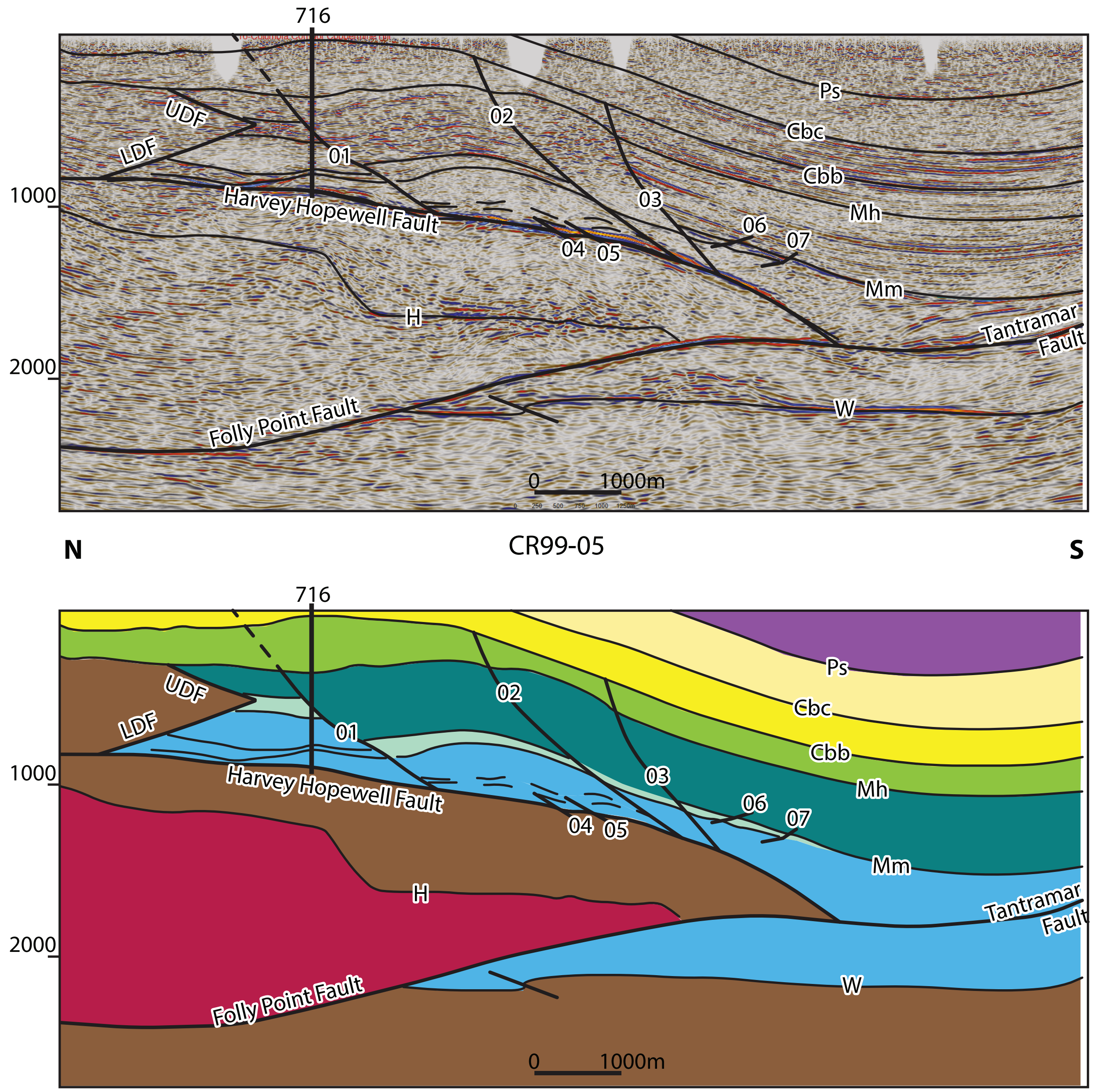


Figure 2.7. Seismic line CR99-05, showing interpreted horizons and faults. Profile shows complex Windsor Group deformation in association with the tectonic wedge defined by the Harvey-Hopewell and Folly Point Faults. Traced horizon Wh is separated by the Folly Point Fault; this cutoff point is used as a marker in the hanging wall and footwall. UDF – Upper Dorchester Fault. LDF – Lower Dorchester Fault. 01 to 07 – numbered faults. Vertical scale milliseconds two-way-travel. For shadings and location: fig. 2.3.

Reflection Cb_c is an internal reflection within the Boss Point Formation, correlated with the base of the Cole Point Member. Cb_c has been picked as a peak that separates an incoherent package above, interpreted to be conglomerate, from a more coherent package below, interpreted to be the sandstone of the Breau Creek Member. Reflection Cb_b is a peak at the base of continuous reflectivity, above a section with poor coherence. Cb_b is associated with the base of the Breau Creek Member and the base of the Boss Point Formation, correlated with the base of the Formation in well 716 on line CR99-05 (Fig. 2.7), in outcrop on lines CR96-01, CR99-07, CR99-06, and in coastal section along the Memramcook Estuary (Fig. 2.3). The interval below the picked reflection on the same line shows poor coherence, interpreted to represent conglomerate of the underlying Mabou Group. Line 5FPTM shows discordant reflectors between the Cumberland Group and the Mabou Group, providing support for the interpreted unconformity between the two (Fig. 2.6).

2.3.3. Mabou Group

The Mabou Group in the Sackville Subbasin is divided into two formations: the conglomerate-dominated Hopewell Cape Formation and the finer-grained Maringouin Formation. Lower units of the Mabou Group are laterally equivalent and interfinger with the Windsor Group (St. Peter and Johnson, 2009); these lower Mabou Group units are correlated with the Percé Group of Québec by Jutras (2015), but this terminology has not been widely adopted in New Brunswick.

2.3.3.1 Hopewell Cape Formation

The Hopewell Cape Formation of the Mabou Group occurs at the surface in the western part of the Sackville Subbasin, where it is exposed in coastal outcrop. The Formation consists of mostly red, but occasionally grey conglomerate, sandstone, and mudstone, interpreted as both proximal and medial parts of alluvial fans (St. Peter and Johnson, 2009). The thickness of the Hopewell Cape Formation ranges from 100 m to 900 m; in well 716 (Columbia-Corridor Coppermine Hill, Fig. 2.3) the recorded thickness of the Formation is 898 m; at the type section in the Sackville Subbasin the thickness is approximately 450 m, though the top of the unit is not present (St. Peter and Johnson 2009). A thickness of approximately 120 m is found in well 325 (Shell Dorchester #1), where the top of the Formation is not present because it has been eroded away at the present day surface. The lower boundary of the Hopewell Cape Formation varies from lying concordantly above Windsor Group strata to interfingering with Maringouin Formation, overlying the Maringouin Formation to sitting unconformably on Sussex Group and Horton Group (St. Peter and Johnson 2009).

Reflection Mh is a peak correlated with the base of the Hopewell Cape Formation in well 716. Due to the varied relationship with underlying units, Mh is one of several internal reflections in the Mabou Group used to aid interpretation; less coherent reflections below Mh likely represent the complex relationship between Mabou and Windsor Group rocks. Line 1FPTM shows the Hopewell Cape Formation thinning to the east and west (Fig. 2.5), and 5FPTM shows the Formation thinning dramatically to the north (Fig. 2.6). Some of this thinning is accounted for by convergence of reflections within the Hopewell Cape Formation (Fig. 2.6), indicating differential subsidence during its deposition.

2.3.3.2 Maringouin (Middleborough) Formation

Beneath the Hopewell Cape Formation are red sandstone and shale of the Maringouin Formation, the basal formation of the Mabou Group in the Sackville Subbasin, interpreted as small river deposits (St. Peter and Johnson, 2009). Outcrop of the Formation is found only in the southernmost part of the subbasin. The Maringouin Formation of New Brunswick is equivalent to the Middleborough Formation in Nova Scotia (Ryan and Boehner, 1994). The Maringouin Formation is intersected in wells 716 (Columbia-Corridor Coppermine Hill) and 330 (Imperial-NBO Dorchester 1). These show that the thickness of the unit can vary from approximately 250 m to an estimated

700 m within the subbasin (St. Peter and Johnson 2009). The Maringouin Formation is cut by a number of small faults, best seen on line CR99-06 (Fig. 2.8), and by the large regional Tantramar and Wood Creek faults (Fig. 2.8). In some places, reflectors show interfingering with Windsor Group strata (Fig. 2.9). Complex relationships between the Mabou and Windsor Groups are best seen on line CR99-62Y (Fig. 2.9), where reflectors undulate and onlap each other within the Mabou Group.

Reflector Mm is correlated with the base of the Mabou Group. Well 716 (Columbia-Corridor Coppermine Hill), on line CR99-05, intersects this boundary at 1426 m depth. Reflector Mm is identified in seismic profiles from this well intersection and correlates with mapped outcrop on lines CR96-01, CR96-03, CR99-06, and CR99-07 (Fig. 2.10, 2.8). Mm correlates to a trough but is more identifiable as a boundary between an upper coherent interval and a lower incoherent interval on seismic line CR99-06 (Fig. 2.8), likely the Windsor Group. Line 5FPTM shows the Mabou Group thinning dramatically toward the northeast, and reflectors converging within the Mabou Group. Visible discordance appears at the boundary between the Mabou and Windsor Groups, caused by the complex depositional and deformational relationship between the two.

2.3.4. Windsor Group

The Windsor Group in the study area comprises the Lime-Kiln Brook, Dorchester, Pugwash Mine, Upperton, Macumber, and Hillsborough Formations. Lower formations of the Mabou Group are laterally equivalent to parts of the Windsor Group (Fig. 2.4)(Kendall, 1992; St. Peter and Johnson, 2009). In seismic profile, it is difficult to distinguish Windsor Group formations from each other without tight well control.

2.3.4.1 Lime-Kiln Brook and Dorchester Formations

The Lime-Kiln Brook Formation consists of limestone, anhydrite, gypsum, dolostone, halite, conglomerate, sandstone, siltstone, and shale (St. Peter and Johnson

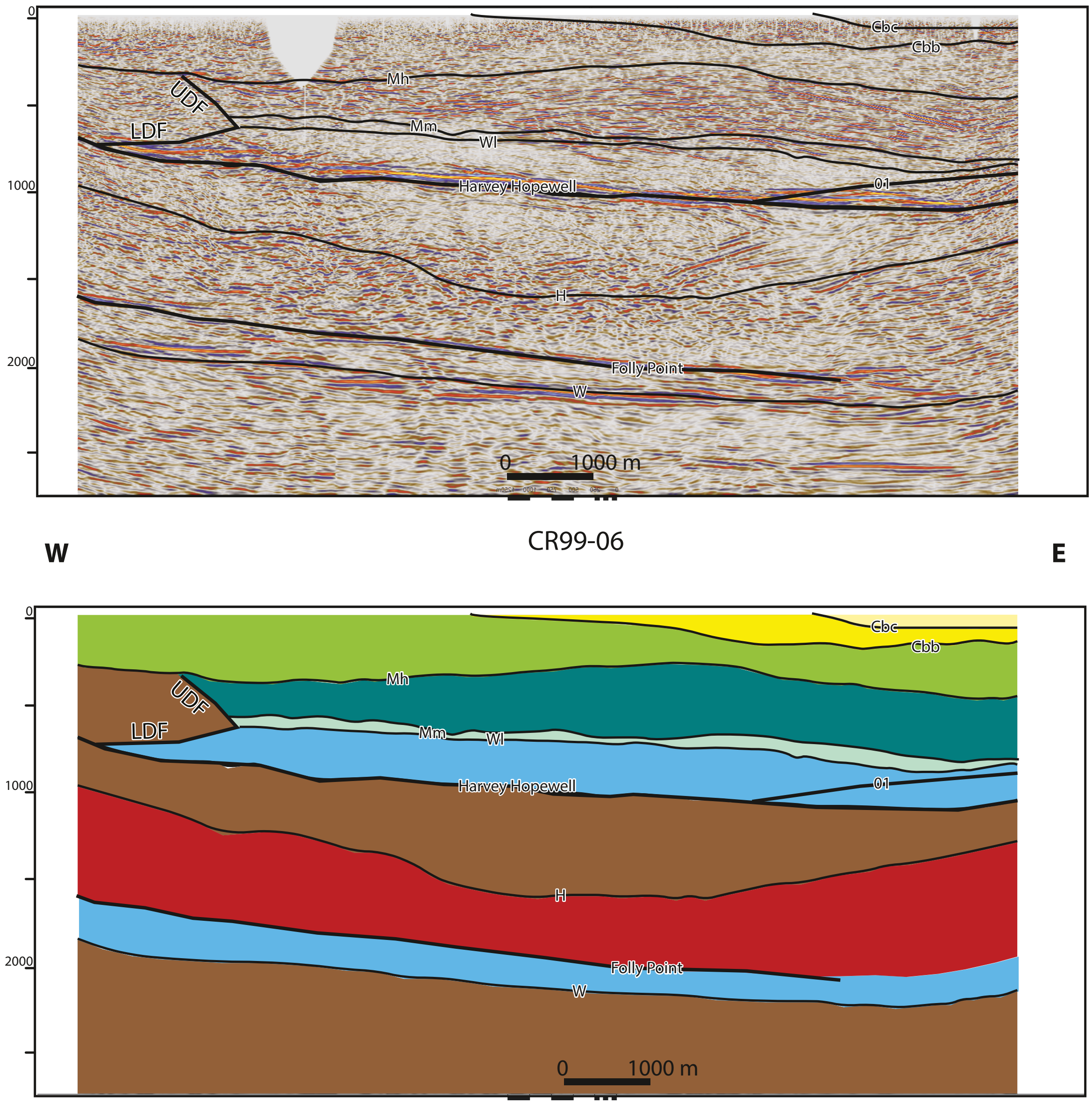


Figure 2.8. Seismic line CR99-06 showing interpreted horizons and faults
E-W profile that shows abruptly changing dips in Horton Group package. Vertical scale milliseconds two-way-travel. UDF – Upper Dorchester Fault. LDF – Lower Dorchester Fault. For shadings and location: fig. 2.3.

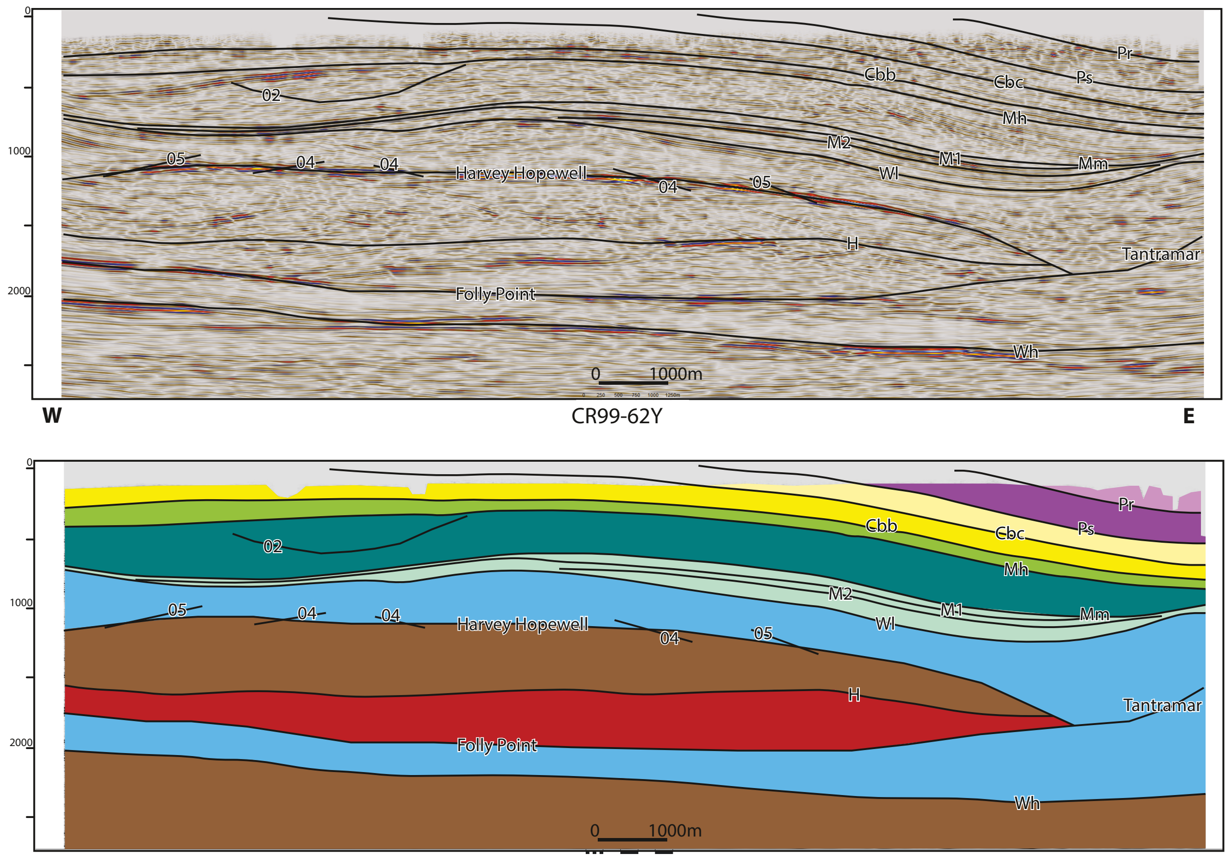


Figure 2.9. Seismic line CR99-62Y – slice through tectonic wedge
Showing interpreted horizons and faults (wedge point is out of the page, toward reader). Shows the complex relationship between Mabou and Windsor Group in the Sackville Subbasin on this line. Vertical scale milliseconds two-way-travel. For shadings and location: fig. 2.3.

2009). The Lime-Kiln Brook and Dorchester Formations are interpreted as products of shallow marine environments (St. Peter and Johnson, 2009). In the Sackville Subbasin the formation does not appear as a complete exposed section. The Formation is present in wells 716 (Columbia-Corridor Coppermine Hill) and 330 (Imperial-NBO Dorchester 1), but unconformities and evaporite expulsion make it impossible to determine true thickness. A thick sulfate interval included within the Lime-Kiln Brook Formation is distinct from the conglomerate and sandstone, and has been proposed as a separate Dorchester Formation (Jutras et al. 2015). At its upper boundary, the Lime-Kiln Brook Formation underlies the Hopewell Cape and Maringouin Formations at an erosional disconformity (St. Peter and Johnson, 2009); the lower part of the formation has been drastically impacted by salt withdrawal, and is in contact with the Pugwash Mine Formation.

The base of the Lime-Kiln Brook Formation is intersected in well 716 at 1745 m depth. Reflection Wl is a peak-above-trough pair that rides above a less coherent package interpreted to be the underlying Pugwash Mine Formation, seen on line CR99-62Y (Fig. 2.9).

2.3.4.2 Pugwash Mine Formation

The Pugwash Mine Formation is largely clean rock salt, with some anhydrite and rare dolostone (St. Peter and Johnson 2009). The Pugwash Mine Formation is interpreted as a deep-water evaporite deposit (Kendall, 1992). In the Sackville Subbasin, the formation appears only in the subsurface. Martel (1987) was the first to document the formation in the Sackville Subbasin; regional gravity data show an anomaly below the Tantramar Fault that has been correlated (Martel 1987; Jutras et al. 2015) to the location of the Pugwash Mine Formation. In the adjacent Cumberland Subbasin, the formation can reach thicknesses of 6000 m (Ryan and Boehner 1994).

The base of the Pugwash Mine Formation is intersected in well 716 at 2,100.5 m depth. Reflector Wp is visible on seismic line CR99-05 (Fig. 2.7). This horizon can be traced laterally as a boundary separating an upper, less coherent package of reflectors from lower, more clearly defined reflectors interpreted to be the Upperton Formation.

2.3.4.3 Upperton Formation

Beneath the Pugwash Mine Formation is the anhydrite-dominated Upperton Formation, which is largely gypsified in exposures. The Upperton Formation, similarly to the Pugwash Mine Formation, is interpreted as a deep-water evaporite deposit (Kendall, 1992). This formation contains lenses of maroon mudstone. It is interpreted to be equivalent to the Cassidy Lake Formation in the Moncton subbasin and other basal anhydrite units of the Windsor Group in Nova Scotia (McLeod, 1980).

The Upperton Formation is intersected in well 716. Wu, an internal reflection within the Windsor Group, is correlated with the base of the Upperton Formation. Tight control between well 716 and CR99-05 (Fig. 2.7) allows the reflector to be traced on one seismic profile fairly accurately, but away from this line significant uncertainty is associated with the location of the horizon, as there is limited well control.

2.3.4.4 Macumber Formation

The Macumber Formation of the Windsor Group is a thin marine limestone unit less than 20 m thick in New Brunswick (St. Peter and Johnson, 2009). The formation is interpreted as deposited in a deep-water environment with sediment from a carbonate shelf (St. Peter and Johnson, 2009). It is difficult to establish a clear reflector that represents the base of this formation, even with well control provided by the 716 well.

2.3.4.5 Hillsborough Formation

The Hillsborough Formation is a redbed succession of conglomerate, sandstone, and mudstone, with megaclasts of schistose felsic and mafic volcanics, metasedimentary rocks, gabbro, and limestone, interpreted as an alluvial fan complex (St. Peter and Johnson 2009). In this paper, it is treated as the basal formation of the Windsor Group, following St. Peter & Johnson (2009). The Hillsborough Formation is intersected by wells 716 and 330, where it is documented to have thicknesses of 335 m and 95 m, respectively.

Well 716 intersects the base of the Windsor Group at 2,553 m depth. This correlates with a pair of trough reflections known in the Maritimes Basin to mark the base of the Windsor Group (Durling 1997), identified here as Wh. This package of reflectors divides the overlying, less coherent, Windsor Group from the underlying jumble of reflections inferred on line CR99-05 (Fig. 2.7) to represent the Horton Group. Following the reflector from north to south on CR99-05, it becomes apparent that two segments of the Wh reflector are separated by a fault but can be used as a marker horizon in both hanging wall and footwall (Fig. 2.7).

2.3.5. Sussex and Horton Groups

The Sussex Group is found only in New Brunswick. It is unconformity bounded, and contains conglomerate, sandstone, mudrock, felsic ash, and glauberite-rich evaporites (St. Peter and Johnson, 2009). It is suspected that the Sussex Group is present in the subsurface of the Sackville Subbasin, but it is not intersected in wells, and is not clearly visible on seismic profiles. There are four formations, of which the Gautreau and Round Hill Formations are the only suspected representations in the Sackville Subbasin. Coarse grey-green grey-red poorly sorted polymictic conglomerate of the Round Hill Formation lies unconformably beneath the Hillsborough Formation (McLeod 1980; Park and St. Peter 2005; Park et al. 2007; St. Peter and Johnson 2009). The Gautreau Formation comprises fine-grained clastics and playa evaporites (St. Peter and Johnson 2009). Recent palynological work (Stimpson, pers. comm. 2015) and seismic interpretation west of the Petitcodiac River (Ch. 3) suggest that the Gautreau Formation in the Sackville Subbasin is separated from the overlying Weldon and Round Hill Formations by an unconformity, and therefore may be reassigned to the Horton Group.

The Horton Group is a thick succession of conglomerate, shale, and mudstone, with a complex history of uplift, deformation, and erosion (Nickerson 1994). It is unconformity bounded. In the Sackville Subbasin, it contains three formations below the Gautreau, from top to bottom; the Albert, McQuade Brook, and Memramcook. The Albert formation is subdivided into three members, discussed below. It is the producing formation for onshore oil and gas fields (Fig. 2.2). Asymmetric shape, listric normal faults, and thickening of the Horton Group in cross-sections show that it was deposited in active half-grabens (Durling 1997).

2.3.5.1 Albert Formation

The Albert formation is exposed in the northwestern edge of the Sackville Subbasin (Fig. 2.3). The formation is difficult to trace in the subsurface; it is intersected in wells 699 (Breau 1) and 369-376 (Upper Dorchester 1-8), but not in 709 (Columbia-Corridor TCH) or 716 (Columbia-Corridor Coppermine Hill), where it is assumed to be below the total depth of the well. The maximum thickness of the Albert Formation is estimated at 1400 m, though St. Peter and Johnson (2009) suggested that this is an exaggeration caused by shortening. Three members make up the Albert Formation. These are, from top to bottom, the Dawson Settlement, Frederick Brook, and Hiram Brook members. The upper and lower members, Dawson Settlement and Hiram Brook, contain sandstone, siltstone, shale, and conglomerate (Greiner 1962; St. Peter and Johnson 2009). The middle Frederick Brook member contains oil shale and kerogenous mudstone (St. Peter and Johnson 2009).

Reflector Ha is correlated with the base of the Albert Formation. Many wells in the Sackville Subbasin intersect the Albert Formation but do not pass through the formation. Reflector Ha is roughly identified by correlation with mapped outcrop on line CR96-03 (Fig. 2.3). Wells 375 and 376 are close, but lie on the other side of a major thrust fault, and so do not offer constraint on the depth of the Albert formation in this part of the subbasin.

2.3.5.2 McQuade Brook Formation

Fine-grained red to maroon and grey fluvial sandstone, siltstone, and mudstone of the McQuade Brook Formation gradationally underlie the Albert Formation (St. Peter and Johnson, 2009). This formation represents the middle of the Horton Group. It is exposed in the northeast part of the subbasin, where it lies directly beneath Mabou Group rocks. The McQuade Brook Formation is intersected by well 716 (Columbia Corridor Coppermine Hill) and 709 (Columbia Corridor TransCanada Highway). It is difficult to distinguish the McQuade Brook Formation from the underlying Memramcook Formation away from well control.

Reflection Hq, close to the base of the formation, is correlation with mapped surface exposure near line CR96-03 (Fig. 2.3). The base of the formation is not intersected by wells in the Sackville Subbasin.

2.3.5.3 Memramcook Formation

Coarse red conglomerate with rounded clasts and occasional sandstone and mudstone make up the Memramcook Formation (St. Peter and Johnson 2009), which lies conformably beneath the McQuade Brook Formation. It is the basal formation of the Horton Group and is the lowest sedimentary rock record in the Maritimes Basin of southeastern New Brunswick. Exposure of the formation lies in the north to northeast section of the subbasin. The Memramcook Formation is intersected in Wells 709 (Columbia-Corridor TransCanada Highway) and 716 (Columbia-Corridor Coppermine Hill). Both wells reach total depth in the formation, and surface exposures are incomplete, so it is impossible to know the true thickness. The Memramcook Formation is cut by numerous small faults, as shown on CR99-05 (Fig. 2.7).

Reflector Hm is correlated with the base of the Memramcook Formation. Hm is identifiable as a bright peak-trough pair, visible between two less coherent packages of reflectors (Fig. 2.7). Line CR99-06 shows that reflectors correlated with the formation have abruptly apparent changing dips (Fig. 2.8), which could be related to erosional contacts in the Sackville Subbasin, or deformation structures.

2.3.6. Basement

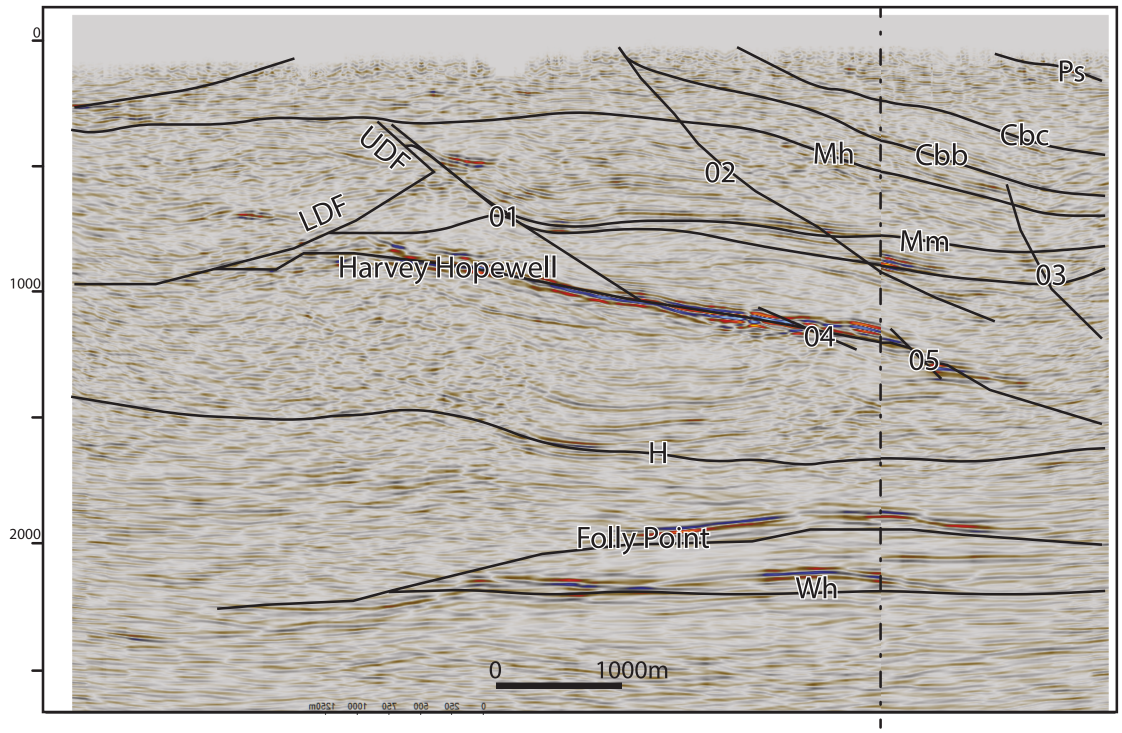
Beneath the sedimentary cover lie Proterozoic to Devonian basement rocks. In the Sackville subbasin, these are entirely buried; there is a small area of outcrop north of the study area (Fig. 2.2), and west across Shepody Bay in the Caledonia Uplift. The Caledonia Uplift contains igneous, low-grade metamorphic, and minor sedimentary rocks; this is a part of the Caledonia terrain, in the domain Avalonia of the northern Appalachians (Barr and White 1996; Barr et al. 2000). To the east of the subbasin lies the buried Westmorland Uplift, which contains igneous and metamorphic rocks, interpreted as part of Ganderia (Barr et al. 2002).

2.4. Structures and Tectonics

2.4.1. Upper Dorchester Fault

Previous workers (Gussow, 1953; Martel, 1987; St. Peter and Johnson, 2009) have identified a major NE-SW fault through Upper Dorchester (Fig. 2.2) as the Dorchester Fault. Near Upper Dorchester this fault juxtaposes Horton Group to the NW against Windsor Group to the SE. The Dorchester Fault was interpreted as moderately NW-dipping by Gussow (1953), and moderately S-dipping by Martel (1987). Traced along strike in both directions, the fault is shown in Fig. 2.3 cutting overlying Mabou and Cumberland Group, but with small offsets. Farther SW the trace of the fault is shown by Park (2007) and Wilson et al. (2006), as cutting steeply thorough basement rocks of the Caledonia Highlands.

In seismic line CR96-01, along strike from the mapped fault at Upper Dorchester, a south-dipping subsurface boundary separates a highly reflective package of Mabou and Windsor Group rocks from a less coherent region below interpreted as basement and Horton Group (Fig. 2.10). This SE-dipping boundary is interpreted as the northeastward extension of the mapped Dorchester Fault beneath Mabou and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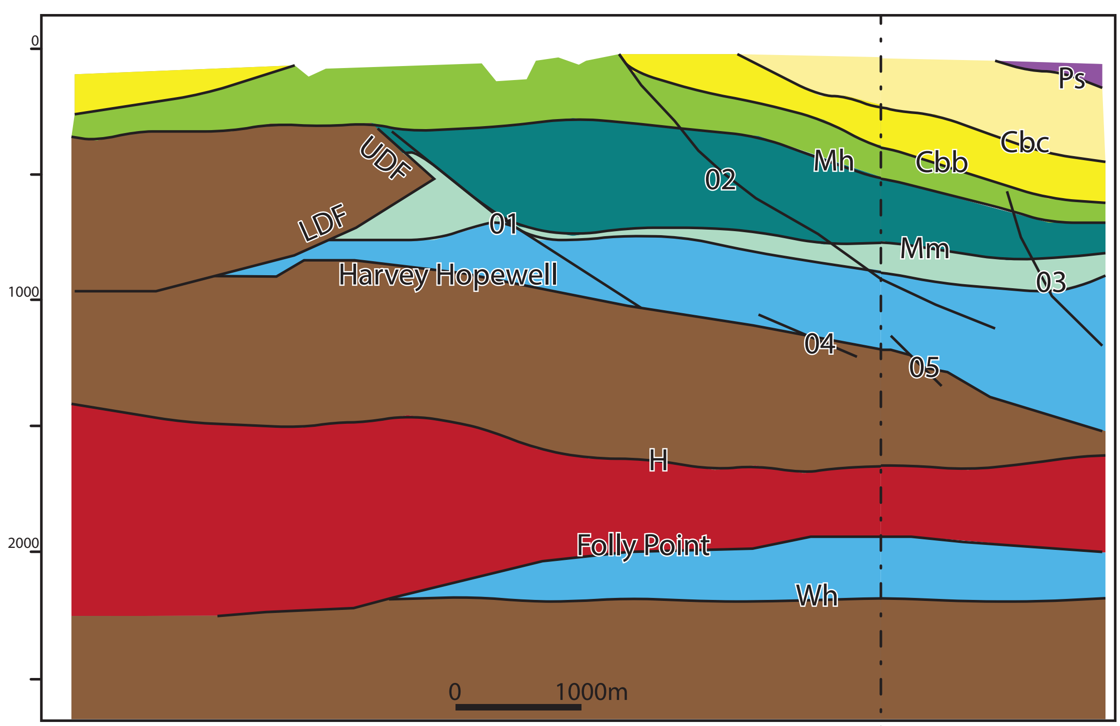
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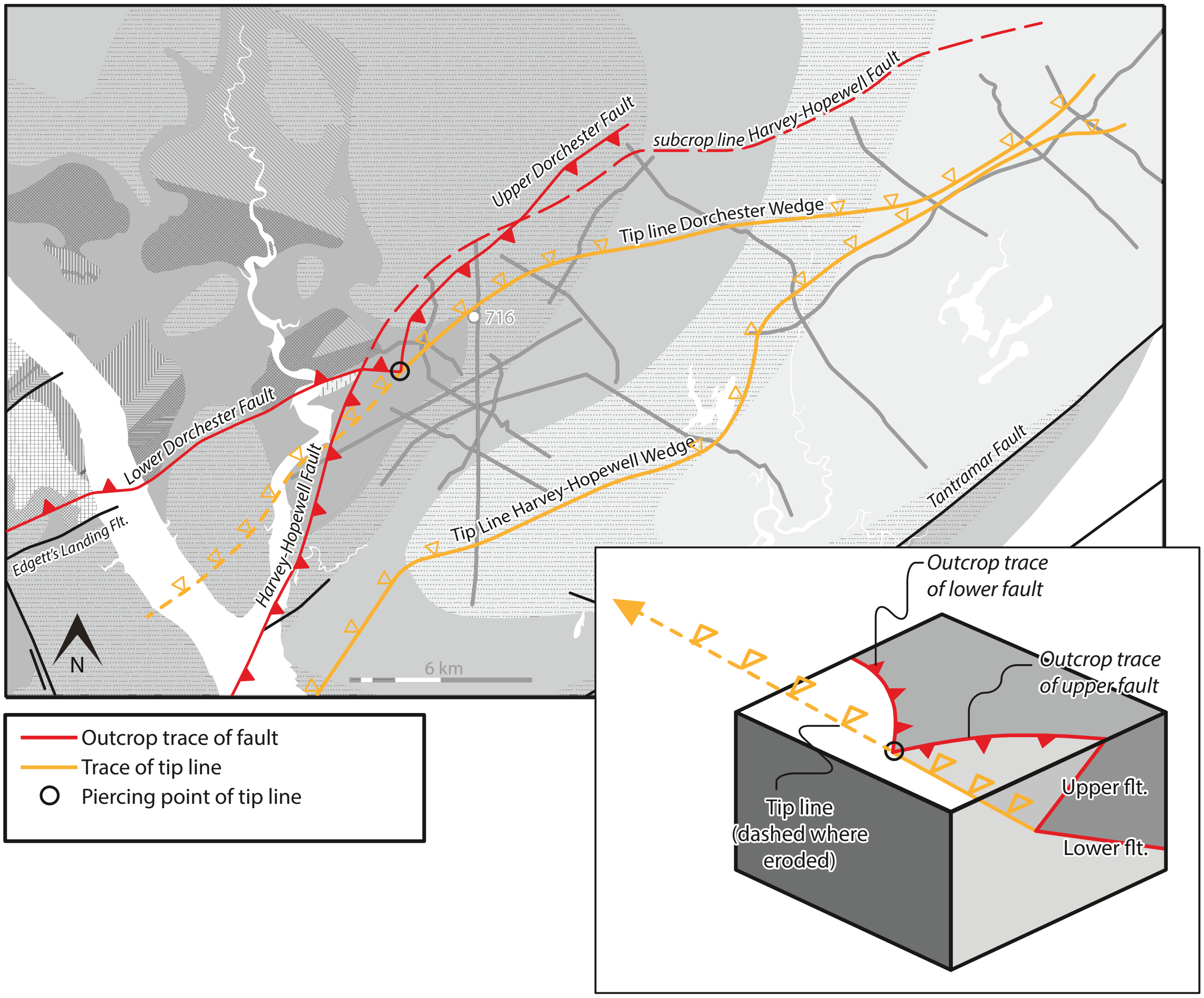

Figure 2.11. Map tracing tectonic wedges across the Sackville Subbasin. This page. Inset image models a tectonic wedge, showing the relationship expected when both the upper and lower faults reach the surface. Circle indicates where the tip-line pierces the surface.

Figure 2.10. Seismic line CR96-01, showing interpreted horizons and faults. Previous page. Profile shows the tip of the tectonic wedge defined by the Dorchester faults closer to the surface than in more eastern profiles. Dot-dash vertical line indicates where a jog in the seismic was trimmed out. UDF – Upper Dorchester Fault. LDF – Lower Dorchester Fault. Vertical scale milliseconds two-way-travel. For shading and location: fig. 2.3.

Cumberland Group cover and is here distinguished as the Upper Dorchester Fault. Traced updip in our interpretation, the boundary appears truncated at reflection Mh, the base of the Hopewell Cape Formation. Traced downdip, the boundary meets another surface interpreted as a north-dipping fault (here termed the Lower Dorchester Fault, see below). Similar relationships are interpreted on CR99-05, CR96-04, 6FPTM, and 5FPTM. The seismic profiles provide no evidence for the small post-Mabou offset implied by the geological map (Fig. 2.3), suggesting that the main movement on the Dorchester Fault was pre-Serpukhovian. Seismic lines 5FPTM and 6FPTM clearly show subhorizontal reflections at depth between 800 and 1200 ms TWT, proving that the Dorchester Fault cannot be a steep structure, as previously interpreted. Instead, our interpretation show that it dips gently (10°-40°) SE. Parts of the fault appear subparallel to the stratigraphy in the overlying Mabou Gp., which suggests that the fault may have originated at a detachment within the Windsor Gp. evaporites. Windsor Gp. gypsum that crops out at the SE wall of the fault at Upper Dorchester may be supporting evidence for this interpretation.

2.4.2. Lower Dorchester Fault

In seismic line 5FPTM, the Upper Dorchester Fault can be traced downdip, where it intersects a north-dipping subsurface boundary between 600 and 1000 ms TWT (Fig. 2.6). This deeper boundary separates a region of poor coherence in its hanging wall, interpreted as Horton Group and basement, from strongly coherent reflectors below, interpreted as Windsor Group (Fig. 2.10). This NW-dipping boundary is here termed the Lower Dorchester Fault, to distinguish it from the SE-dipping Upper Dorchester Fault. The intersection point of the Upper Dorchester and Lower Dorchester Faults forms the tip of a tectonic wedge inserted southward into the Windsor Group evaporites (Fig. 2.10). Similar relationships are interpreted on 2FPTM, 3FPTM, 4FPTMX, 5FPTM, 6FPTM, and CR99-05.

The tip of the tectonic wedge is a linear feature that can be traced from profile

3FPTM in the northeast, where it occurs at a depth of ~1600 ms TWT, shallowing to the southwest as far as line CR96-01, where it is interpreted at a depth of ~500 ms TWT. Farther southwest, this tip line is not seen on profile 57YA; instead, the Lower Dorchester Fault appears truncated at reflection Mh, representing the base of the Hopewell Cape Formation, suggesting that the upper part of the wedge, bounded by the Upper Dorchester Fault, was removed by erosion prior to deposition of the Hopewell Cape Formation. Between line CR96-01 and 57YA, the tip of the wedge must be truncated by the unconformity at the base of the Hopewell Cape Fm. These relationships are shown on figure 2.11, and are further discussed below.

Southwest of the Petitcodiac River, previous workers (Norman 1941, Gussow 1953, McLeod 1980) identified a major NE-SW fault through Edgett's Landing as the Dorchester Fault. This fault dips NW, in contrast to the SE-dipping Upper Dorchester Fault (with which it was formerly correlated). We correlate this NW-dipping fault to the Lower Dorchester Fault.

2.4.3. Harvey-Hopewell Fault

The Harvey-Hopewell Fault has been identified as a major SE-dipping fault along the southern edge of the Caledonia Highlands, passing through Hopewell Cape (Fig. 2.2). Previous workers (St. Peter and Johnson, 2009) have traced the fault northward up the Memramcook Estuary into the Sackville Subbasin merging with the Dorchester Fault System near Upper Dorchester (Fig. 2.2). Gussow (1953) interpreted the Harvey-Hopewell Fault as a SE-dipping structure.

In seismic line CR99-05 (Fig. 2.7), a south-dipping subsurface boundary between 800 and 1500 ms TWT separates a coherent package of reflectors interpreted to be the Windsor Group from a less coherent package interpreted to be basement and Horton Group (Fig. 2.7). Traced updip to the northwest, the boundary is intersected by the north-dipping Lower Dorchester Fault (see above). Traced downdip to the southeast, the boundary intersects another surface at 1500 ms TWT on line CR99-05, interpreted as a north-dipping fault (here termed the Folly Point Fault, see below) and defining a second tectonic wedge. A similar relationship is interpreted on CR99-62Y (Fig. 2.7). Because of its position at the top of a wedge of basement and possible Horton Group, correlative with the Caledonia Highlands, the SE-dipping boundary is interpreted as the northeastward extension of the Harvey-Hopewell Fault beneath Windsor, Mabou, Cumberland, and Pictou Group cover.

The Harvey-Hopewell Fault is offset by smaller unnamed normal faults visible on lines CR99-05 and CR99-962Y (Figs. 2.9 and 2.7).

2.4.4. Folly Point Fault

In seismic line CR99-05 (Fig. 2.7) the previously described Harvey-Hopewell Fault can be traced downdip, where it intersects a north-dipping subsurface boundary at 1500 ms TWT. This lower boundary separates a region of poor coherence, interpreted as basement and Horton Group, from coherent reflectors below, interpreted as Windsor Group (Fig. 2.7). Reflector Wh is offset along the boundary by approximately 5 km (Fig. 2.7). This NW-dipping boundary is here termed the Folly Point Fault. The intersection point of the Harvey-Hopewell and Folly Point Faults forms the tip of a second tectonic wedge, inserted southward into Windsor Group evaporites (Fig. 2.7).

A similar relationship is seen on CR99-62Y (Fig. 2.9). The Folly Point Fault and Harvey-Hopewell Fault therefore meet at the tip line of a tectonic wedge, which can be traced as a subsurface linear feature between lines CR99-05 and CR99-62Y. Availability of seismic lines across the Sackville Subbasin is limited, and the tip of the wedge is just south of most of the other seismic profiles in the Corridor data set. In the Sahara series data set (FPTM), the intersection of these two faults occurs at ~2500 ms TWT, and is difficult to distinguish due to poor coherency. However, the linear feature plunges to the northeast similarly to the tip of the upper wedge; on line 3FPTM, the tip is estimated at a depth of 2500 ms TWT, shallowing to 1500 ms TWT on line CR99-05. Southwest, the tip line is lost as the wedge extends underneath the Bay of Fundy (Fig. 2.11).

Reflectors become much less coherent at depth; beyond ~2750 ms TWT the Folly Point Fault becomes impossible to trace downdip to the north (Fig. 2.7). This makes it nearly impossible to determine what happens to the root of the fault. Traced updip, the Folly Point Fault is lost in more poorly coherent reflectors, interpreted as Windsor Group (Fig. 2.7).

2.4.5. Tantramar, Wood Creek, and unnamed Faults

The Tantramar Fault is present only in the southernmost part of the study area. It is mapped on the surface (Fig. 2.3) and traced at depth in seismic profiles as a north-dipping structure (Fig. 2.7); the mapped fault trace is located just south of the extremity of the seismic profiles.

The Wood Creek Fault is located in the southeast of the study area (Fig 2.3). It dips to the south and is part of a system of faults, here collectively termed the Wood Creek Fault System. Only a small section falls within the study area (Fig. 2.2). The interaction with the Tantramar Fault is unclear because it has been eroded away. The Wood Creek Fault either intersects and truncates, or is intersected and truncated by, the Tantramar Fault.

Several unnamed, smaller faults are splays off the major named faults that aid in constraining the timing of fault movement. Three splays off the Harvey-Hopewell Fault accommodate movement along the fault (Fig. 2.7). Fault 01 appears to come to the surface, though it is difficult to trace through incoherent near surface reflectors. Faults 02 and 03 are truncated by an unconformity between the Boss Point and Hopewell Cape Formations. Two small faults offset the Harvey Hopewell Fault. Faults 04 and 05 are located between splays 01, 02, and 03. Faults 04 and 05 both have a normal sense of offset (Fig. 2.7). Within the lower wedge (Fig. 2.7), many small faults indicate a complex history for the wedge itself. Faults 06 and 07 are associated with salt expulsion from the Sackville Syncline. These root into the Windsor Group (Fig. 2.7). They are normal faults, and moved during deposition of the Mabou Group, evidenced by the truncation at the unconformity below the Cumberland Group.

2.5. Discussion

2.5.1. Upper wedge

2.5.1.1 Geometry

The northern boundary of the Sackville subbasin has long been recognized as the Dorchester Fault (Martel, 1987). However, previous authors (Gussow, 1953; Webb, 1963, 1969; Bradley, 1982; Martel, 1987; McCutcheon and Robinson, 1987, St. Peter and Johnson, 2009) have differed on the dip and significance of the fault. The observations above clearly indicate that the Dorchester Fault is actually two oppositely dipping faults with reverse offset that bound a tectonic wedge inserted into the Sackville subbasin at the level of the Windsor Group. Wilson et al. (2006) described a similar wedge in the western Moncton subbasin inserted towards the SE surrounded by Windsor Group.

2.5.1.2 Timing of insertion

The wedge contains basement, Horton, and possibly Sussex Group rocks, which are cut by the Upper and Lower Dorchester Faults. Because the faults cut these units, insertion of the wedge must post-date the Horton and Sussex Groups. The Dorchester Fault System is the northern boundary of the Windsor Group in the Sackville Subbasin, as there is no evidence that the Windsor Group extended to the north. It is probably that the Dorchester Fault System was active and controlled deposition during the Visean.

Immediately south of the Upper Dorchester Fault, well 716 intersects overturned Windsor Group (Fig. 2.7, Keighley, 2001). We interpret that movement the fault postdated the deposition of Windsor Group evaporites. The wedge is unconformably overlain by Hopewell Cape Formation at the northern most part of CR99-05.

The Upper Dorchester Fault was active during the Visean as a northern basin boundary. As the wedge was emplaced, the fault was inverted. Movement along the fault ceased before the deposition of the Serpukhovian Hopewell Cape Formation. Deformation above the wedge through the deposition of the Cumberland Group is minimal and likely related to events occurring in the adjacent Cumberland subbasin (Craggs et al, 2015).

2.5.2. Lower wedge

2.5.2.1 Geometry

The lower wedge is defined by two oppositely dipping faults; the Harvey-Hopewell and the Folly Point Fault. The tectonic wedge defined by the Harvey-Hopewell and Folly Point faults was inserted southward into the Windsor Group, similar to the upper wedge, with Windsor Group both above and below.

2.5.2.2 Timing

The Upper Dorchester Fault is truncated by the Hopewell Cape Formation of the Mabou Group, but splays from the Harvey-Hopewell are truncated by the Cumberland Group (Fig. 2.7). Therefore, the Harvey-Hopewell Fault was active after the Upper Dorchester Fault, but major movement along the fault ceased by the Baskirian, when the Cumberland Group was deposited.

Well 716 intersects overturned Windsor Group immediately above the Harvey-Hopewell Fault (Fig. 2.7, Keighley, 2001). We interpret that major movement of this wedge postdated the deposition of Windsor Group evaporites. South-dipping branch faults from the Harvey-Hopewell Fault cut Windsor and Mabou Group, but are truncated by Cumberland Group. Major movement of the lower wedge must have ceased during the late stages of Mabou deposition, prior to the deposition of the Cumberland Group.

In contradiction to what is seen in the seismic section, mapped interpretation based on outcrop shows slight offset in the Cumberland Group (St. Peter and Johnson, 2009). We propose that Mississippian faults such as the Dorchester Fault System and the Harvey-Hopewell Fault were reactivated again in the Pennsylvanian. The Harvey-Hopewell Fault can be traced to the edge of the Cumberland Basin (Fig. 2.2). Major deformation associated with salt expulsion occurred in the adjacent Cumberland Subbasin during the Pennsylvanian (Waldron and Rygel, 2005), and the Pennsylvanian faults could have accommodated movement from the adjacent basin, causing the slight offset seen in the mapped Cumberland Group.

2.5.3. **Wedge insertion and salt tectonics**

Tectonic wedges with similar geometry are widely known in thrust belts but do not usually involve basement. Waldron et al (2015) have suggested that major faults in this part of the Maritimes Basin have substantial strike-slip motion active during deposition of the Horton Group, moving the initiation of strike slip, previously thought to be early to mid Tournaisian (Webb, 1969), nearer to the Famennian/Tournaisian boundary.

Initial basin inversion uplifted sections of Horton and Sussex Groups. Normal faults from the Devonian and early Tournaisian were reactivated as reverse faults, possibly explained by the creation of a flower structure associated with a restraining bend in a transpressional environment (Martel, 1987; Waldron et al, 2010). After deposition of the Hillsborough in the early Visean, the Visean Windsor Sea deposited evaporites and carbonates of the Windsor Group (Martel, 1987; McCutcheon, 1981).

In the late Visean, salt expulsion began in the Subbasin. Rapid subsidence was caused by expulsion of the Windsor Group evaporites (Waldron and Rygel, 2005; Calder, 1994). This expulsion was likely initiated by the insertion of the lower tectonic wedge at the level of the Windsor Group during the late Visean.

2.5.4. Analogues

2.5.4.1 Local Analogues

To the NW, in the McCully Field area, Wilson et al. (2006) described a wedge inserted SE during the late stages of Mabou deposition. Up to 5 km dextral strike-slip displacement is interpreted along the wedge and up to 2 km dip-slip displacement. This is similar to what is seen in the Sackville Subbasin, where up to 5 km dip-slip displacement is interpreted. Southeastward thrusting that occurred close to the Mississippian-Pennsylvanian boundary in the Kennetcook area to the SE of the Sackville subbasin (Waldron et al, 2010) was produced by dextral transpression related to the Minas Fault Zone (Waldron et al, 2007), a geometry similar to that seen in the Sackville Subbasin. In the Kennetcook area and the Cumberland Subbasin, evaporite expulsion led to subsidence in minibasins (Waldron and Rygel, 2005; Waldron, et al, 2010).

2.5.4.2 Global Analogues

In the Maracabo Basin of the Venezuelan Andes (Fig. 2.12), uplift occurred at the same time as strike-slip movement (Hervouët et al, 2001). Right-stepping en echelon faults suggest that the deformation was controlled by nearby (10 km) dextral strike-slip movement (Duerto et al, 2006). Multiple tectonic wedges are inserted into Upper Cretaceous shales and limestone (Fig. 2.12, Duerto et al, 2006), associated with shortening through inverted normal faults, a large strike-slip fault, and a pop-up structure. Tectonic wedges inserted into more ductile units is a relationship is similar to what we interpret in southeastern New Brunswick.

2.6. Conclusions

The Sackville subbasin records a complex history of Devonian to Carboniferous deformation. This deformation can be correlated to strike-slip faulting and expulsion of evaporites from the subbasin. In the Late Devonian and early Tournaisian, the Horton and Sussex Groups were deposited in half-graben basins. Thick evaporite successions of the Windsor Group and early Mabou Group were deposited in the Visean. Basins filled with Horton and Sussex groups were inverted, forming two tectonic wedges bounded by the Dorchester Fault system and the Harvey-Hopewell and Folly Point Faults,

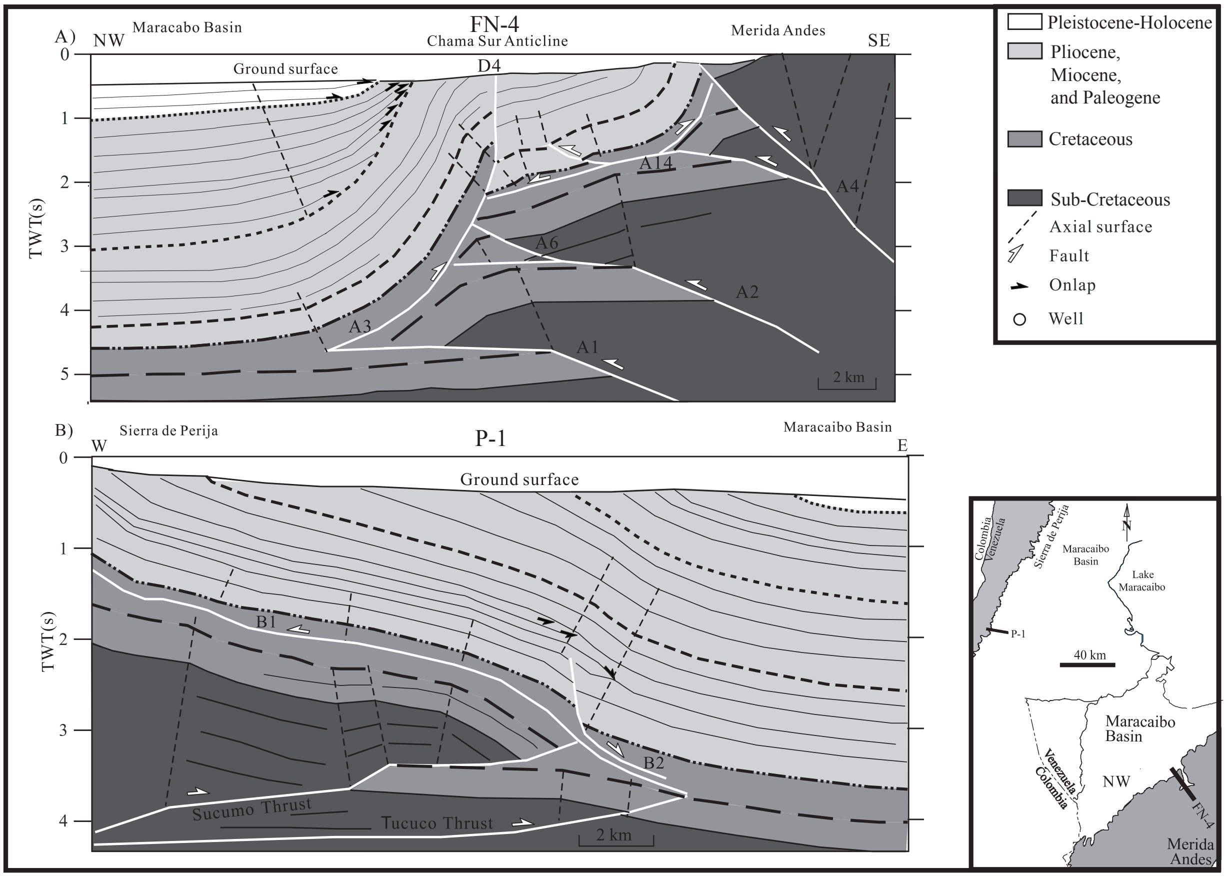

Figure 2.12. The Maracaibo Basin

From Duerto et al. (2006). The Maracaibo basin has a complex history of north-south strike-slip movement and east-west shortening. Upper and Lower Cretaceous designated in this diagram are shale, siltstone, sandstone, and limestone. Sub-Cretaceous rock comprises Paleozoic basement, conglomerate, and shale. Super-Cretaceous is largely sandstone, conglomerate, and some shale. Wedges are inserted into the Cretaceous limestone and shale.

respectively. These major low angle faults used zones of relative weakness created by the more ductile evaporites in the Visean Windsor Group. Located in a restraining bend of a strike-slip system, these wedges created a positive area, likely associated with a flower structure. In the Serpukhovian and Bashkirian, salt expulsion, likely initiated by the emplacement of these wedges, controlled local stratigraphy, causing rapid subsidence of the late Mabou and Cumberland Groups, particularly seen in thickness changes within the Sackville syncline.

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Chapter 3. Basin development by transpression and reactivated pre-existing basement faults: The eastern Moncton Subbasin of southeastern New Brunswick, Atlantic Canada

3.1. Introduction

The Maritimes Basin of Atlantic Canada (Fig. 3.1) is a large, structurally and stratigraphically complex basin filled from the Late Devonian to the Permian. The known depth of the Basin is 12 km beneath the Magdalen Islands (Hibbard and Waldron, 2009). Basin bounding faults or uplifts subdivide the Maritimes Basin into smaller depocenters or subbasins, these subbasins have common stratigraphy, which shows that some tectonic events occurred on a basin-wide scale (Martel, 1987; van de Poll, 1993; Calder, 1998; St. Peter and Johnson, 2009; Waldron et al., 2015).

Oil and gas exploration started in New Brunswick's history in the mid-1800s. The Stoney Creek Field (Fig. 3.2) was in production from 1910 to 1991, yielding both oil and gas (St. Peter and Spady, 2003). In 2000, the McCully Gas Field (Fig. 3.2) was discovered in the eastern Moncton subbasin (St. Peter and Spady, 2003). In 2003, this field entered production (Wilson and White, 2006). Gross production at year-end in 2015 was 5.6 x 10^6 standard cubic feet per day (Corridor Resources Inc., 2015).

Carboniferous sedimentary rocks in southeastern New Brunswick lie unconformably on Ganderian and Avalonian terranes of the Appalachian orogen (Barr and White, 1996). The complex Carboniferous structural evolution of southeastern New Brunswick has created conflicting interpretations as geologists have tried to unravel the history of the area. A thrust-belt origin was favored by Gussow (1953), oblique extension by Webb (1963, 1969), strike-slip by Martel (1987), and a rift model by McCutcheon and Robinson (1987). Previous interpretation shows that basin inversion

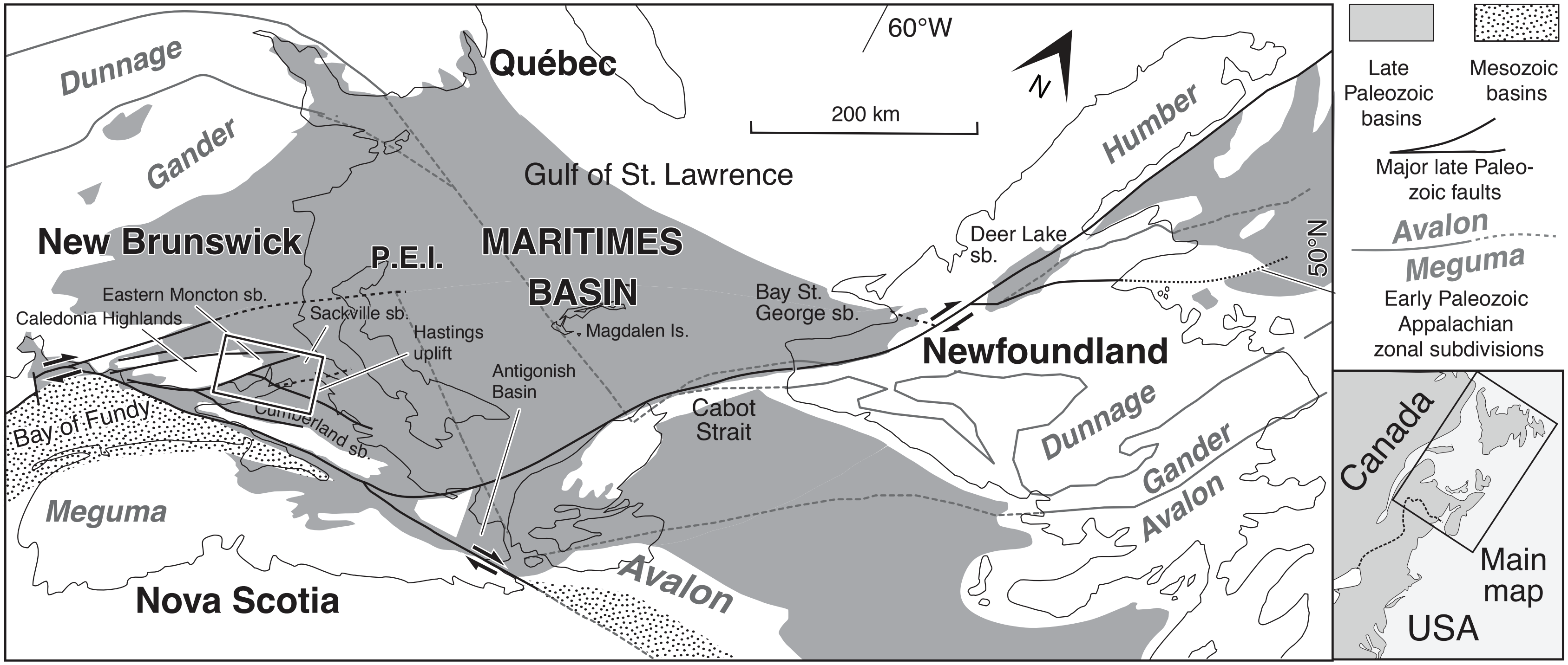
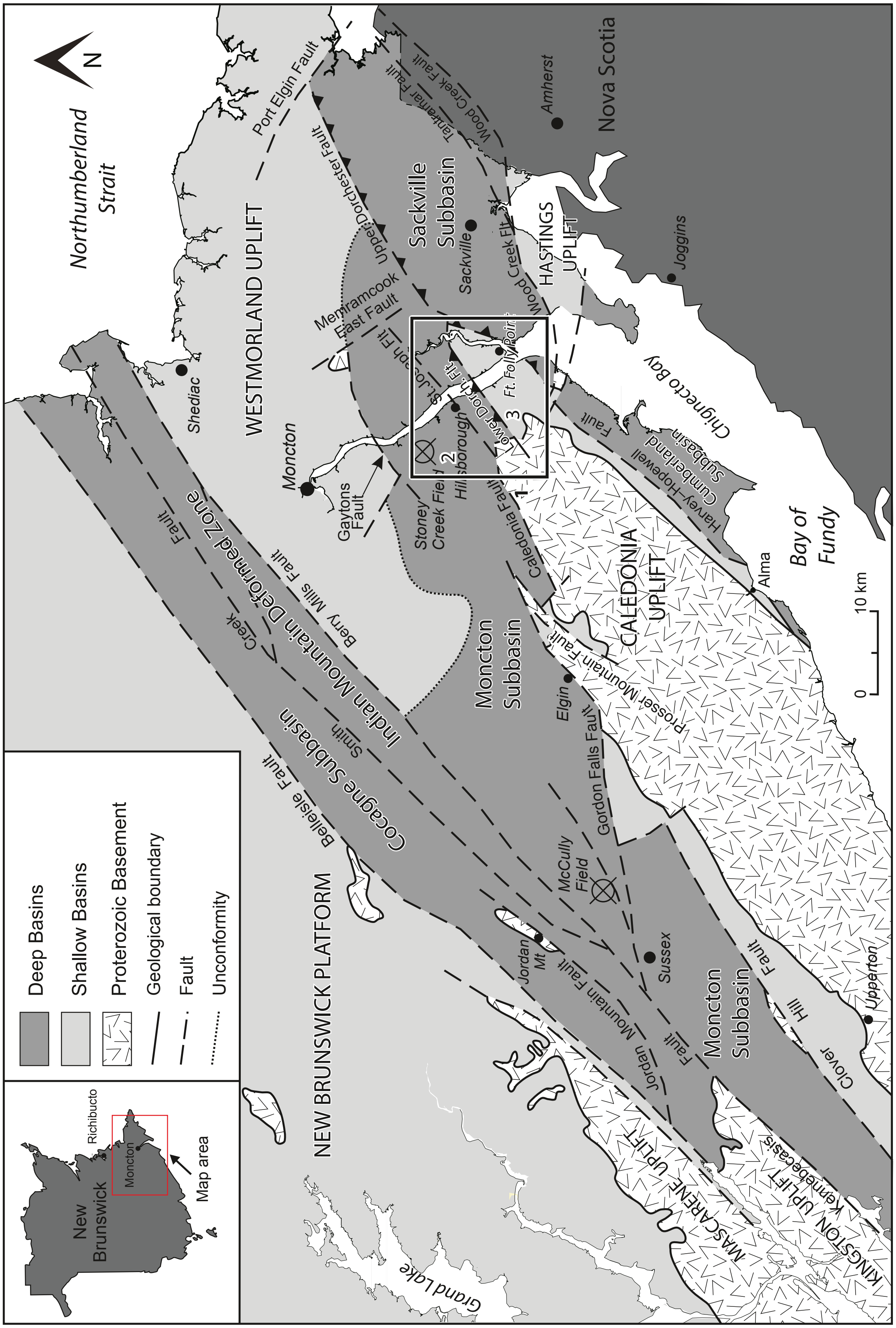


Figure 3.1. Location of the Maritimes Basin of Atlantic Canada,
showing the locations of select subbasins (sb.), and structural features. Rectangle encloses area of Fig. 3.2. After Waldron et al. (2013) and Gibling et al (2008).

Figure 3.2. Distribution of subbasins and basement uplifts in southeastern New Brunswick.
Next page. Fault traces are projected to surface. Rectangle encloses area of Fig. 3.4. In this Figure: 1 – location of Rosevale outcrop. 2 – location of Dawson Settlement, 3 – location of Frederick Brook outcrop. Modified from St. Peter and Johnson, 2009.


Deep Basins
Shallow Basins
Proterozoic Basement
Geological boundary
Fault
Unconformity
New Brunswick
Moncton
Richibucto
Map area
N
Northumberland Strait
WESTMORLAND UPLIFT
NEW BRUNSWICK PLATFORM
Shediac
Moncton
Port Elgin Fault
Upper Dorchester Fault
Tantramar Fault
Wood Creek Fault
Wood Creek Flt.
Memramcook East Fault
St. Joseph Flt.
Lower Dorch. Flt.
Ft. Folly Point
Sackville Subbasin
Sackville
Amherst
Nova Scotia
Joggins
HASTINGS UPLIFT
Chignecto Bay
Cumberland Subbasin
Harvey-Hopewell Fault
Bay of Fundy
Alma
CALEDONIA UPLIFT
Caledonia Fault
Hillsborough
Stoney Creek Field
Gaytons Fault
1
2
3
Moncton Subbasin
Elgin
Prosser Mountain Fault
Gordon Falls Fault
McCully Field
Sussex
Jordan Mt
Jordan Mountain Fault
Moncton Subbasin
Clover Hill Fault
Upperton
Indian Mountain Deformed Zone
Berry Mills Fault
Smith Creek Fault
Cocagne Subbasin
Belleisle Fault
MASCARENE UPLIFT
KINGSTON UPLIFT
Kennebecasis
Grand Lake
0
10 km

after deposition of the Sussex Group relates to regional deformation in a fold-thrust belt (Park et al, 2007). Other authors have documented evidence that shows significant strike-slip motion in the Basin (Waldron, 2004; Waldron et al, 2007; Hibbard and Waldron, 2009; Murphy et al 2011; Waldron et al 2013), although these models invoke both transtensional and transpressional movement during basin development. Waldron et al (2015) demonstrate that major dextral movement began in the late Devonian and suggest that it amounted to 200 – 300 km movement along abundant faults striking NE-SW, approximately parallel to the Appalachian orogen.

Northeast of the Petitcodiac Estuary, seismic data show (Ch. 2) that two tectonic wedges that comprise basement and units of the Horton Group (Fig. 3.3) were inserted from north to south at the level of the Windsor Group. In Ch. 2, we interpreted that these wedges were formed by inversion of normal faults, possibly associated with a flower structure.

In this paper, we focus on the eastern Moncton Subbasin (Fig. ZS), a depocenter located in southeastern New Brunswick, cut by major NE-SW striking faults. Host to the McCully and Stoney Creek Oil and Gas fields, this subbasin has been extensively explored by industry. We provide new interpretation of the tectonic history of the subbasin, based on interpretation of ten seismic profiles, new palynology data, strike-slip faults, and low-angle thrust faults associated with salt expulsion during deposition of Carboniferous strata.

3.2. Data and Methodology

Structural and stratigraphic data from the field were combined with subsurface seismic and well log data. Ten wells were initially selected from the data set provided by the New Bunswick Department of Natural Resources (NBDNR). These were then checked for sonic and density logs, both of which are needed to create synthetic ties. Only wells 331, 333, 698, 703, and 760 had all necessary data; 331 and 333 were deemed most important based on their position relative to important horizons, faults, and folds.

Ten seismic profiles and one 3D volume were provided by Contact Exploration for this study, spanning the Hillsborough area and one profile east across the Petitcodiac River (Fig. 3.4). All profiles were loaded into Schlumberger's Petrel software as SEG-Y files, displayed in two-way travel time (TWT). Five profiles trend approximately north-south, and five approximately east-west. Well-log correlations were drawn from petroleum and mineral holes. Outcrop correlation, seismic characteristics, and geometric relationships were used along with the well data to interpret the history of the subbasin.

3.3. Stratigraphy

The fill of the Maritimes Basin is divided into six groups that range from Late Pennsylvanian to Late Devonian in age. From oldest to youngest, these are the Horton, Sussex, Windsor, Mabou, Cumberland, and Pictou Groups (Fig. 3.3). These stratified rocks lie above pre-Late-Devonian metamorphic and igneous basement rocks. Deformation throughout the basin's history caused faulting, folding, uplift, and widespread erosion. The basin fill is largely non-marine clastic rocks, but a marine incursion during the Visean produced carbonates and thick evaporates in the Windsor Group. Subsequent movement of the Windsor Group evaporites strongly impacted the strata of the Maritimes Basin (Waldron and Rygel, 2005; Craggs et al, 2015).

The complex nature of the stratigraphy in this area is best unraveled by starting with the less complicated younger units, progressing to the more complicated older formations. It is common practice in industry to label reflections as the top of formations, but due to the number of angular unconformities in the study area, reflections are labeled as the base of the overlying unit, as this allows angular unconformities to be labeled consistently across the region.

3.3.1. Cumberland Group: Boss Point Formation

In the eastern Moncton Subbasin, the Bashkirian Cumberland Group contains

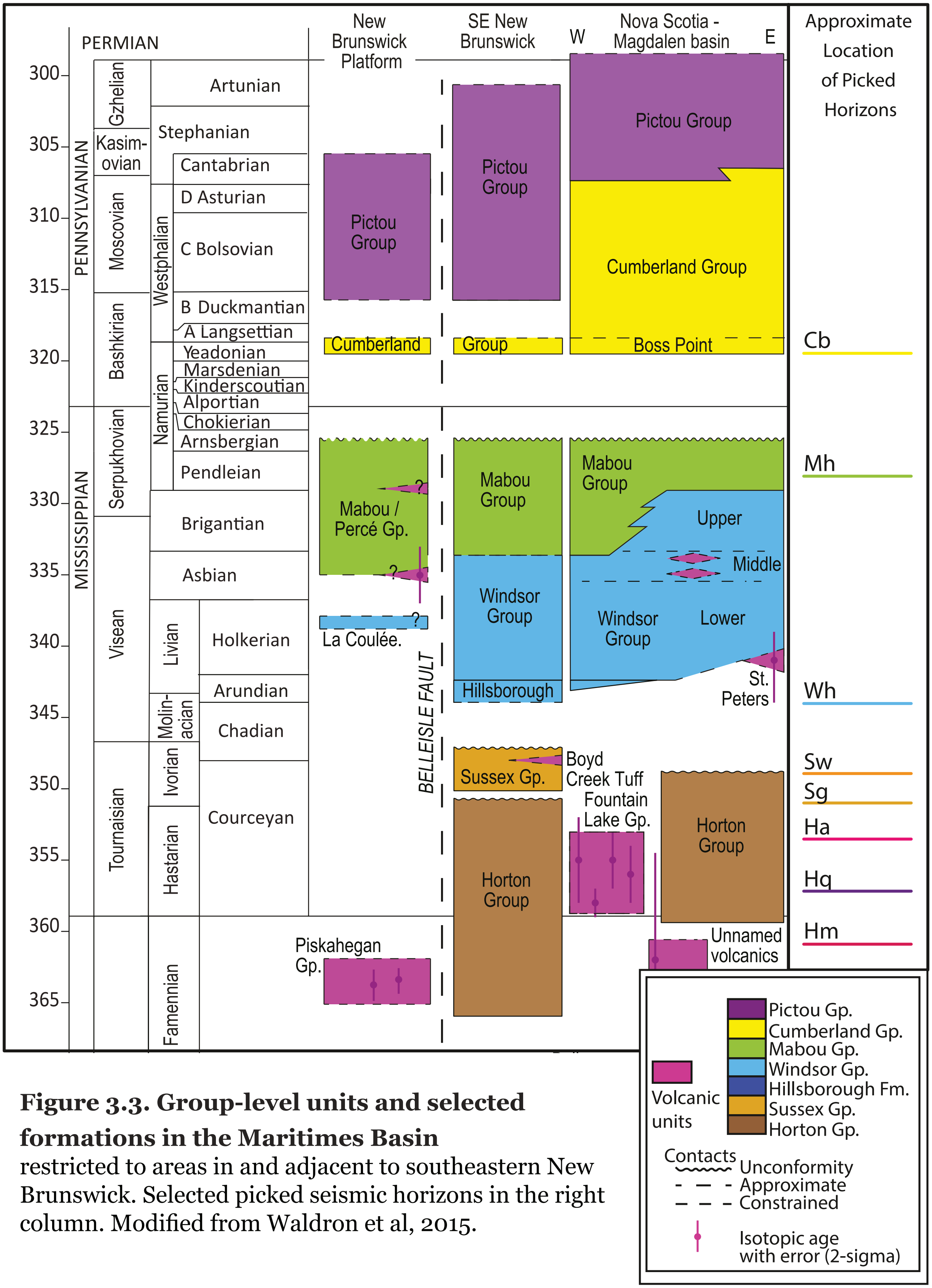


Figure 3.3. Group-level units and selected formations in the Maritimes Basin restricted to areas in and adjacent to southeastern New Brunswick. Selected picked seismic horizons in the right column. Modified from Waldron et al, 2015.

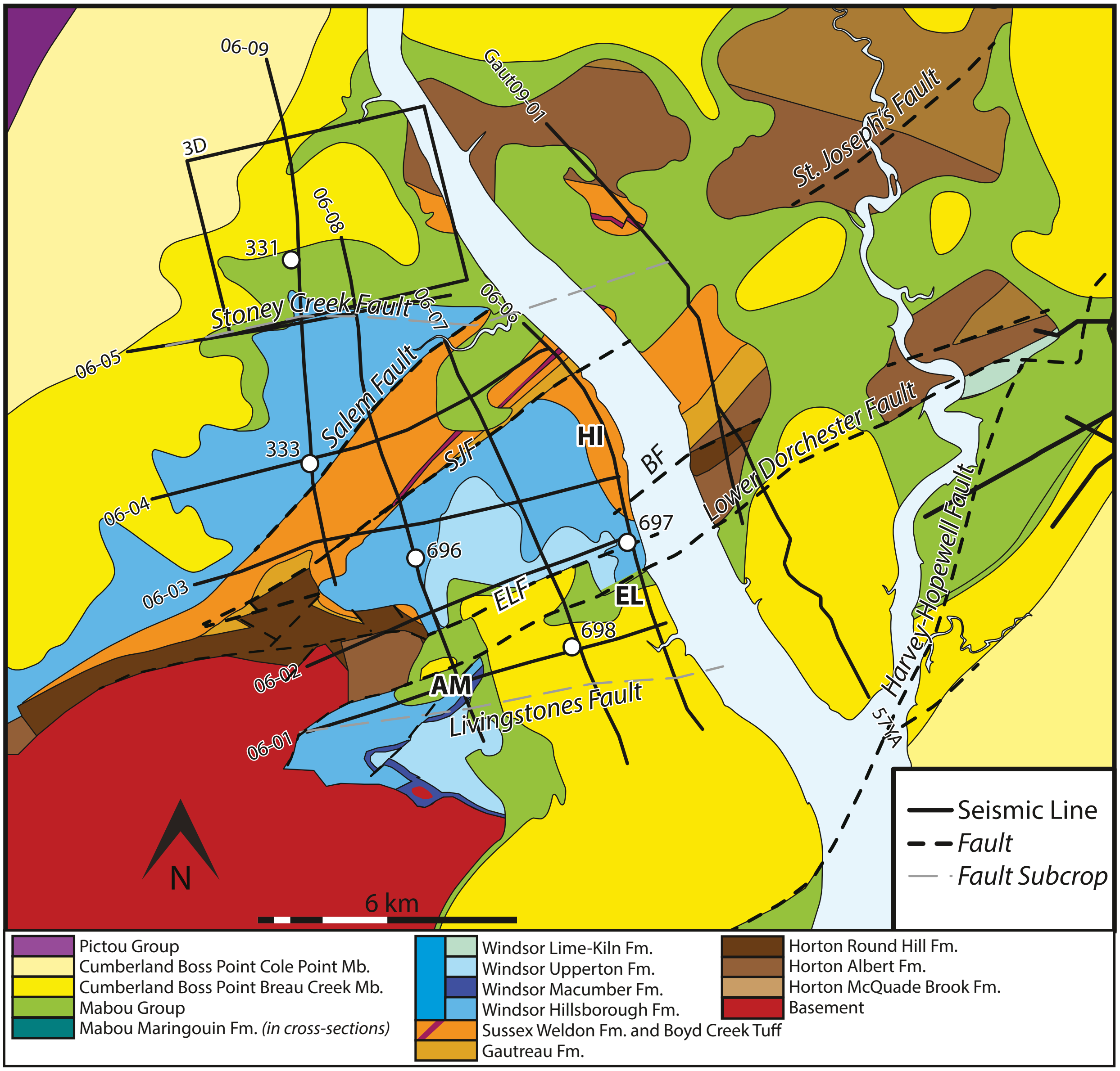


Figure 3.4. Location map of seismic lines, faults traces, and geologic boundaries in the eastern Moncton Subbasin.
AM – Albert Mines area; EL – Edgetts Landing area; HI - Hillsborough area.

only the coal-bearing, sandstone-rich Boss Point Formation. In contrast, the adjacent Cumberland Subbasin of Nova Scotia contains a thick succession of Boss Point, Little River, Joggins, Springhill Mines, Ragged Reef, and Malagash Formations (Rygel et al., 2014). The Boss Point formation contains coalified fossil logs and plants in grey to red sandstone, mudstone, and conglomerate (St. Peter and Johnson, 2009). The lower boundary is interpreted as an unconformity (Ryan and Boehner, 1994). Near Edgetts Landing and Albert Mines (Fig. 3.4), the formation is cut by the Edgetts Landing Fault and Lower Dorchester Fault (Ch. 2). Fort Folly Point Peninsula (Fig. 3.4) is almost entirely blanketed with Boss Point Formation south of the Lower Dorchester Fault.

The Boss Point Formation is intersected in well 698 (Albert Mines 5), west of the Petitcodiac River, and well 790 (Petroworth Stoney Creek West), near Dawson Settlement (Fig. 3.2). Well 698 sits at the NW-corner of the intersection between seismic lines Hill 06-07 and Hill 06-01, and has been used to help control contacts seen between the spud and 500 m depth. Well 790 was drilled just west of the 3D volume and has been used to help with understanding the formations intersected near the Stoney Creek Gas and Oil field.

Reflection Cb is a peak, correlated with the base of the Boss Point Formation in outcrop on lines Hills 06-09, Hills 06-08, SC81-63Y, Hills 06-07, Hills 06-06, and Hills 06-01. Numerous artifacts are present in the near surface reflections, particularly on line Hills 06-06 near Hopewell Cape (Fig. 3.5). These artifacts possibly result from diffraction by near-surface glacial features. Line Hills 06-09 (Fig. 3.6) shows Cb separating a more coherent package above from an incoherent package below, correlated with conglomerate of the Mabou Group.

3.3.2. Mabou Group: Hopewell Cape Formation

The Mabou Group in the eastern Moncton subbasin is primarily represented by the Hopewell Cape Formation. The Hopewell Cape Formation consists of mostly red, but locally grey conglomerate, sandstone, and mudstone (St. Peter and Johnson, 2009). Reflection Mh is a peak correlated with the base of the Mabou Group. Line Hills 06-01 shows the Hopewell Cape Formation thickening to the east (Fig. 3.7); this line also shows an angular unconformity between the Windsor and Mabou Groups, where west-dipping reflectors are truncated by the shallow east-dipping boundary formed by Mh. Line Hills 06-07 shows the Hopewell Cape Formation thickening to the south (Fig. 3.8). Above Mh are discontinuous gently folded or near-horizontal reflections with poor coherence; in units below Mh (interpreted to be the Sussex Group), folding is more pronounced. This relationship is seen on Hills 06-05, Hills 06-06, Hills 06-07, and Hills 06-08.

3.3.3. Windsor Group

The Upperton, Macumber, Gays River, and Hillsborough formations make up the Windsor Group in the study area. It is often difficult to distinguish the Windsor formations from each other on seismic profiles without well control.

3.3.3.1 Upperton Formation

The Upperton Formation of the Windsor Group is present in the southeastern part of the eastern Moncton subbasin (Fig. 3.4). It consists of anhydrite and gypsum, and appears at surface in abandoned quarries and large outcropping cliffs near Wilson Brook (Fig. 3.9). Sinkholes and underground caves occur in the Upperton formation; the areas mapped as Upperton have a distinctive topography. The upper boundary of the Upperton formation in the eastern Moncton subbasin is interpreted as an angular unconformity (St. Peter and Johnston, 2009; McCutcheon, 1981). The lower boundary of the Upperton formation is conformable with the underlying Macumber formation (McCutcheon, 1981). The Upperton formation has been subjected to at least two karstification events (St. Peter and Johnston, 2009).

There are no well intersections with the base of the Upperton formation. It outcrops at surface near seismic lines Hills 06-02, Hills 06-07, and Hills 06-08 (Fig.

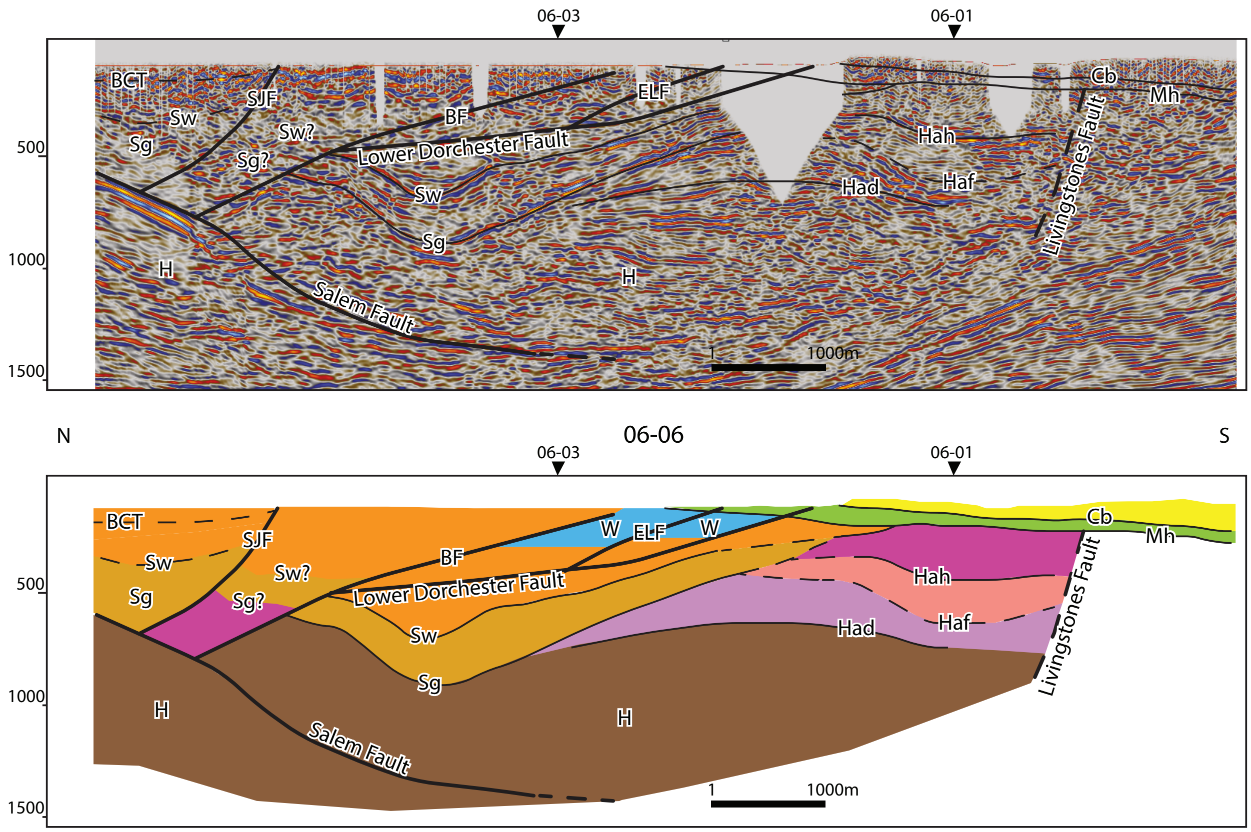
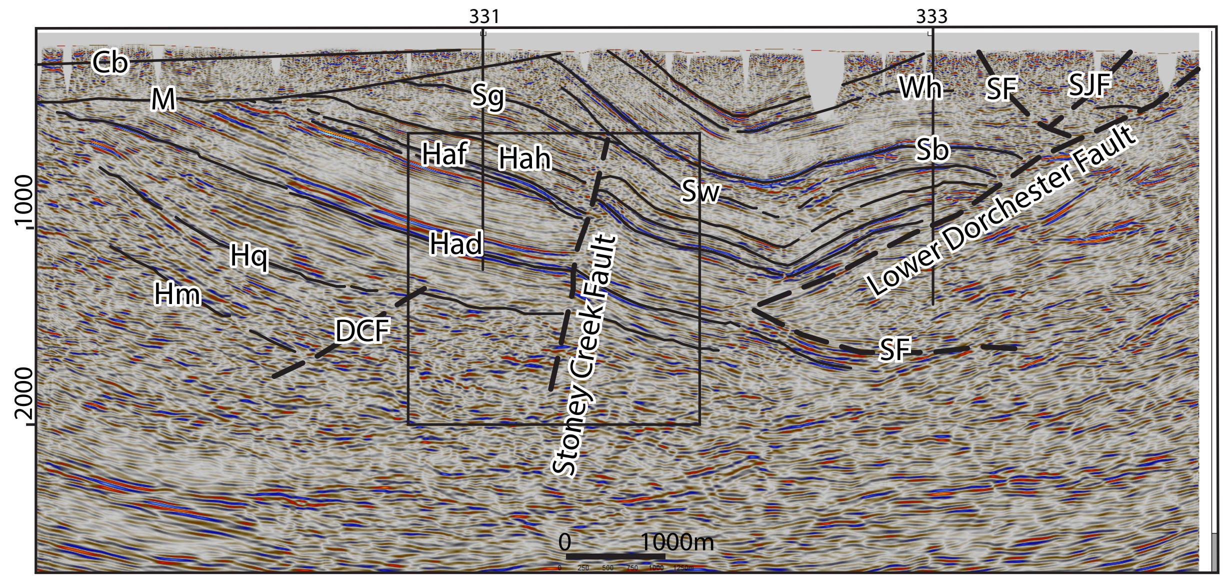


Figure 3.5. Seismic profile 06-06, showing interpreted horizons and faults. Directly west of the Petitcodiac River, the Salem Fault has not been separated by the Lower Dorchester Fault. (BCT – Boyd Creek Tuff, SJF – Saint Joseph Fault, BF – Boudreau Fault, ELF – Edgetts Landing Fault. Vertical scale milliseconds two-way-travel. For location and shadings, see Fig. 3.4.

Figure 3.6. Seismic profile 06-09; progressive evolution of the Stoney Creek Fault

Next page. Top: Seismic profile 06-09, showing interpreted horizons and faults. Square around portion shown in flattened profiles below. Bottom: Progressive evolution of the Stoney Creek Fault shown by successive flattening of line 06-09. 1. Flattened along base Dawson Creek, offset normal 2. Flattened along internal Frederick Brook horizon, offset reverse 3. Flattened along base Hiram Brook, offset normal 4. Flattened along unconformity at the base of the Weldon Formation, offset normal. SF – Salem Fault (two parts), SJF – Saint Joseph Fault, DCF – Dawson Creek Fault. Vertical scale milliseconds two-way-travel. For location, see Fig. 3.4.


331
333
Cb
M
Sg
Haf
Hah
Sw
Wh
SF
SJF
Sb
Lower Dorchester Fault
Had
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Stoney Creek Fault
1000
2000
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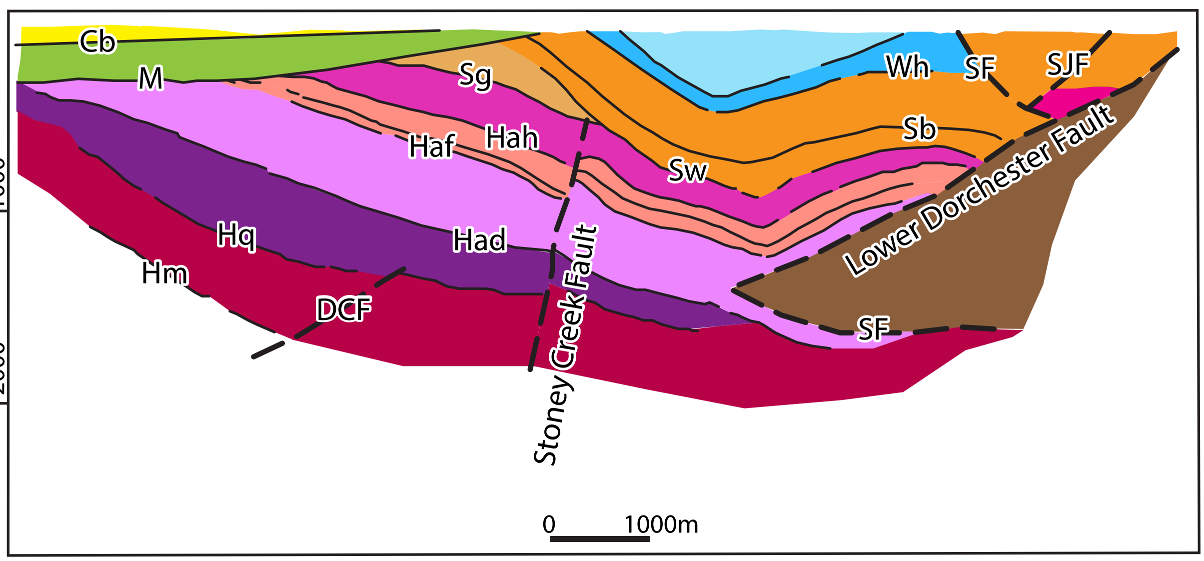
1000m

N 06-09 S


Cb
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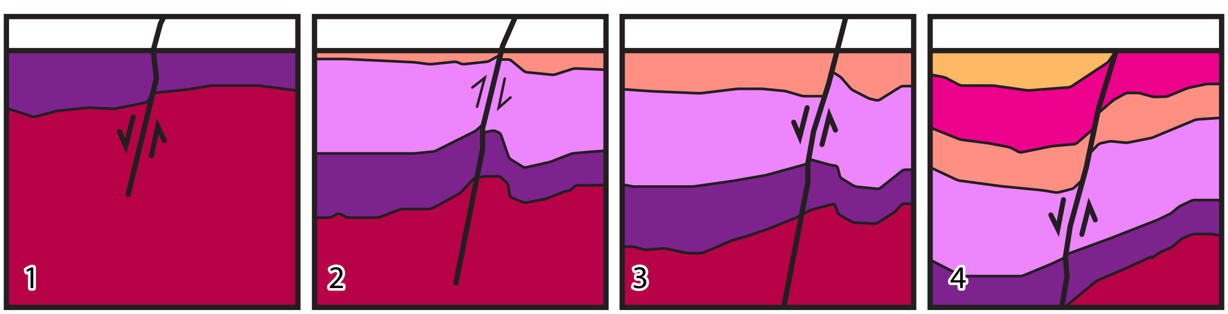
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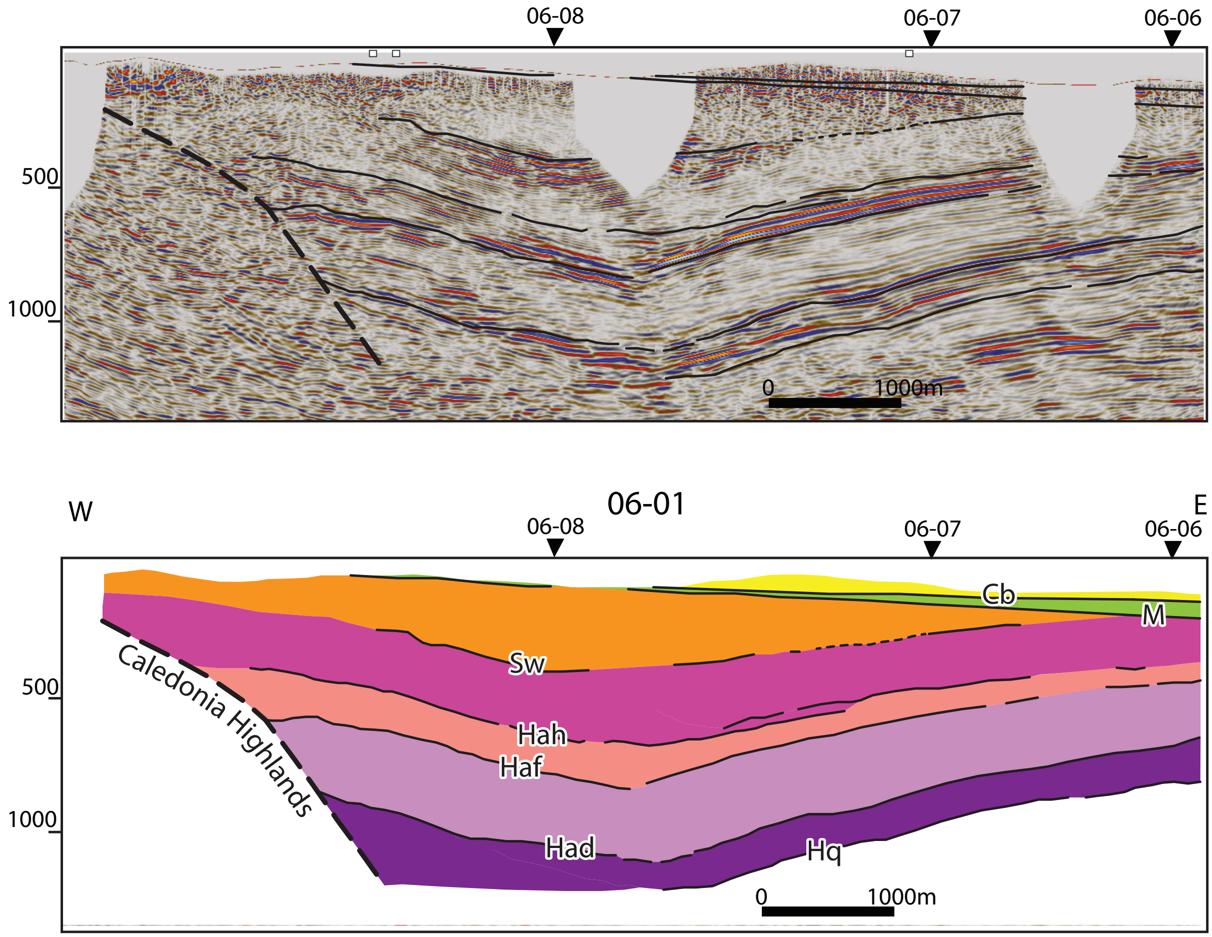

Figure 3.7. Seismic Line 06-01, showing interpreted horizons and faults. Note how the Hopewell Cape Formation thickens to the east, and how the fault at the eastern edge of the Caledonia Highlands cuts all formations. The Livingstones Fault would pass just south of this line. Vertical scale milliseconds two-way-travel. For location and shadings, see Fig. 3.4.

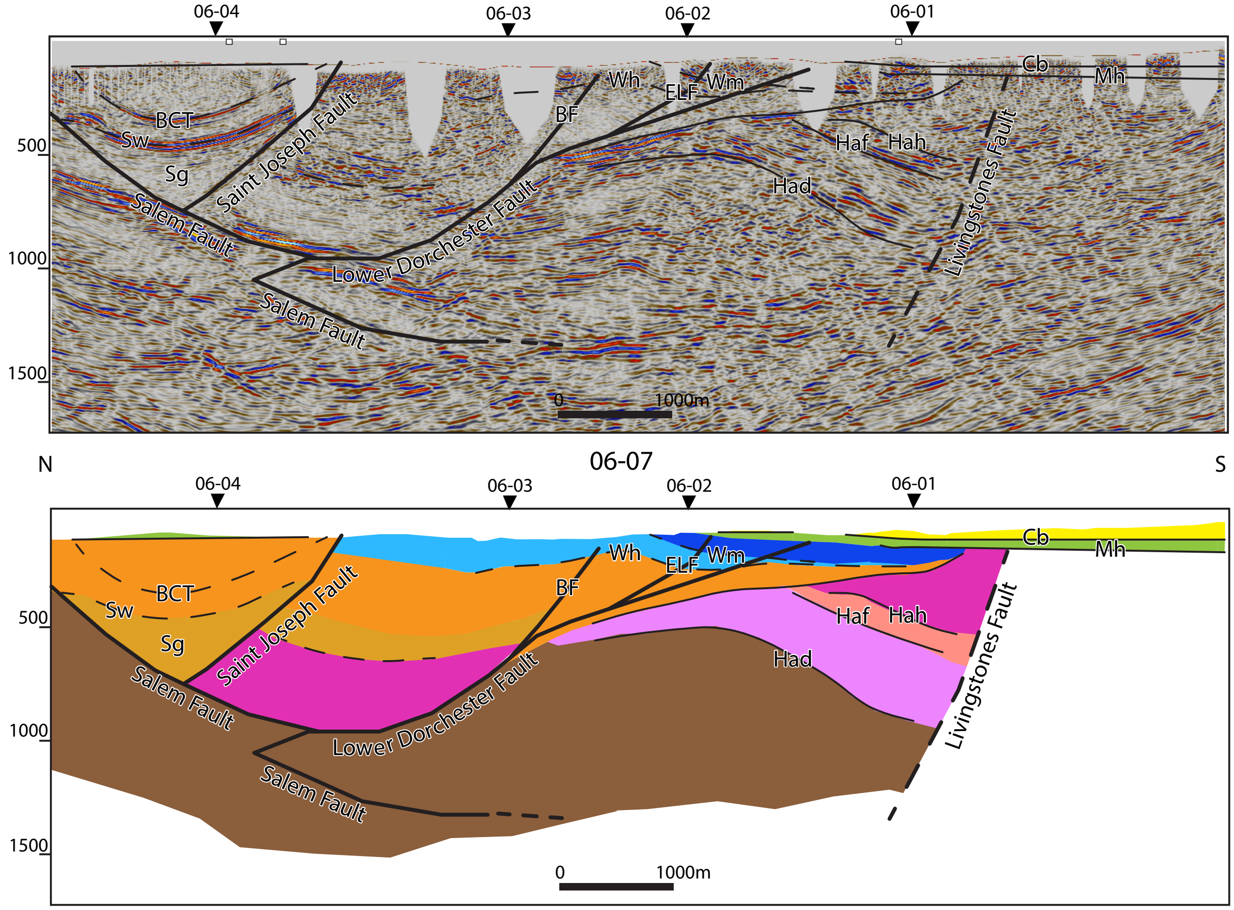

Figure 3.8. Seismic Line 06-07, showing interpreted horizons and faults. The Salem Fault cut and offset by the Lower Dorchester Fault at depth. BCT – Boyd Creek Tuff, BF – Boudreau Fault, ELF – Edgetts Landing Fault. Vertical scale milliseconds two-way-travel. For location and shadings, see Fig. 3.4.

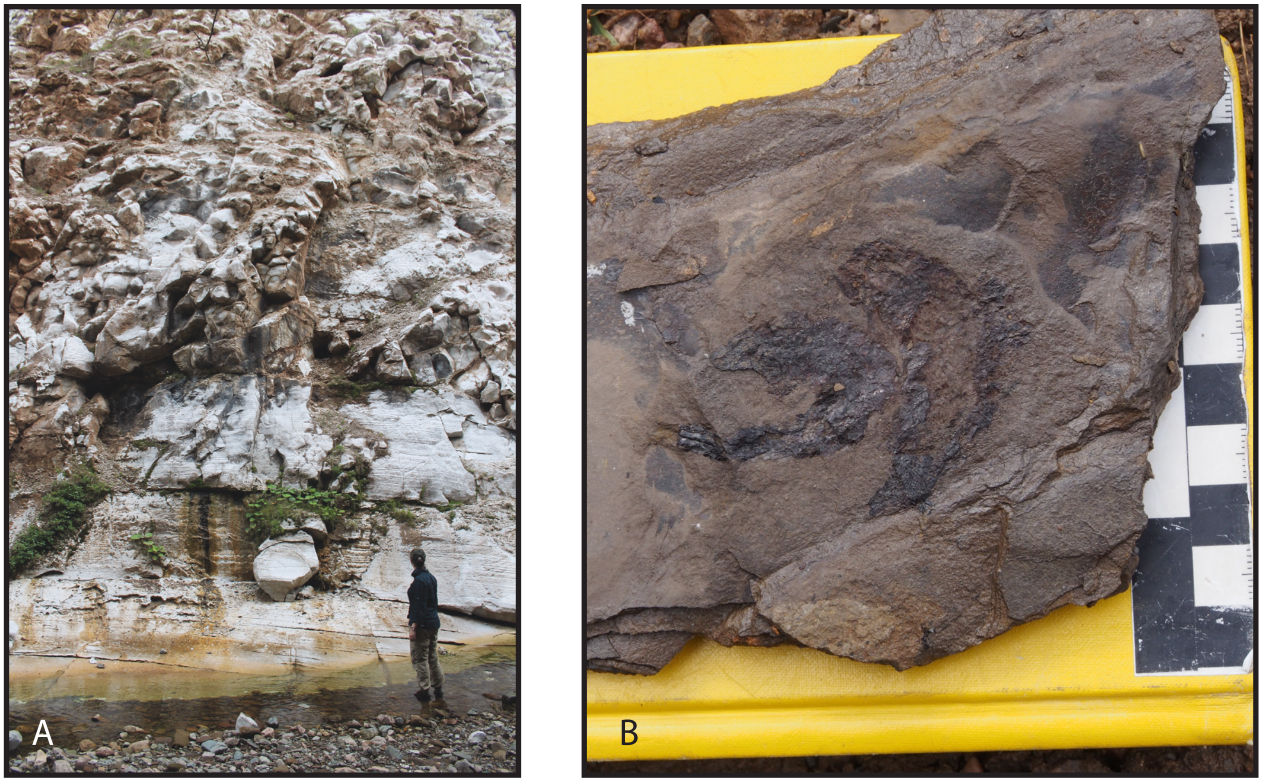

Figure 3.9. Field photographs.
A: gypsum and anhydrite cliffs along Wilson Brook; Lauren for scale, approx. 1.7 m. B: fish fossils found in the Albert Mines/Frederick Brook area. Scale bar 10 cm.

3.4). Wu is an internal reflection within the Windsor group, near the base of the Upperton Formation. Wu is a very poorly resolved surface with numerous artifacts, perhaps resulting from diffraction from karstification.

3.3.3.2 Macumber Formation

The Macumber Formation is mainly laminated limestone. The formation is quite thin, with a thickness between 9 and 18 m in the eastern Moncton subbasin (St. Peter and Johnston, 2009). It is mapped west of Edgetts Landing in the Albert Mines area (Fig. 3.4). Like the Upperton Formation stratigraphically above it, the Macumber Formation has sinkholes and underground caves where it occurs near the surface.

Reflection Wm is correlated with the base of the Macumber formation. Wm has been picked as a peak that separates bright reflectors above, interpreted to be laminated limestone of the formation, from dim reflectors below, interpreted to be the Hillsborough Formation conglomerate. There are no well intersections with the Macumber formation; however, Wm is traced to the surface on seismic profiles Hills 06-07, and Hills 06-08 (Figs. 3.8, 3.10), which supports the mapped interpretation (Fig. 3.4).

3.3.3.3 Hillsborough Formation

The Hillsborough formation is the basal formation of the Windsor Group, following St. Peter and Johnston (2009). It is in places a redbed succession with conglomerate, sandstone, and mudstone. In outcrop, it is often difficult to distinguish from the Weldon formation of the underlying Sussex Group; however, the two are believed to be separated by an angular unconformity.

The Hillsborough formation is intersected in many wells across the eastern Moncton subbasin. Well 331 (Irving/Chevron Stoney Creek No. 1) intersects conglomerate at 52 m depth, but it is difficult to tell from well logs if the conglomerate belongs to Hillsborough Formation or underlying Sussex Group. Well 333 (Hillsborough

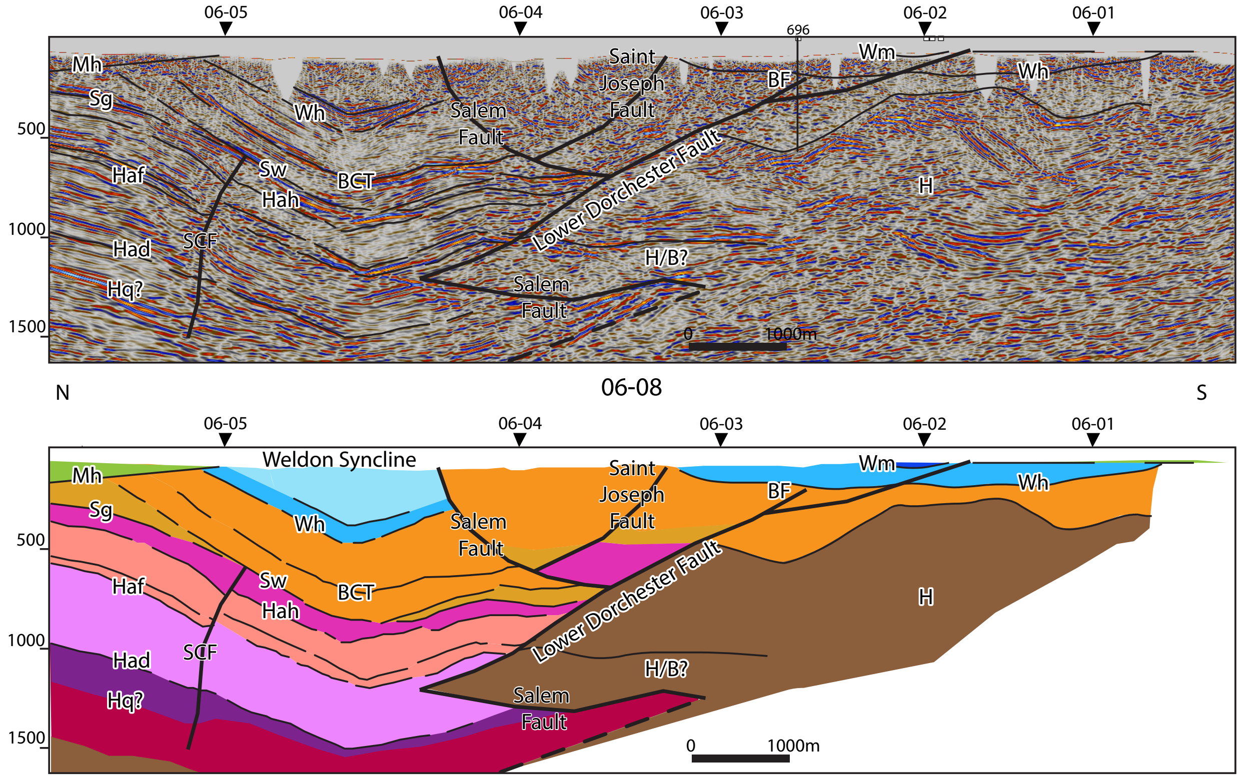

Figure 3.10. Seismic profile 06-09, showing interpreted horizons and faults, showing the Weldon Syncline and the Boyd Creek Tuff (BCT) reflector in the Weldon Formation. SCF – Stoney Creek Fault, BF – Boudreau Fault, H/B - Horton Group or basement. Vertical scale milliseconds two-way-travel. For location and shadings, see Fig. 3.4.

1) starts in the Hillsborough formation and intersects the base of the formation at 65 m depth. Well 703 (Albert Mines 4) is similar; the base of the formation is intersected at 116 m depth. Well 790 (Petroworth Stoney Creek West) intersects the base at 275 m. Well 698 (Albert Mines 5), intersects the top of the Hillsborough Formation at 157 m depth, and the base of the formation at 473 m depth. These intersections correlate with a bright peak between two trough reflections (a doublet) that marks the base of the Windsor Group throughout Atlantic Canada (Durling, 1997), identified as Wh (Fig. 3.6).

Wh separates divides overlying reflectors of the Windsor Group from low amplitude reflectors of the Sussex Group. Following the reflector from north to south on line Hills 06-09, it becomes apparent that there is an unconformity between the Hillsborough Formation and the underlying Sussex group, visible in the subsurface under the Weldon syncline (Fig. 3.6, 3.10). South from the syncline, Wh is truncated in the hanging wall of a fault. Seismic line Hills 06-07 shows Wh cut in the footwall of a different fault, farther south (Fig. 3.8).

3.3.4. Sussex and Horton Groups

The Sussex Group is unique to New Brunswick. Unconformity bounded, this group contains conglomerate, sandstone, mudrock, felsic ash, and glauberite-rich evaporites. Recent palynological work on the glauberite-bearing units suggests they may be part of the underlying Horton Group (M. Stimpson, NBDNR, pers. comm. 2016). The Horton Group is much more widespread, extending to subbasins outside of New Brunswick, and is a thick succession of conglomerate, shale, and mudstone. Listric normal faults, asymmetric shape, and thickening show that the Horton Group was deposited in active half-grabens (Durling, 1997). Normal faults were later reactivated by transpression (Durling, 1997), contributing to the complex deformational history.

3.3.4.1 Weldon Formation and Boyd Creek Tuff

The Weldon Formation is largely redbeds with minor carbonates (St. Peter and Johnson, 2009). The formation is present in wells 331 (Irving Chevron Stoney Creek 1), 333 (Hillsborough 1), and 703 (Albert Mines 4). The upper boundary of the Weldon Formation is an angular unconformity between the Weldon and the overlying Hillsborough (Fig. 3.8; St. Peter and Johnson, 2009). St. Peter and Johnson (2009) interpreted the lower boundary of the Weldon Formation as conformable on underlying Gautreau Formation, which was included in the Sussex Group based on palynological data in the Moncton area. Our interpretation of seismic data and new palynology results (M. Stimpston, New Brunswick Department of Natural Resources, personal communication, 2016) suggest that the Gautreau in the type area is older, and is separated from the Weldon by an unconformity (Fig. 3.10). We therefore include the Gautreau Formation in the Horton Group.

The base of the Weldon Formation is intersected in well 333 (Hillsborough 1) at 1330 m depth. Reflection Sw (Fig. 3.6), traced near the base of the Weldon Formation, is a relatively bright trough-peak pair that separates low-amplitude reflectors above, interpreted to be the carbonates and redbeds of the Weldon Fm., from the brighter reflectors below, interpreted to be the Gautreau Formation and the Albert Formation on line 06-09 (Fig. 3.6).

The Boyd Creek Tuff is a felsic ash unit with a thickness not exceeding 35 m (St. Peter and Johnson, 2009); it is present within the Weldon Formation at or near surface around Stoney Creek, Weldon, Hillsborough, and Gautreau Village, in the far east of the Eastern Moncton subbasin (Fig. 3.4). It is intersected in well 333 (Hillsborough 1), and has limited outcrop in the Hillsborough and Weldon area. Reflector Sb, a reflection within the Weldon Fm. (Fig. 3.6) near the Boyd Creek Tuff, is connected to well 333 and traced to surface. Sb appears on seismic lines GAUT09-01, Hills06-04, Hills06-05, Hills06-06, Hills06-07, Hills06-08, and Hills06-09 as a bright peak above the traced reflection Sw (Fig. 3.11, 3.5, 3.8, 3.10, 3.6).

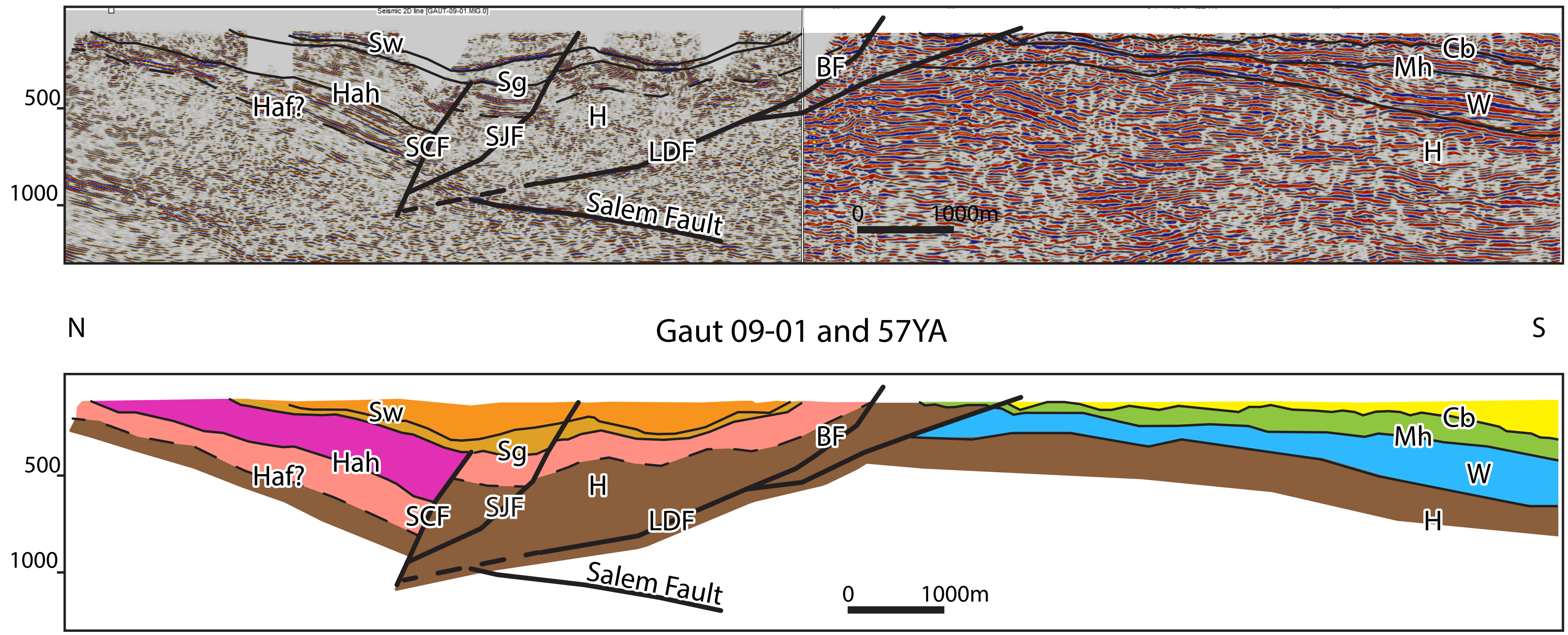

Figure 3.11. Composite of Gaut 09-01 and 57YA, showing interpreted horizons and faults.
This shows the north-dipping faults that create a possible flower structure. SCF – Stoney Creek Fault, LDF – Lower Dorchester Fault, BF – Boudreau Fault. H- undifferentiated Horton Group. Vertical scale milliseconds two-way-travel. For location and shadings, see Fig. 3.4.

3.3.4.2 Round Hill Formation

The Round Hill Formation is a coarse-grained clastic unit on the northern margin of the Caledonia Uplift (McLeod, 1980). The formation thins away from the Caledonia Uplift and has a complex relationship with the Weldon and Gautreau formations (St. Peter and Johnston, 2009). The upper boundary is unconformably overlain by the Weldon Formation (M. Stimpston, New Brunswick Department of Natural Resources, personal communication, 2016). The lower boundary of the formation is in different places an angular unconformity, disconformity, or nonconformity (St. Peter and Johnson, 2009). The angular unconformity and disconformity are found at the contact between the Round Hill formation and the Albert Formation. The nonconformity is found between the Round Hill formation and the basement rock. The formation lies unconfromably below the Weldon Formation.

The Round Hill formation is intersected in well 290 (Shenstone 151), 342 (Belliveau 1), and 706 (Columbia Beaumont L-24). The base of the formation is not traced on line 57YA, but the contact between the overlying Hillsborough Fm. and the top of the Round Hill is traced by reflector Wh (Fig. 3.11). An angular unconformity or disconformity is seen where internal Round Hill Formation reflectors are truncated against the Hillsborough Formation (Fig. 3.11). This separates the relatively brighter reflectors of the Hillsborough Formation from the relatively dimmer reflectors interpreted to be the Round Hill Formation.

3.3.4.3 Gautreau Formation

The Gautreau formation is a Tournaisian evaporite and clastic succession (St. Peter and Johnston, 2009). There are no surface exposures of the Gautreau Formation, so the type section has been defined in well 251 (St. Peter and Johnston, 2009).
The upper part, as defined by Hamilton (1961), is an 89 m interval of grey shale and mudrock. In this interval, 2 m are massive glauberite (St. Peter and Johnston, 2009).
The Upper Gautreau is included in the Sussex Group by St. Peter (1992) consistent with

the Gautreau formation of Norman and Greiner (1932; 1962), although recent work by Stimson (New Brunswick Department of Natural Resources, personal communication, 2016) using spore dates, places the Gautreau in the Horton Group, consistent with other studies in the area (Gussow, 1953; McLeod, 1980; St. Peter 1992, 1993). Our interpretation of the seismic data (below) supports this recent reinterpretation.

The lower part of the Gautreau Formation is a 479 m section of rock salt, shale intervals, and minor sandstone (Hamilton, 1961). Contained within the salt are two sections of abundant glauberite, each less than 3 m thick (Hamilton, 1961; St. Peter and Johnson, 2009). The base of the Gautreau Formation is intersected in well 251 (St. Peter and Johnson, 2009). Reflector Sg, a peak at the base of series of three bright trough-peak pairs, is correlated with the base of the Gautreau Formation, best traced on Line Hills 06-09 (Fig. 3.6). Sg is difficult to trace with certainty away from this line, because the boundary is cut by many faults that were reactivated multiple times (Park et al, 2010). A disconformity, identified by a palynostratigraphic break, separates the Gautreau Formation anhydrite- and glauberite-bearing shales from Albert Formation shales (Henderson, 1940; St.Peter and Johnson, 2009; Stimson, New Brunswick Department of Natural Resources, personal communication, 2016).

The upper boundary of the Formation is best seen on Line Hills 06-08. The package above reflection Sg thins under the northern edge of the Weldon Syncline, is cut out entirely, then reappears and thickens on the southern side of the syncline, toward the Caledonia Highlands (Fig. 3.6). We interpret this to be an erosional surface that cuts out the Gautreau Formation, creating an angular unconformity at the base of the overlying Sussex Group, clearly supporting the reinterpretation of the Gautreau Formation as part of the Horton Group.

3.3.4.4 Albert Formation

The Albert formation is exposed in the southern part of the eastern Moncton subbasin (Fig. 3.4), near Albert Mines. The formation is subdivided into three members

(Greiner, 1962). From bottom to top, these are the Dawson Settlement, Frederick Brook, and Hiram Brook members.

Hiram Brook Member

The Hiram Brook Member of the Albert Formation consists of sandstone, mudstone, and kerogenous shale and has surface exposures and outcrops along creeks, brooks, and the Petitcodiac River (St. Peter and Johnson, 2009). The thickness of the Hiram Brook Member is between 560 m and 800 m (St. Peter and Johnson, 2009). The lower boundary of the Hiram Brook Member is interpreted as transitional with the Frederick Brook Member, described below (Park et al, 2007).

Reflection Ha_h is a trough correlated with the base of the Hiram Brook Member. Ha_h is an internal reflector aiding in the interpretation of the complex and thick Albert Formation. Line 06-08 shows the Hiram Brook Member at depth in the Weldon Syncline (Fig. ZO), Line 06-05 shows Ha_h at the southern edge of the Stoney Creek Field, and 06-01 shows the Member truncated against the Caledonia Uplift (Fig. 3.7).

Frederick Brook Member

In the middle of the Albert Formation lies the Frederick Brook Member. This Member contains the high-kerogen Albert Mines zone and comprises oil shales and kerogenous mudstone (Macauley et al, 1980; Park et al, 2007). Soft-sediment structures, fish, and fish scales are common in the Member (Fig. 3.9). Outcrops occur at the surface near Mapleton and at the type section along Frederick Brook (Greiner, 1962; Park et al, 2007). The Frederick Brook Member has an estimated thickness ranging from approximately 70 m (Well 317, near Dawson Settlement; St. Peter and Johnson, 2009) to 300 m (Park et al, 2007). The boundary between this Member and the underlying Dawson Settlement Member is interpreted to be gradational (Greiner, 1962).

Reflection Ha_f is a peak that represents a horizon near the base of the Frederick Brook Member. Correlation from two wells on the adjacent 06-09 seismic line aids in the interpretation on 06-08. On line 06-08, Ha_f separates less coherent reflections from more coherent reflections interpreted to be the Dawson Creek Member below. Ha_f is traced farther south on line 06-06 (Fig. 3.5) and shows the same characteristics as in the north.

Dawson Settlement Member

The Dawson Settlement Member of the Albert Formation is exposed at the surface near Rosevale (Fig. 3.2). It consists of grey sandstone, siltstone, and shale; it has an estimated thickness of 300-400 m (St. Peter and Johnson, 2009). The true thickness is unknown because the member is difficult to distinguish from the Hiram Brook member where the Frederick Brook member is absent. The upper boundary is interpreted to be gradational with the Frederick Brook Member (St. Peter and Johnson, 2009). The lower boundary is interpreted as conformable and gradational with the McQuade Brook Formation (Gussow, 1953; Greiner 1962; St. Peter and Johnson, 2009).

Numerous wells intersect the Dawson Settlement Member in the Albert Mines and surrounding area. Reflection Ha_d is a trough-peak pair, associated with a horizon near the base of the Dawson Settlement Member. This is based on correlation between limited mapped outcrop and wells 331 and 333 on seismic lines 06-09, 06-04, and 06-08. It is best seen on line 06-09, where the reflector shows as a bright pair between two packages of coherent, but less well defined reflectors (Fig. 3.6). The interval below is interpreted to represent the McQuade Brook and Memramcook Formations.

3.3.4.5 McQuade Brook Formation

The McQuade Brook Formation of the Horton Group outcrops along streams on the western side of the Memramcook River and is exposed in the Indian Mountain Deformed Zone (St. Peter, 2006). In the eastern Moncton Subbasin, the McQuade Brook Formation outcrops as maroon mudstone, shale and siltstone, with some sandstone (St. Peter and Johnson, 2009). Thickness of the Formation ranges from 440 m to approximately 870 m; this assumes that the Formation is not repeated by faults in well 709, where ~870 m thickness was recorded (St. Peter and Johnson, 2009). The lower boundary is assumed gradational with the Memramcook Formation (Gussow, 1953). The upper boundary is gradational and assumed diachronous with the overlying Albert Formation; this boundary is intersected in wells 331 and 332 (St. Peter, 1992).

Reflection Hq is a peak correlated with the base of the McQuade Brook Formation. This is interpreted from the outcrop found along the Memramcook River and intersections in wells 331 and 332, which lie on seismic lines 06-09 and in the 3D seismic volume.

3.3.4.6 Memramcook Formation

Purple-red conglomerate and sandstone makes up the Memramcook Formation (Wilson, 2002; St. Peter and Johnston, 2009). This is the basal formation of the Horton Group. Its true thickness is difficult to determine, as the base of the Formation is not intersected in wells; the boundary with the McQuade Brook Formation is uncertain, and it doesn't appear as a continuous section in outcrop. The lower boundary of the Memramcook Formation is interpreted as an unconformity, based on the early Cambrian to late Devonian time gap (Barr and White, 1996; St. Peter and Johnson, 2009).

Reflection Hm, a bright trough-peak reflector pair around 1200 ms TWT on line 06-08 (Fig. 3.10), is interpreted to be the nonconformity between the Memramcook Fm. and the underlying igneous and metamorphic rocks.

3.3.5. Basement

Under the Carboniferous and Late Devonian strata lie the Proterozoic to mid-Devonian basement rocks. These rocks are exposed at the surface in the Caledonia Uplift (Fig. 3.2). Near the eastern Moncton subbasin, the ca. 620 Ma Broad River Group forms most of the Caledonia Highlands (Barr and White, 1996). The Broad River Group is a unit in the Appalachian domain Avalonia and contains volcanic and sedimentary rocks that have been deformed and cut by faults (Barr and White, 1996).

3.4. Structures and Tectonics

Previous work in the eastern Moncton Subbasin has interpreted most faults as steep structures. Our interpretation of seismic lines (e.g. Fig. 3.6) shows that low angle faults are common. Here, we describe the faults from northwest to southeast and show that both high-angle and low-angle faults are important to the development of the subbasin. In this data set, faults were picked on individual seismic profiles, then traced across the seismic data to create a 3D model. Multiple episodes of deformation in the Subbasin create a complicated picture, with nearly all faults cut by, truncated by, or intersecting with other faults.

3.4.1. Stoney Creek Fault

In seismic line 06-09, a steeply north-dipping subsurface boundary below base of the Sussex Group divides and offsets all Horton Group reflectors (Fig. 3.6). This boundary is identified as the Stoney Creek Fault. In map view (Fig. 3.4), the Stoney Creek Fault runs along the southern edge of the Stoney Creek Oil and Gas Field. Traced downdip (Fig. 3.11), the boundary is lost in reflectors interpreted to be igneous and metamorphic basement rocks. Traced updip, the boundary is truncated by the base Gautreau reflector, Sg. A similar relationship in seen on adjacent line 06-08. The Stoney Creek Fault runs just along the southern edge of the 3D volume, where the reflectors are not clear. Truncation by Sussex Group reflectors on 06-09 and 06-08 shows that movement on the fault ended in the late Tournaisian. (Fig. 3.6, 3.10).

06-09 shows most clearly the deformation along the north and south sides of the Stoney Creek Fault. Folds visible on the profile suggest that the fault was most active after the deposition of the Dawson Settlement and Frederick Brook Members, as these show the greatest offset (Fig. 3.10).

The Stoney Creek Fault is cut by the same disconformity that cuts the Gautreau Formation. When flattened along horizon Sw, the sense of offset on the Stoney Creek Fault is normal (Fig. 3.6). When flattened along horizon Ha_h, the sense of offset is normal, but significantly less, indicating that a large part of this normal offset was accumulated during deposition of the Hiram Brook Member. When flattened on a horizon just above Ha_f, the sense of offset is reverse, but when flattened along horizon Hq, the sense of offset again appears normal. If the Stoney Creek Fault were a dip-slip fault, this undulating behavior would require repeated inversion events. However, changes in the sense of dip slip are common on strike-slip faults, which is our preferred explanation of the complex history of the Stoney Creek Fault. Without cut-off points, it is impossible to tell how much lateral movement was accommodated along the fault, but based on estimates of other authors (Hibbard and Waldron, 2009; Waldron et al, 2015), there could be tens to hundreds of kilometers of dextral movement on faults of similar orientation in southern New Brunswick.

3.4.2. Salem Fault

The Salem Fault has been identified as a NE-SW fault that divides the Weldon Syncline from the Shenstone Syncline (described below). Previous workers traced the fault northward from the Albert Mines area across the Petitcodiac Estuary to Pré d'en-Haut (Fig. 3.4). It has previously been interpreted as a northeast-trending splay of the Saint Joseph Fault (St. Peter and Johnson, 2009).

In seismic line 06-08, a south-dipping boundary between 0 and 750 ms TWT separates a poorly coherent package of weak reflectors interpreted to be the Weldon Formation from a more resolved package interpreted to be Sussex and Horton Group, with the possibility of some basement. Traced updip to the north, the boundary can be identified where it comes to the surface along the mapped Salem Fault. Traced downdip to the south, the boundary intersects the Boudreau Fault at approximately 750 ms TWT, where it is cut by the Boudreau Fault (Fig. 3.10); a smiliar relationship is seen on N-S seismic lines 06-07 and 06-09.

On seismic line 06-06, the Salem Fault can be traced downdip to an intersection with the Boudreau Fault, at approximately 800 ms TWT (Fig. 3.5). On this line, it appears that the Salem Fault is not truncated by the Boudreau Fault, but instead continues at depth into a package of reflectors interpreted as basement. West of line 06-06, the Salem Fault is separated into two faults. On seismic line 06-09, the heave on the Lower Dorchester Fault between the high and low segments of the Salem Fault is nearly 3 km. The low Salem and Lower Dorchester Faults define a northward wedge, best seen on line 06-09 (Fig.3.6).

3.4.3. Saint Joseph Fault

The Saint Joseph Fault has been previously interpreted as a major SE-trending splay of the Caledonia Fault, dipping approximately 60° NW (Wright, 1922; St. Peter and Johnson, 2009). On seismic line 06-07 (Fig. 3.8), a north-dipping boundary brings Gautreau Formation evaporites and shales close to the surface on the NW side of this boundary. Well 326 (Fig. 3.4) sits close to the line and intersects a fault at 518 m vertical depth (St. Peter and Johnson, 2009). The north-dipping boundary visible on the seismic profile intersects the Salem Fault (described above). This fault has a complicated history, with both normal and reverse movement, before deposition of Mabou Group. We interpret this boundary to be the Saint Joseph Fault.

3.4.4. Boudreau Fault

There is a north-dipping boundary visible on lines 06-07 and 06-08. Updip, this boundary is lost in Windsor Group reflectors, truncated by Mabou Group, and is overall difficult to trace to the surface. In map view, a corresponding boundary appears along strike to the east, where it is possible to trace the boundary in an inlier to the Sussex and Horton Groups. Downdip, the boundary intersects the Lower Dorchester Fault on seismic line 06-08 at approximately 300 ms TWT. We interpret this boundary to be the Boudreau Fault, which accommodated some of the movement from the Lower Dorchester Fault (Wilson, 2005).

3.4.5. Edgetts Landing Fault

In seismic line 06-07, a north-dipping boundary traced from the surface intersects the Lower Dorchester Fault at 500 ms TWT. Our interpretation is that this boundary is the Edgetts Landing Fault (Park and St. Peter, 2005). Similarly to the Boudreau Fault, this fault accommodated movement from the Lower Dorchester Fault.

3.4.6. Lower Dorchester Fault

A second major NE-SW fault through Edgetts Landing has been previously described as the Dorchester Fault (Norman, 1941; Gussow, 1953; McLeod, 1980). In Chapter 2, we describe this NW-dipping boundary as the Lower Dorchester Fault, to distinguish it from a gently SE-dipping structure exposed farther NE, which we distinguish as the Upper Dorchester Fault (Ch. 2). We interpret that the NW-dipping boundary is the westernmost expression of the Lower Dorchester Fault. The Lower Dorchester Fault is visible on lines 06-06, 06-07, and 06-08, where it places Sussex and Horton Groups to the NW against Windsor and Sussex Groups to the SE. In seismic line 06-07, the north-dipping boundary separates a half-graben and syncline to the north from an anticline to the south. Traced updip to the south, the boundary intersects the north-dipping Boudreau and Edgetts Landing Faults (described below), before reaching the surface just south of Hillsborough (Fig. 3.4). Downdip, the boundary meets another surface at 1100 ms TWT, interpreted as the south-dipping low segment of the Salem Fault.

The Lower Dorchester and the low Salem Faults define a northward-narrowing wedge, inserted into the Horton Group (Fig. 3.8). The geometry of this northward-narrowing wedge is similar to that found in the adjacent Sackville Subbasin between the Lower Dorchester Fault and the Harvey-Hopewell Fault. The tip-point of the wedge can be traced as a linear feature in the subsurface; this is visible on lines 06-06, 06-08, and 06-09. The tipline shallows as it is traced east in the subbasin; from an estimated 1400 ms TWT on line 06-09 (the westernmost line) to an estimated 750 ms TWT on 06-06 (the easternmost line).

3.4.7. Subsurface Faults: Dawson Settlement and Livingstones Fault

On seismic line 06-09, there is a north-dipping boundary visible in the McQuade Brook and Memramcook Formations (Fig. 3.6). This boundary is lost in the basement reflectors at about 1750 ms TWT. Traced updip, the boundary can be followed to 1200 ms TWT; it nowhere reaches the topographic surface. We interpret the boundary to be a normal fault, here termed the Dawson Settlement Fault, that was active during the early deposition of the McQuade Brook Formation. Around 1200 ms TWT, internal reflectors of the McQuade Brook Formation are unbroken; fault movement must have ceased at this point. The fault is too far north to be seen on any other 2D lines in the data set.

A second subsurface fault is inferred at the southern extremity of the Horton Group, which is clearly resolved on Hills 06-01, but which is absent from the southern extremity of Hills 06-08, 06-07, and 06-06, and also from the southern region of the Caledonia Highlands, where Windsor Group overlies basement. The precise location of this boundary is poorly resolved, but we speculate that an E-W fault passes beneath Livingstones Hill in the subsurface (Fig. 3.4).

3.4.8. Weldon Syncline

The Weldon Syncline plunges west, roughly parallel to the Saint Joseph Fault trace (Fig. 3.4), and contains Horton, Sussex, and Windsor Group strata. The Salem Fault truncates the syncline on its southern edge near the surface; the Lower Dorchester Fault defines the southern boundary of the syncline at depth (Fig. 3.10). The Stoney Creek Fault occurs beneath the syncline; when the syncline is flattened (fig. 3.10), the Stoney Creek Fault is near vertical. The northern edge of the syncline shows an angular unconformity between the stratigraphic groups in the syncline and the Mabou Group; the Mabou Group is clearly not folded by the syncline.

3.4.9. Shenstone Syncline

A second syncline, just south from the Weldon Syncline, sits between the Salem and St. Joseph faults. This syncline plunges northeast, parallel to the Saint-Joseph Fault. It contains Horton and Sussex Group strata; there may be some Windsor Group hidden in the center of the syncline beneath Mabou Group cover. The Mabou Group is not deformed.

3.5. Discussion

3.5.1. Timing and geometry of faults

Previous authors have had differed over the relative roles of extension, shortening, and strike-slip in the eastern Moncton Subbasin. The seismic data interpreted here allow some of these controversies to be resolved.

Evidence from Horton Group stratigraphy shows that deformation of the eastern Moncton Subbasin was primarily controlled by pre-existing basement faults that controlled sedimentation during the Tournaisian. For example, thickness changes in the Horton Group together with localized unconformable relationships show that the Stoney Creek Fault was active and controlled sedimentation during the Tournaisian. Horton Group extends in the subsurface to the south of the Stoney Creek area at least as far as the NE extremity of the Caledonia Highlands, where it is exposed immediately north of the Lower Dorchester Fault at the surface in the area of Albert Mines (Fig. 3.4). Horton Group also occurs north of the Dorchester Fault system, to the NE of the Petitcodiac Estuary (Ch. 2). South of the Dorchester Fault system, the distribution of the Horton Group is limited to the subsurface in a belt about 2 km wide where it is imaged on Line 06-01. The southern limit of the Horton Group is poorly resolved in the seismic data, but we suggest that it is bounded by the interpreted Livingstones Fault, connecting with the Lower Dorchester Fault to the west.

The majority of the faults identified southwest of the Petitcodiac dip moderately north; the Boudreau and Edgetts Landing faults traced downdip connect with the gently north-dipping Lower Dorchester fault. The Saint Joseph fault also dips gently northwest; both it and the Lower Dorchester fault connect with the steeply north-dipping Stoney Creek Fault at depth, in a geometry that resembles a flower structure (Fig. 3.11). Park et al. (2010), working at outcrop scale, identified numerous faults in the Peck Creek area that also dip to the NW and show predominantly reverse offsets. Park et al. (2010) suggest that these faults were active before deposition of the Windsor Group and possibly before the Sussex Group was fully dewatered.

Stratigraphic relationships can be used to determine the timing of movement on the strands of the fault system seen in the seismic data. The Stoney Creek Fault was active throughout the deposition of the Horton Group, but it appears to be truncated at the base of the Sussex Group. In contrast, the Saint Joseph and Boudreau Faults cut the Sussex and Windsor Groups, but are truncated at the base of the Mabou Group. The Lower Dorchester Fault offsets Windsor and Mabou Groups; relationships on this fault east of the Petitcodiac River (see Ch. 2) show major offset of the Windsor Group, but minor offset of the overlying Mabou Group. This suggest that the majority of movement on the Lower Dorchester Fault was late Visean or early Serpukhovian. Fault movement in the flower structure therefore clearly propagated from northwest to southeast and earlier faults in the system were carried passively above the Lower Dorchester Fault. Relationships described in Chapter 2 show that all these faults must have been contained within a tectonic wedge, bounded by the Upper and Lower Dorchester Faults, the roof of which has been removed by erosion SW of the Petitcodiac Estuary.

The only major south-dipping fault is the Salem Fault, which shows a complicated geometric and kinematic relationship with the Lower Dorchester Fault. In the hanging wall of the Lower Dorchester Fault, the Salem Fault is shown on geological maps as a north-dipping structure (St. Peter and Johnson, 2009-2) with normal offset. However, seismic data show that the fault clearly dips moderately south, with reverse offset, cutting Windsor Group, but unconformably overlain by Mabou Group. The fault is clearly cut by the Lower Dorchester Fault, and we identify a south-dipping feature in the footwall of the Lower Dorchester Fault that is a probable continuation of the Salem Fault. The offset of the Salem Fault by the Lower Dorchester Fault appears to increase to the southwest as far as Line 06-09, where the Lower Dorchester Fault and the Salem Fault in its footwall appear to bound a tectonic wedge inserted northward into the Horton Group (Fig. 3.6). The overlying Weldon Syncline, which affects Horton, Sussex, and Windsor Groups, was probably formed as a consequence of the insertion of this wedge (Fig. 3.6). These relationships indicate that although the Salem Fault must have moved before the Lower Dorchester Fault, it must have been reactivated southwest of Hills 06-07 during movement of the Lower Dorchester Fault to form the tectonic wedge. Both the Salem and Lower Dorchester faults are constrained to have undergone major displacement after the deposition of the Windsor Group, but before deposition of the Hopewell Cape Formation.

Faults in the Peck Creek and Albert Mines area dip to the NW and show reverse offsets; these are connected to the regional Caledonia Fault farther south by Park et al. (2010). The Caledonia Fault shows normal, reverse, and strike-slip motion (Park et al, 2010, Waldron et al 2015), which is similar to the Stoney Creek Fault. Park et al. (2010) suggest that the smaller faults seen in Peck Creek were active before deposition of the Windsor Group, but that the Caledonia Fault was reactivated later, displacing Hillsborough Formation. Movement on the Caledonia Fault ceases after Windsor Group deposition (Park et al, 2010). We suggest that the Caledonia Fault forms several splays as it enters the study area, contributing to the complex geometry of the flower structure. The Stoney Creek Fault is too far north to connect with the Caledonia Fault, but it is possible that it is a splay of the Prosser Mountain Fault (Fig. 3.2). Between them, these

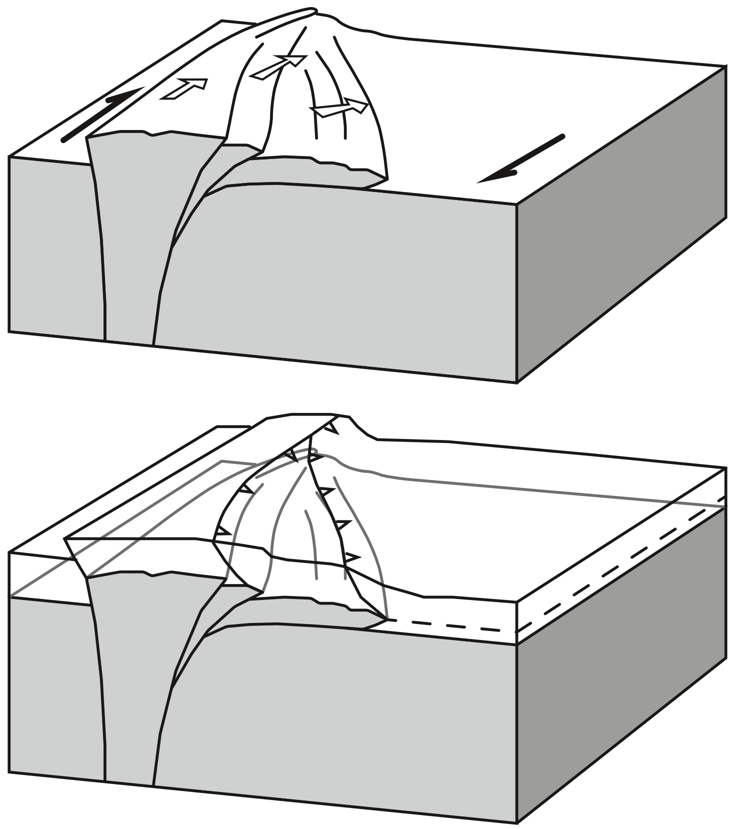

Figure 3.12. Cartoons depicting possible explanations of relationships seen in the Sackville and eastern Moncton Subbasins.
Top: Lower Dorchester and Fort Folly Point faults inverted in a transpressional setting. Bottom: Tectonic wedges as part of a flower structure. Modified from Waldron et al., 2010.

faults and their splays controlled deposition in the early Carboniferous.

3.5.2. Tectonic Wedges and Flower Structure

In the Sackville Subbasin, it is unclear what happens to the roots of the tectonic wedges (Ch. 2). In the eastern Moncton Subbasin, seismic line Gaut09-01 shows that the Lower Dorchester Fault meets the Stoney Creek Fault at 1000 ms TWT (Fig. 3.11). Here, we see that a thick Horton Group succession is preserved in the hanging wall of the Lower Dorchester Fault, along which major reverse offset occurred. The intersection shown on Gaut09-01 resembles a positive flower structure (Fig. 3.12). This positive flower structure contains low angle faults. However, low angle faults are unusual in a flower structure. We suggest two explanations for this. First, Waldron et al. (2010, 2015), showed that southeastern New Brunswick has evidence of both dextral strike slip deformation and transtensional normal faults, active early in basin history; the basin resembled the modern-day basin-and-range of the western United States (Dickinson, 2006). In this environment, normal listric faults accommodate extension. Strike-slip faulting in the Tournaisian, combined with a transition to a compressional environment, reactivated these faults as reverse structures to accomodate shortening. These inverted listric faults formed the initial flower structure, and its associated wedges, which were therefore dominated by low-angle faults.

Second, tectonic wedges were initially inserted southward into Windsor Group evaporites, placing evaporites both above and below the wedge (Fig. 3.13). Each wedge was dominated by higher density Horton Group and basement; it is interpreted that these wedges collapsed into the lower density Windsor Group, undergoing rotation in the process. This changed the geometry of the flower structure from the expected steep reverse faults to low-angle faults that are seen in the seismic data. We suggest that the structure may be termed a “wilted” flower structure.

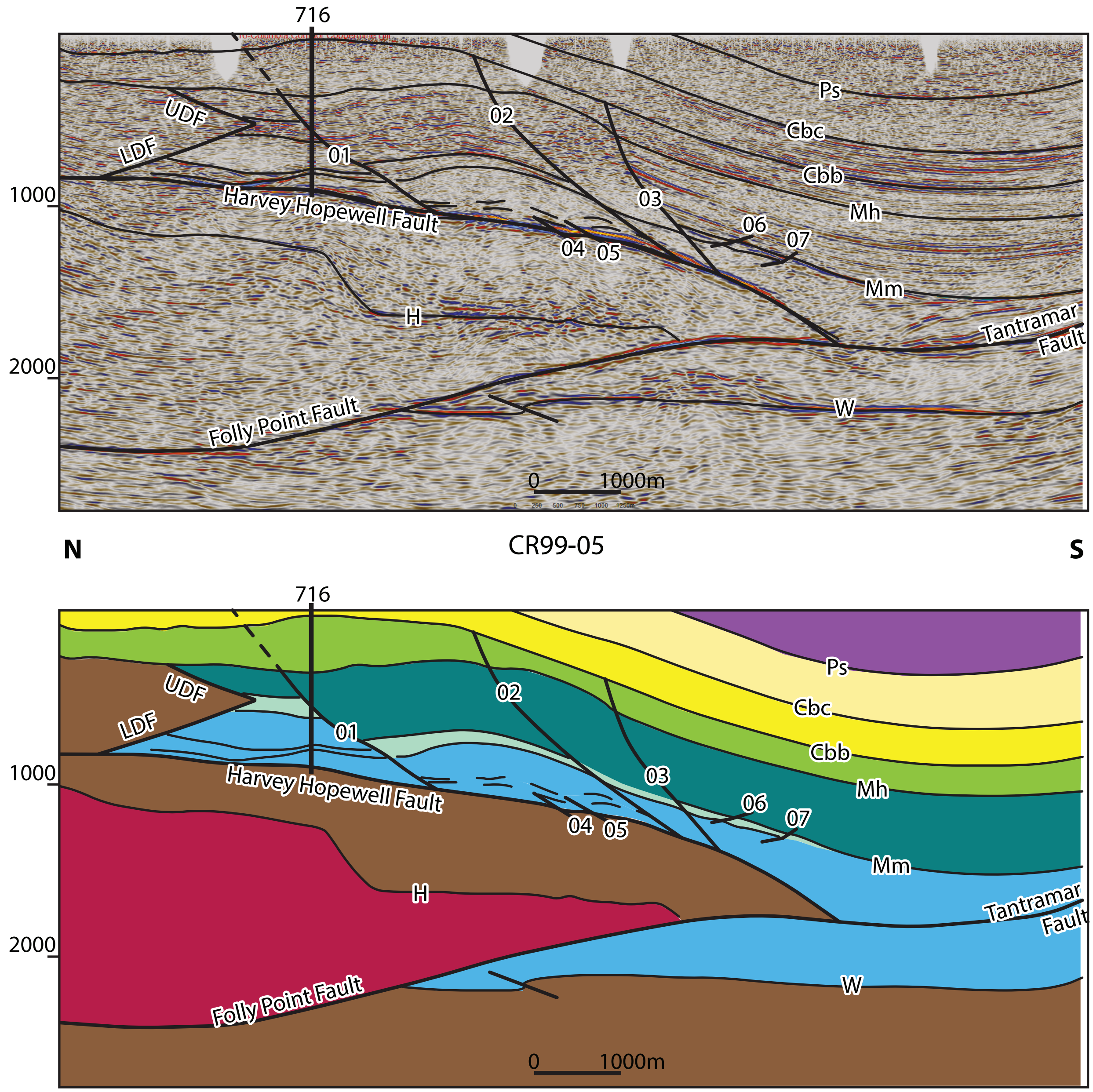

Figure 3.13. Seismic line CR99-05 of the adjacent Sackville Subbasin, showing interpreted horizons and faults.
Profile shows complex Windsor Group deformation in association with the tectonic wedge defined by the Harvey-Hopewell and Folly Point Faults. Vertical scale milliseconds two-way-travel. For further information, see Ch. 2

3.6. Conclusions

Stratigraphic relationships determine the timing of movement on the fault systems that span the eastern Moncton Subbasin. Horton Group stratigraphy shows pre-existing basement faults with normal, reverse, and strike-slip movement that controlled deformation and sedimentation during the Tournaisian, which led to basin inversion and the creation of a positive flower structure. The tectonic wedges forming this structure contain, and are bounded by, low-angle faults, which is unusual in such a structure. We explain these low-angle faults through a series of steps. First, listric normal faults were developed in a basin-and-range setting. This area was subjected to shortening, which reactivated the faults into reverse thrusts and created a positive flower structure in which low-angle normal faults were reactivated. Finally, the tectonic wedges that formed the petals of the flower structure collapsed into Windsor Group evaporites, rotating the wedges and producing the "wilted" flower structure geometry seen on modern seismic profiles.

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Chapter 4. Conclusions

The Sackville and eastern Moncton subbasins record a complex kinematic and geometric history of Devonian to Carboniferous deformation. Stratigraphic relationships are used to determine the timing of movement on the fault systems that span the two subbasins. Horton and Sussex Group stratigraphy shows basement faults with normal, reverse, and strike-slip movement that controlled deformation and sedimentation during the late Devonian and early Tournaisian. During this time, the region was analogous to a basin-and-range environment. Normal listric faults formed graben and half-graben in an extensional setting. The region was subjected to shortening and strike-slip, which reactivated the listric faults and created a positive flower structure spanning the subbasins. A thick evaporite succession was deposited in the Windsor Group in the Visean, followed by the Mabou during the late Visean and early Serpukhovian. The stratigraphic record shows that major movement of faults defining the flower structure occurred prior to the deposition of the Hopewell Cape Formation of the Mabou Group. In the Serpukhovian and Bashkirian, salt expulsion controlled local stratigraphy, causing rapid subsidence of the Mabou and Cumberland Groups. Tectonic wedges of the flower structure collapsed into less-dense Windsor Group evaporites, rotating the wedges and producing the “wilted” flower structure geometry with low-angle faults.

Future work in the subbasins might look at the Port Elgin Fault (of Martel, 1987), located in the far east of the Sackville Subbasin and its role as a basin-bounding fault. In the eastern Moncton Subbasin, questions remain about the connection between the McCully and Stoney Creek oil and gas fields. Are they correlated? Is it possible to connect them through the maze of strike slip and reverse faults that cross the Moncton Subbasin? Last, it would be interesting to delve into how flower structures and tectonic wedges interact with evaporite successions in strike-slip basins in other areas. Perhaps tectonic wedges and flower structures are normal where transpression affects weaker sedimentary rock and evaporites.

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