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Seismic-reflection interpretation of the Carboniferous Cumberland Basin, northern Nova Scotia

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ABSTRACT

An interpretation of approximately 1700 km of seismic data was completed in 1996. The seismic analysis, together with well information and geological map data, were used to map thirteen seismic horizons in the Cumberland Basin. Ten of the horizons were mapped only in limited areas, whereas three horizons could be mapped regionally. These are: BW (base of the Windsor Group), BP (base of the Boss Point Formation), and PG (base of the Pictou Group).

The BW horizon is the deepest regional horizon mapped. The horizon generally dips southerly toward the Cobequid Highlands. It is affected by faults adjacent to the Scotsburn Anticline and the Hastings Uplift; the horizon was not recognized over part of the uplift. On the seismic reflection data, the horizon varies between 500 ms and 3200 ms two-way travel time (approximately 800-7600 metres) and rocks corresponding to this horizon do not outcrop in the basin.

The BP and PG horizons can be traced to outcrop on the flanks of the major anticlines. Time structure maps of these horizons mimic the distribution of synclines mapped from outcrop geology. The BP horizon is affected by more faults and is more tightly folded than the PG horizon south of a major fault (Beckwith Fault). North of the Beckwith Fault, both horizons are essentially flat and not deformed.

Several geological relationships were documented during this study. A thick (up to 1600 m) clastic unit was recognized in the central portion of the southern margin of the Cumberland Basin. It is interpreted as Windsor Group equivalent. Seismic reflections from within the Falls and Millsville conglomerates were recognized and suggest that these rocks correlate with the Windsor Group. Seismic profiles that cross the southern margin of the Cumberland Basin image parts of the basement complex to the south of the basin (Cobequid Highlands) and show reflection patterns consistent with mountain fronts. The seismic data image the folded and faulted Cobequid Highlands basement complex, which is interpreted as a thrusted structural wedge.

ACKNOWLEDGEMENTS

This report summarizes the results of work completed under a contract to the Geological Survey of Canada from June 1, 1995 to March 29, 1996. The work was funded in part through the Canada-Nova Scotia Cooperation Agreement on Mineral Development (1992-1995), a subsidiary agreement under the Canada-Nova Scotia Economic and Regional Development Agreement.

The images of seismic reflection data presented in this report are subject to Seismic Licence Agreement with Repsol Canada. I acknowledge the efforts of Paul J. Harvey (retired, Nova Scotia Department of Energy) who encouraged publication of this report. Thanks are due to John Waldron (University of Alberta) for his in-depth review of this report and constructive comments that have greatly improved the final report. Thank you to Natalie Shea, Gary Sonnichsen and Ted Little for their support to publish this overdue report.

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INTRODUCTION

The Cumberland Basin underlies a triangular shaped, lowland area of northern Nova Scotia that is bounded to the northwest by Chignecto Bay, to the northeast by the Northumberland Strait and to the south by the Cobequid Highlands (Fig. 1). Using this geographic definition, the basin occupies an area of roughly 4700 km^2. However, regional studies (Howie and Barss, 1975) have shown that the strata within the Cumberland Basin extend offshore in southwesterly and northeasterly directions beneath the Chignecto Bay and Northumberland Strait, respectively. The basin is a southwesterly extension of the expansive Magdalen Basin, located beneath the Gulf of St. Lawrence (Howie and Barss, 1975).

Ryan and Boehner (1994) present results of bedrock mapping completed in the Cumberland Basin. Seismic reflection data acquired in the 1970's and 1980's in the basin presents an opportunity to map the subsurface distribution of the rocks mapped in outcrop. The results presented in this report describe seismic reflection data interpretation that was completed in 1996. Subsequent to this work, additional seismic data were acquired during 2001 and 2002 (Waldron et al., 2013) in the southern parts of the Cumberland Basin. Neither the newer data, nor the interpretation of the 2001 and 2002 data, were included in this report. As such, the present report describes the state of knowledge as of 1996. Analysis of the 2001-2002 seismic data is described by Waldron and Rygel (2005) and Waldron et al. (2013). These authors present evidence to suggest that the Cumberland Basin fill was largely accommodated by salt expulsion and mini-basin development. Where appropriate, comments and updated seismic interpretations were included in this report to reflect these results. The seismic interpretations and structural implications presented herein differ somewhat from these authors and may be subject to revision; however, this work forms a basis for future regional studies that would encompass the analysis of all seismic data in the basin.

The seismic data interpreted for this report comprise a combination of digital seismic data re-processed by the Geological Survey of Canada (Marillier and Durling, 1995) and paper copies of seismic lines acquired by Chevron Canada Resources Limited. These seismic data provide widespread regional subsurface coverage of the Cumberland Basin and the structure maps presented in this report provide basin scale subsurface information that is not available elsewhere.

Structure

The main structural features within the Cumberland Basin are three large synclines (Amherst, Athol, and Tatamagouche), and a highly deformed zone comprising faults, salt diapirs, and minor synclines (Fig. 1). The Athol and Tatamagouche synclines are located in the southern part of the

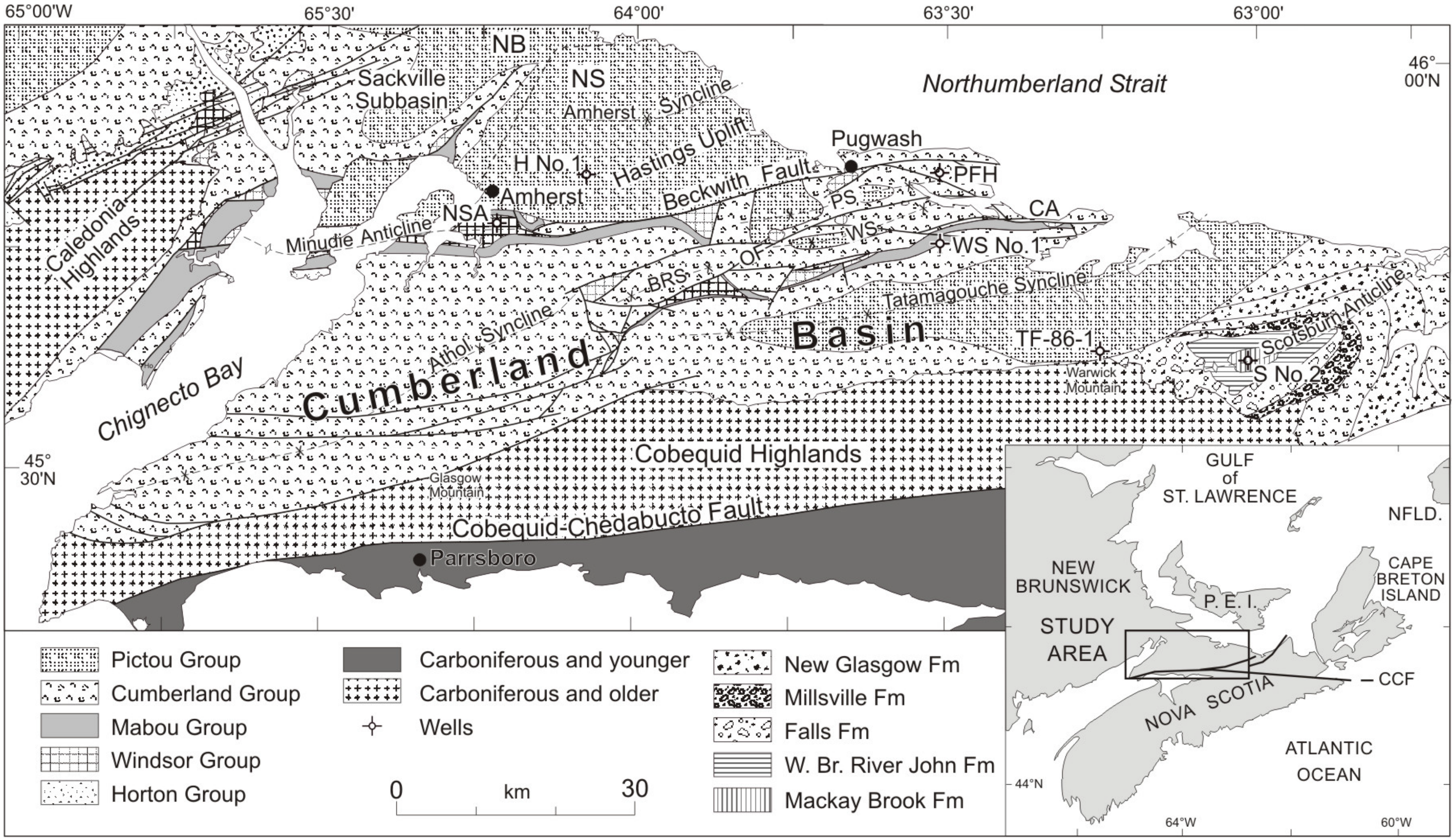


Figure 1: Simplified geological map of the Cumberland Basin (after Ryan and Boehner, 1994). Abbreviations: BRS – Black River Syncline; CA - Claremont Anticline; H No.1 - Hastings No.1; NSA - Nappan No.1A, Sunoco No.1, and Amherst No.1 wells; NB - New Brunswick; NS - Nova Scotia; OF – Oxford Fault; PFH - Pacific Fox Harbour well; PS – Pugwash Syncline; S No.2 - Scotsburn No.2 well; WS – Wallace Syncline; WS No.1 - Wallace Station No.1.

basin, immediately north of the Cobequid Highlands. The synclines are broad, rounded folds, but dips as high as 80° are recorded on their limbs. Some faults are also noted on the limbs of the synclines. The Athol Syncline is oriented northeast-southwest, whereas the axis of the Tatamagouche Syncline has an east-west trend in its western part and a northeasterly trend in the east, adjacent to the Scotsburn Anticline (Fig. 1). The Amherst Syncline is a broad gently folded structure in the northern part of the Cumberland Basin, with dips rarely exceeding 10°. Its southernmost limit is the Beckwith Fault. The Amherst Syncline is underlain by a basement block of unknown extent, referred to as the Hastings Uplift (Howie, 1986).

Two major salt cored anticlines occur within the Cumberland Basin, the Claremont and Minudie Anticlines (Fig. 1). In contrast to the synclines, the anticlines are narrow, tight to isoclinal structures with dips of ~80° on their limbs. The Minudie Anticline is an overthrust evaporite structure (Howie, 1986) at the western extension of the Beckwith Fault, between the Amherst and Athol Synclines. The Claremont Anticline occurs within a structurally complex zone between the Tatamagouche Syncline and the Beckwith Fault. Several isolated evaporite structures (Boehner, 1986) occur between the Beckwith Fault and the Claremont Anticline, and are often spatially associated with ENE trending faults (Fig. 1). Salt structures have not been reported in the Cumberland Basin north of the Beckwith Fault.

Stratigraphy

<u>Horton and Fountain Lake Groups</u>

Deposition in the Cumberland Basin began with the Fountain Lake and Horton Groups (Fig. 2). Exposures of these rocks are limited to the Cobequid Highlands and the Scotsburn Anticline (Pe-Piper and Piper, 2002). Keppie (2014) mapped a small area of Fountain Lake Group in the core of the Scotsburn Anticline (Fig. 1), which he assigned to the Mackay Brook formation (informal). In general, the Fountain Lake Group (Donohoe and Wallace, 1982) comprises mafic and felsic volcanic rocks, and red to grey sandstone, siltstone and conglomerate. Age dates for the volcanic rocks range between 354 and 358 Ma (Dunning et al., 2002). The Horton Group is of Late Devonian to Early Carboniferous in age, and comprises red to grey sandstone, siltstone and conglomerate (Piper, 1994). The oldest Horton Group conglomerates contain clasts of granite and diorite derived from the Cobequid Highlands. Younger Horton Group conglomerates contain increasing amounts of rhyolite clasts, suggesting erosion of the Fountain Lake Group (Pe-Piper and Piper, 2002).

Deposition of the Fountain Lake and Horton groups was in part contemporaneous with the intrusion of Late Devonian to Early Carboniferous diorite/gabbro and granite plutons (Pe-Piper and Piper, 2002). One of these plutons is in igneous contact with Horton Group conglomerate (Piper, 1994); both the Horton Group conglomerate and the pluton show evidence for north-directed thrusting (Pe-Piper and Piper, 2002). Surface exposures of several plutons show evidence for syn-magmatic and post-crystallization deformation of the plutons (Pe-Piper and Koukouvelas, 1994).

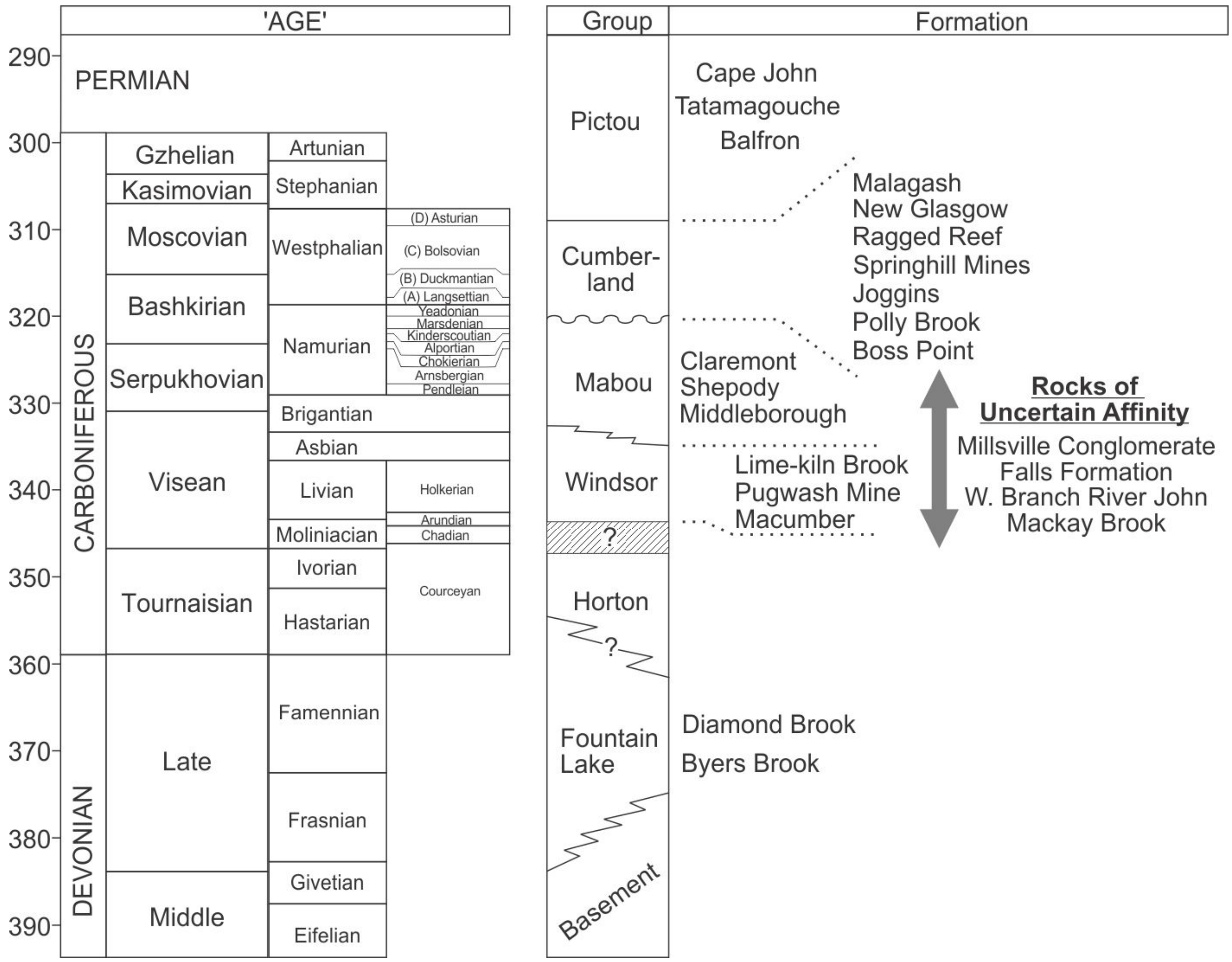


Figure 2: Stratigraphy for the Cumberland Basin, after Ryan and Boehner (1994), Pe-Piper and Piper (2002), Keppie (2014) and Chandler (1998). Time scale after Davydov et al. (2004) and British Geological Survey website (accessed November, 2018): (https://www.bgs.ac.uk/discoveringGeology/time/timechart/phanerozoic/carboniferous.html).

<u>Conglomerate Rocks of Uncertain Affinity</u>

A thick succession of clastic rocks overlies the Fountain Lake Group on the crest of the Scotsburn Anticline (Fig. 1). Keppie (2014) subdivided these rocks into four units. The basal unit comprises fine-grained, calcareous clastic rocks assigned to the Mackay Brook formation (informal), which Keppie (2014) interpreted to be capped by a single basalt flow of varying thickness. These rocks are overlain by mainly calcareous clastic rocks in the north (informally assigned to the West Branch River John formation; Keppie, 2014) that transition laterally to the west and south into a clast-supported conglomerate assigned to the Falls Formation (Donahoe and Wallace, 1982). The laterally equivalent West Branch River John and Falls formations are interpreted by Keppie (2014) as a medial clastic succession between the underlying Mackay Brook formation and the overlying Millsville Formation (Donahoe and Wallace, 1982), a clast-supported conglomerate.

Ryan and Boehner (1994) indicate a Visean age for the fine-grained rocks on the north limb of the Scotsburn anticline based on a sample location on the West Branch River John, approximately 2 km north of the village of the same name. These fine-grained rocks were included by Keppie (2014) in West Branch River John formation, whereas Ryan and Boehner (1994) assigned them to the Middleborough Formation (see Mabou Group below). Its lateral equivalent (Keppie, 2014), the Falls Formation, is a clast-supported, mainly basaltic clast conglomerate characterized by moderate sorting and rounding. The Falls Formation was interpreted as Horton Group equivalent by Yeo (1987). However, Ryan and Boehner (1994) considered all conglomeratic rocks in the Scotsburn Anticline to be correlative with the Claremont Formation.

The Millsville Conglomerate overlies the Falls Formation with reported unconformity (Yeo, 1987; Keppie, 2014), although bedding attitudes are very similar between the Falls and Millsville formations (Chandler et al., 1994). The Millsville Conglomerate is distinguished from the Falls Formation by the presence of angular, white quartzite and felsic plutonic clasts with poor sorting (Keppie, 2014). Otherwise the units are sufficiently similar that Ryan and Boehner (1994) considered the differing clast composition to be due to different source areas, and assigned the Millsville conglomerate to the Claremont Formation. The Millsville Conglomerate was assigned a Late Namurian to Early Westphalian age (Bashkirian) by Yeo (1987). The Falls and Millsville conglomerates will be treated separately from the Claremont Formation (Hamblin, 2001) in this report.

Windsor Group

Marine evaporite deposition began in nearly all Carboniferous basins of eastern Canada during the early to middle Visean (Giles, 1981). These rocks in the Cumberland Basin are assigned to the Windsor Group (Ryan and Boehner, 1994). Typically, the Windsor Group consists of up to 30 evaporite cycles. Each cycle records a new marine transgression, and usually consists of, in ascending order, limestone, anhydrite, salt, and siltstone (Giles, 1981). The Windsor Group is poorly exposed in the Cumberland Basin and the highest Windsor Group marine bands appear to be absent (Ryan and Boehner, 1994). The Windsor Group outcrops in the cores of major anticlines and in small isolated areas. Many Windsor Group outcrop areas are associated with low gravity anomalies (Howie, 1986), suggesting significant quantities of salt in the subsurface. Salt in the Cumberland Basin is probably highly deformed due to the highly mobile nature of salt, and flowage of the salt into diapiric structures (Boehner, 1986). All Windsor Group outcrop areas in the Cumberland Basin are probably the result of evaporite flowage (Boehner, 1986, p. 103; Waldron et al., 2013).

Mabou Group

The Windsor Group appears to be transitional with the overlying Mabou Group, which comprises mainly siltstone, shale and fine-grained sandstone (Ryan and Boehner, 1994). The Mabou Group outcrops on the flanks of diapir structures and in the core of the Scotsburn Anticline.

Ryan and Boehner (1994) included the Claremont Formation in the Cumberland Group, whereas Hamblin (2001) included the formation in the Mabou Group. The Claremont Formation consists of mainly red, boulder to pebble, polymictic conglomerate with minor sandstone interbeds (Ryan and Boehner, 1994). The conglomerate clasts are usually representative of rocks that outcrop in the nearby highlands.

Cumberland and Pictou Groups

The Boss Point Formation at the base of the Cumberland Group (Fig. 2) comprises grey, medium grained, trough cross-stratified sandstone, grey and red fine-grained sandstone and mudstone, and minor pebble conglomerate (Ryan and Boehner, 1994). The sandstone occurs as thick tabular bodies, which average 35 m in thickness at the base of the unit and only 5-10 m at the top. The interbedded mudstones are rare at the base, but become increasingly thicker and more abundant toward the top of the Boss Point Formation.

The Boss Point Formation is widely distributed throughout the Cumberland Basin (Ryan and Boehner, 1994). It occurs in all the major synclines, and on the southern margin of the Tatamagouche Syncline it oversteps older Carboniferous strata and onlaps basement rocks. The Boss Point Formation represents the beginning of a distal source for Cumberland Basin sediment (Gibling et al., 1992).

An influx of coarse clastic material into the Cumberland Basin is recorded by deposition of the Polly Brook Formation (Fig. 2), a conglomerate with clasts that range from pebble to boulder size. Clast lithologies comprise basement rocks derived from the Cobequid Highlands, as well as reworked quartz-rich sandstone clasts from the Boss Point Formation (Ryan and Boehner, 1994). The Polly Brook Formation is laterally transitional with, and overlain by, the Joggins and Springhill Mines Formations. The Joggins Formation comprises grey and red siltstone and shale with grey cross-stratified sandstone bodies averaging 6 m in thickness. The Springhill Mines Formation consists mainly of grey sandstone interbedded with grey mudstone. Both formations contain numerous thin coal seams, up to 4 m in thickness. The Springhill Mines and Joggins Formations are well developed in the Athol Syncline, but are believed to be very thin or absent in the Tatamagouche and Amherst Synclines.

A second pulse of coarse detritus (conglomerate, sandstone and mudstone) entered the Cumberland Basin with deposition of the Ragged Reef Formation (Ryan and Boehner, 1994). The Ragged Reef Formation is overlain by the Malagash Formation, the uppermost formation in the

Cumberland Group, which is in turn overlain by the Pictou Group. The Pictou Group comprises varying amounts of sandstone, siltstone and shale, deposited in a dominantly fluvial environment.

DATA

Well Data

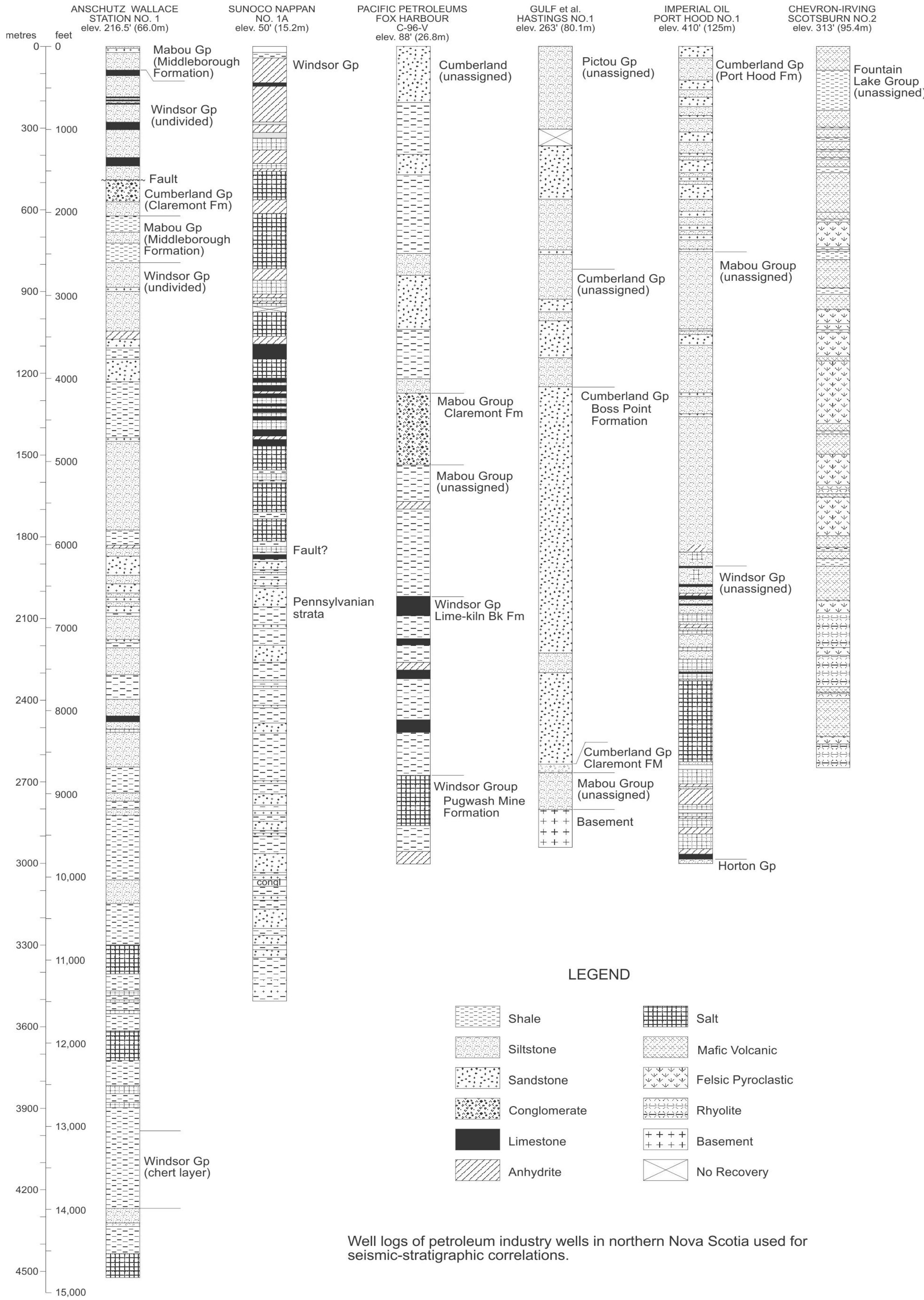
<u>Wallace Station No.1</u>

The well was drilled on the steeply dipping south limb of the Claremont Anticline (Fig. 1) north of the Tatamagouche Syncline. The following is a summary of the rocks encountered in the well taken from MacDonald (1973).

Surface exposures indicate the Middleborough Formation at the top of the well (Fig. 3), with attitudes ranging from 70º to 80º south. Rocks of the Windsor Group were noted at 90 m, as indicated by a high percentage of limestone, accompanied by anhydrite, in the cuttings. At 491 m, a quartz pebble conglomerate was encountered, which was interpreted as Claremont Formation. A southerly dipping thrust fault was postulated at this depth to account for Windsor Group overlying the Claremont Formation. The Middleborough Formation was again identified at 613 m, based upon a lithologic change from the course clastic rocks of the Claremont Formation to shale and siltstone. The Windsor Group was identified at 792 m on the basis of continuous anhydrite and anhydritic siltstone occurrences. A significant limestone occurrence was noted at 2455 m, and Windsor Group salt was encountered at 2506 m. The base of the Windsor Group salt zone was picked at 3891 m.

The base of the Windsor Group was picked at the base of a succession of interbedded shale and chert (4267 m). These rocks were dated as Lower Windsor Group on the basis of gastropod and annelid specimens (MacDonald, 1973). The top of the Horton Group was placed at 4267 m where lithologies changed from the chert zone to a siltstone and shale succession. The siltstones and shales yielded inconclusive spore results, indicating either Horton or Windsor Group aspect depending on the palynologist involved. Arkosic conglomerate, typical of Horton Group was encountered at 4319 m and the top of a lower salt interval was encountered at 4444 m. There was no indication whether the salt was of marine or lacustrine origin.

Structural dip measured in the well bore using a dip meter log indicates southerly and south-southeasterly dips ranging from 20º to 70º in the interval 914-3117 m. These are consistent with surface measured bedding dips, which are southerly 70º to 80º. The dip meter log was not interpretable from 3810 to 4524 m; however, bedding dip measured in a cored interval from 4353 to 4390 m were 5º to 20º, indicating structural dip to be relatively flat below 3980 m (MacDonald, 1973).



Well logs of petroleum industry wells in northern Nova Scotia used for seismic-stratigraphic correlations.

Figure 3

Pacific Fox Harbour C-96-V

The Pacific Fox Harbour well was drilled in 1964, almost 30 years before the stratigraphic work of Ryan et al. (1991). The geologic tops assigned in the well history report bear little resemblance to the stratigraphic subdivisions described by Ryan and Boehner (1994). New geologic tops were assigned as part of the work completed for this report, in accordance with the nomenclature of Ryan and Boehner (1994). This well was drilled on a peninsula on the southern shore of Northumberland Strait (Fig. 1), about 12 km east of Pugwash. The well collared in the Malagash Formation (Ryan et al., 1990). However, the strata in the upper part of the well are described as undifferentiated Cumberland Group (Fig. 3), which comprise red to grey sandstone, siltstone and shale. The massive, grey quartz rich sandstones of the Boss Point Formation were not recognized in the cuttings. However, a coarse unit was reported from 1271 to 1536 m, and comprises quartz rich grey and minor red conglomerate and sandstone interbedded with shale. This interval is tentatively assigned herein to the Claremont Formation based on the description of the cuttings as conglomerate. If the rocks are actually coarse sandstone, this unit may represent the Boss Point Formation.

The top of a dominantly shale package was intersected at 1536 m. These rocks are characterized by mainly red shale, siltstone and minor fine grained sandstone interbedded with anhydrite. This succession of redbeds may be equivalent to the Middleborough Formation (Mabou Group; Belt, 1965) of Serpukhovian-Bashkirian age; however, the high proportion of interbedded anhydrite suggest they may be laterally equivalent to the upper part of the Windsor Group (Visean). The top of the first carbonate unit was reported at 2018 m. According to Giles (1981), this carbonate represents the top of the Windsor Group. The top of the Lime-kiln Brook Formation (top of the Windsor Group in the Cumberland Basin; Fig. 2) was picked at 2036 m by Ryan and Boehner (1994). The well was completed in the Windsor Group at a total depth of 3003 m. The Windsor Group lithologies comprise red shale, anhydrite, limestone and minor amounts of salt.

No seismic data in the present database tie directly with the well (Fig. 4). The nearest seismic line used in this report is C44x, located approximately 5 km from the well. Seismic data adjacent to the well were interpreted by Beaver Geophysical (1965). They mapped a "possible top of Windsor" event and produced a time structure map of the area (Fig. 4). This map was used in this study to help tie the Pacific Fox Harbour well with the present seismic reflection data and to constrain structure maps in the vicinity of the well.

The "possible top of Windsor" map (Beaver Geophysical, 1965) shows that the Pacific Fox Harbour well was drilled on a structural high, on the north side of a northwest striking fault. The dip meter log from the well shows considerable scatter of the dip measurements, but most of the recorded dips are to the north and northeast consistent with the time structure map (Fig. 4). The map (Beaver Geophysical, 1965) shows the top of the Windsor Group at about 900 ms at the proposed well location. Subsequent to drilling, the top of the Windsor Group was located at 730 ms, indicating that the seismic top of Windsor is 170 ms deeper than the lithologic top of Windsor. Their map shows several northwesterly striking faults which show down-to-the-west offset of the top of the Windsor Group. In the vicinity of line C44x, the "possible top of Windsor" event (Beaver Geophysical, 1965) occurs at about 1900 ms. High amplitude reflections occurring at 1850-2000 ms on line C44x are interpreted as Windsor Group reflections, which is consistent with the Beaver Geophysical (1965) interpretation.

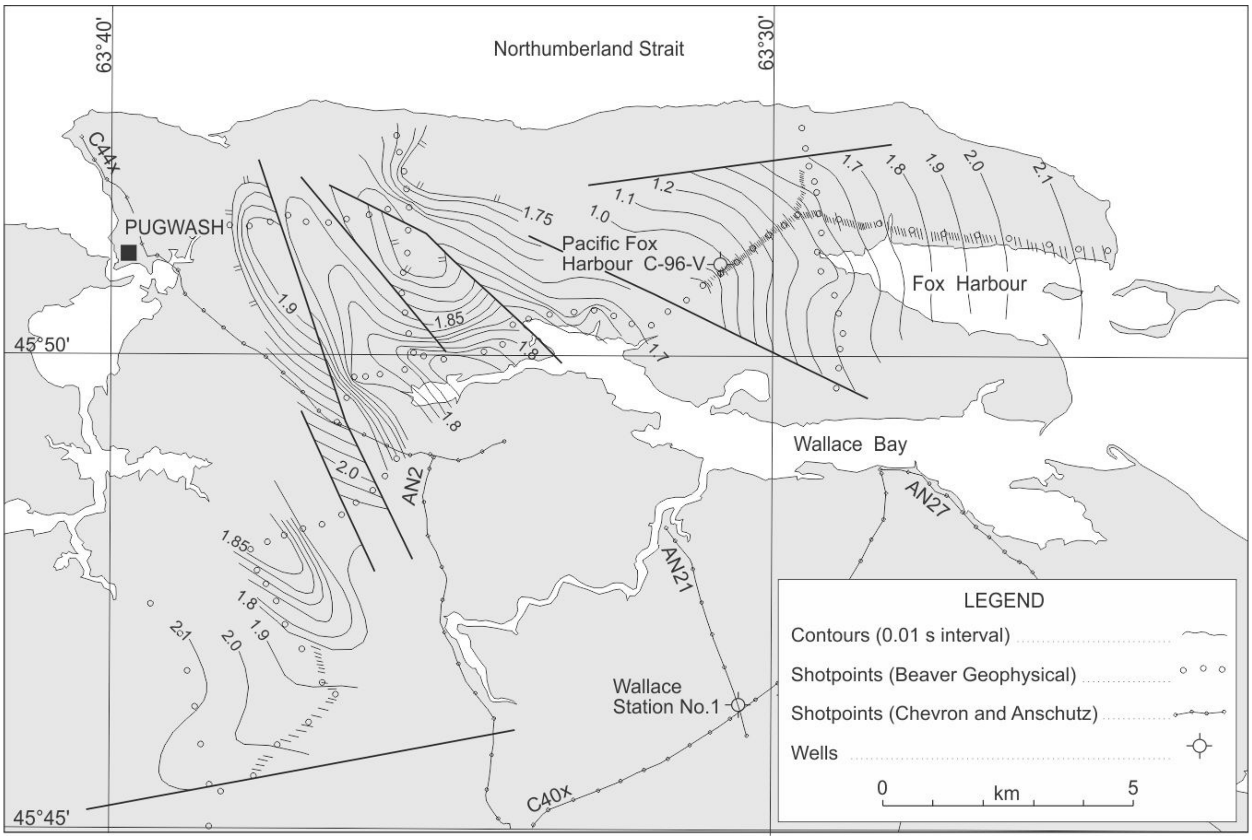


Figure 4: Time structure map on the "Purple leg: possible top of Windsor" (Beaver Geophysical, 1965). This map was used as a guide to constraining contours in the vicinity of the Pacific Fox Harbour well, due to the lack of seismic data in the area.

Sun Oil Co. Nappan No.1A

The well was drilled about 4 km south of the town of Amherst (Fig. 1). It was the second attempt to drill at this location. The first well (Nappan No.1) was drilled 46 m south of Nappan No.1A and reached a total depth of 1981 m before it was abandoned.

Interbedded salt, anhydrite, limestone and shale were intersected in the upper part of the well. The base of salt in the well occurs at 1850 m and the bottom of the deepest limestone interval was interpreted as the "base" of the Windsor Group (Giles, 1981). At 1882 m, interbedded, red and grey sandstone, siltstone and shale were intersected. Similar lithologies were encountered to a depth of 3506 m where the well was completed. These rocks were initially interpreted as Horton Group rocks (Sun Oil Company, 1945), but spore analyses conducted by M.S. Barss (unpublished data) indicate that the age of these rocks is Pennsylvanian (Howie, 1986). Therefore, Windsor Group rocks overlie younger Carboniferous strata in the well. The "base" of the Windsor Group indicated above at 1850 m is where the Beckwith Fault (Fig. 1) intersects the wellbore (Howie, 1986).

The Nappan No.1A well is located about 1500 m north of seismic line C9x and 3 km west of line AN30 (Fig. 5). Coherent reflections are absent from line C9x in the vicinity of the well. The nearest north-south trending seismic profiles occur 3 km east (AN30) and 8 km west (G12) of the well location. Since the well does not tie directly with any seismic profiles, the well was used only as a guide for seismic data interpretation in the area. A velocity log is not available for this well, so the Magdalen Basin velocity model (Durling and Marillier, 1993b) was used to tie the well data with the seismic data.

Hastings No. 1

The Hastings No.1 well (Fig. 1) was drilled on the Hastings Uplift (Howie, 1986). The well penetrated siltstones, sandstones and a thin conglomerate unit before intersecting metamorphic basement rocks at 2798.0 m (Fig. 3). The well was completed at 2939.5 m. The geologic tops used in this study were modified after the well history report (Souaya, 1975), using criteria outlined by Ryan et al. (1991). Redbed clastic rocks of the Pictou Group outcrop at the surface. The cuttings from the well are predominantly red to 819.9 m, where the cuttings become mostly grey. The redbeds were assigned to the Pictou Group (Ryan et al., 1991) and the underlying grey strata were assigned to the Cumberland Group. The upper part of the Cumberland Group in the well was not assigned to any formation due to its indistinctive nature. A coarser sandstone package was recognized starting at 1246.6 m, which was assigned to the Boss Point Formation. A conglomerate unit starting at 2621.3 m was assigned to the Claremont Formation. Fine grained sandstones and siltstones of the Mabou Group were recognized at 2667.0 m. Basement rocks occur at 2798.0 m.

Borehole TF-86-1

A shallow borehole (TF-86-1) drilled by the Nova Scotia Department of Mines and Energy was used to help constrain seismic stratigraphy in the eastern Tatamagouche Syncline. The borehole intersected the Balfron (47.8-144 m), Boss Point (144-338 m) and Claremont (338-785.5 m) formations (Ryan, 1986). Correlation of the borehole to seismic data is described later in the report (see pages 51-52).

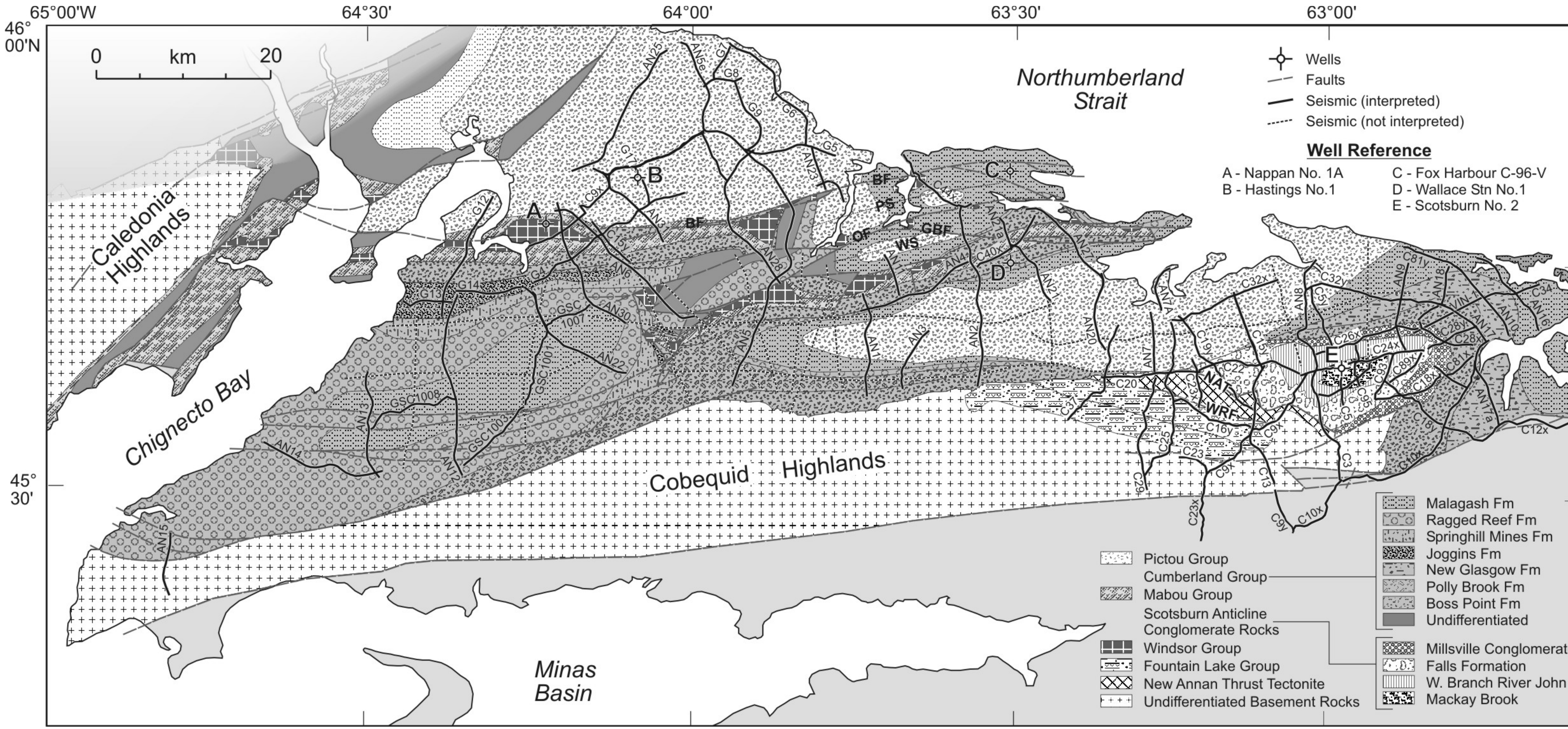


Figure 5: Distribution of seismic reflection profiles in the Cumberland Basin. Bedrock geology was compiled from Ryan and Boehner (1994), Chandler et al. (1994), Keppie (2014), and Pe-Piper and Piper (2002). Abbreviations: BF-Beckwith Fault; GBF-Golden Brook Fault; NAT-New Annan Fault; OF-Oxford Fault; PS-Pugwash Syncline; WS-Wallace Syncline WRF-Waugh River Fault.

Seismic Reflection Data

Seismic reflection data acquired by Anschutz (1972), Gulf (1974-75), Chevron (1980-81) and the Geological Survey of Canada (1985-87) were used in this study to assess the subsurface structure and stratigraphy of the Cumberland Basin (Fig. 5). Paper seismic sections were obtained from the respective companies; however, structural stack versions of most Chevron lines were publically available through the Nova Scotia Department of Natural Resources. Digital seismic reflection data were generously supplied to the Geological Survey of Canada (Atlantic) by Pembina Corporation (Repsol Canada present data owner) and Gulf Canada Resources. The GSC data were available in digital form.

Forty-one lines were reprocessed under contract by Pulsonic Geophysical Limited (Marillier and Durling, 1995). The lines were selected for reprocessing to provide widespread coverage of the Amherst area, the Athol Syncline and the western part of the Tatamagouche Syncline. Paper seismic sections were available in the eastern Tatamagouche Syncline and the Scotsburn Anticline area. Migration versions of these data were provided by Chevron Canada Resources, Ltd.

The reprocessed seismic lines provided improved imaging of stratigraphic and structural features (especially near salt structures and faults) in the Cumberland Basin (Marillier and Durling, 1995). The reprocessing increased signal-to-noise ratio, improved coherency and continuity of reflections, and provided enhanced structural imaging through 2D migration.

Geological Map Data

The Cumberland Basin is a structurally segmented basin. Many faults and salt-cored anticlines produced isolated blocks of Carboniferous strata, which have not been sampled by deep drilling. In such areas, geological control for the seismic data was provided by 1:50,000 geological maps (Ryan and Boehner, 1990; Donohoe and Wallace, 1982; Chandler et al., 1994). In addition, detailed 1:10,000 scale maps were available for the Cumberland Basin (Ryan et al., 1988). These maps provided detailed outcrop descriptions, shallow borehole descriptions and attitude data not available on the 1:50,000 scale maps. This information was used to identify subtle unconformities and near surface reflections on the seismic data.

The following is a brief summary of the seismic interpretation process used in this study. Digital seismic data were interpreted on a LandMark seismic workstation. Paper seismic sections were interpreted concurrently and the horizons were digitized using a tablet connection direct to the workstation. Preliminary time structure maps were prepared using the LandMark software to check for interpretation errors, using built-in gridding and contouring routines. Data files were exported to a mapping package (Z-Map Plus) where final time structure maps were prepared (see gridding and contouring below). Graphics software was used to add text and graphics to the final time structure maps.

METHODS

A description of specific data interpretation issues (seismic bulk data shifts, misties, correlation of geological map and seismic data) is given below.

Bulk Data Shift

The project datum for the Cumberland Basin was chosen to be 120 m above sea level, the processing datum of the Chevron paper seismic sections. Digital seismic data were adjusted to the project datum during data loading to the workstation.

Table 1 shows the bulk shifts employed during data loading. Bulk shifts were established by comparing paper seismic profiles at line intersections. To reduce mistie errors resulting from 2D migration, structural stack sections were used to establish the amount of the bulk data shift.

Table 1

Bulk Data Shifts Applied to Seismic Reflection Data

SEISMIC SURVEY	BULK SHIFT
Chevron	0 ms
Anschutz	-80 ms
Gulf	+45 ms
GSC lines 1001 and 1003	+100 ms
GSC line 1007	+112 ms

Misties

Misties between seismic reflection lines are caused by a number of geological and geophysical factors. Misties caused by 2D migration were of primary concern in this study. The study area is highly faulted and folded with bedding dips of up to 80º. Migrated data are necessary to obtain structurally accurate interpretations.

During migration of 2D seismic data, the amount a reflection is moved is proportional to the apparent dip of the reflection in the plane of the 2D seismic line. Therefore, reflections on strike lines and dip lines are moved by different amounts, thus causing misties. It was observed in this study that the migration computed by Pulsonic shows reflections with steeper dips on the final migrated stacks than the Chevron processing.

In areas of very steep dips (i.e. Scotsburn Anticline), lines were tied using structural stack sections to ensure correct identification of horizons throughout the study area. Horizon picks were transferred from the stack data to the migrated data. Resulting misties were generally sufficiently small that they were not noticeable on the final contour maps. Where misties were large (i.e. AN9), the variable mistie option of the seismic interpretation software was used to compensate for the misties during contour map generation.

Correlation of Geological Map Data and Seismic Data

Reflections occurring within the upper 100 to 200 ms of the seismic reflection data are obscured by surface seismic noise and are generally poor quality. Reflections deeper than 200 ms were identified geologically by extrapolating outcrop geology to depth trigonometrically using bedding attitudes. Depths calculated trigonometrically were converted to two-way travel time using an average velocity function from seismic refraction measurements in the Gulf of St. Lawrence (Durling and Marillier, 1993b). A detailed description of seismic correlations for most lines is provided in the appendix. For some lines, correlation with surface geology was not possible or not required (e.g. where strata are horizontal).

Gridding and Contouring

The contour maps presented in this report were produced using Z-Map Plus digital mapping software program. The input data for mapping, which included horizon data, fault location data, fault polygons, calculated fault heaves and throw, and manual contours (converted to map points), were imported from LandMark seismic interpretation software.

The mapping package provides a multitude of gridding, geophysical and data processing operations. The intent of this mapping exercise was to obtain geologically plausible contour and fault patterns that honour the available seismic reflection data.

Prior to gridding the horizon data, some pre-processing of the data was performed to increase computation efficiency. First, the horizon data were re-sampled by a factor of five to one. The horizons were sampled every trace during interpretation (67 m spacing for Gulf and Anschutz data, 25 m for Chevron) and the re-sampling resulted in a sample every 5th trace (maximum sample spacing of 335 m). The data were gridded using a 1000 m grid, the re-sampled data provided 3 data points per grid cell, which decreased the computation time with no apparent degradation in interpretation quality. In addition to re-sampling the horizon data, manual contours were drawn to constrain grid node values in areas of sparse seismic data distribution. The manual contours were converted to pseudo-horizon data points and merged with the horizon data.

SEISMIC STRATIGRAPHY

Seismic facies analysis forms the basis of this work. Seismic horizons were traced on the seismic data through the identification of various seismic facies in an attempt to construct a consistent seismic stratigraphy throughout the basin. The resulting seismic horizons were subsequently correlated with well and outcrop information to relate the seismic horizons to established lithostratigraphy. Thirteen horizons were mapped; only three were recognized in more than one syncline (Table 2), and they are described in this report as regional horizons. They are interpreted to correspond to the bases of the Windsor Group, Boss Point Formation and the Pictou Group. Only the Pictou Group horizon is not present in all three synclines, being absent from the Athol Syncline. The regional horizons will be described first to establish a framework, within which all remaining horizons can be placed (Table 2).

Table 2

Seismic Horizons Mapped in the Amherst, Athol, and Tatamagouche synclines

Amherst Syncline	Athol Syncline	Tatamagouche Syncline
Base Pictou (PG)		Base Pictou (PG)
		Base Malagash (TA8)
Horizon (AM5)	No. 2 Seam	Base Polly Brook (TA7)
	Chignecto-40 Brine	? Top low energy zone (TA6)
Base Boss Point (BP)	Base Boss Point (BP)	Base Boss Point (BP)
Top Windsor salt (AM3)		Intra-conglomerate reflection (TA4)
		Top Windsor clastic unit (TA3)
Base Windsor (BW)	Base Windsor (BW)	Base Windsor (BW)
Basement (AM1)		Top FLG volcanics (TA1)

Reflection horizons that can be correlated between two or more synclines (Regional Seismic Horizons) are linked by dotted lines. Relative correlation of other horizons between the synclines is uncertain.

Regional Seismic Horizons

<u>Base Windsor Horizon (BW)</u>

This horizon has a unique seismic reflection character that is remarkably consistent throughout the Cumberland Basin. On individual seismic profiles, it is commonly the deepest reflection that could be traced on the seismic data (acoustic basement); however, reflections deeper than BW were recognized locally. Two horizons believed to occur stratigraphically below horizon BW (Hastings basement [AM1] and top FLG volcanic rocks [TA1], Table 2) were mapped in the Amherst and Tatamagouche Synclines, respectively.

Horizon BW was mapped at the base of a series of high amplitude, low frequency, continuous reflections (Fig. 6). The series of reflections usually includes about 3-6 peak-trough pairs. In some localities lenses of low reflectivity rocks are observed within the band of reflections (Fig. 6 at 6 km and 2.3 s), and in other areas the band thickens toward vertical zones of incoherent reflections. These areas of low seismic energy and incoherent reflections commonly coincide with low gravity anomalies and are interpreted as Windsor Group salt diapirs (Boehner, 1986; Howie, 1986; Waldron et al., 2013). On some seismic profiles, the continuity of individual reflections decreases, and the series of reflections assumes an "anastomosing" character; however, the overall continuity of the reflection package is preserved. The reflection package is most discontinuous in the Tatamagouche Syncline, where the reflections are higher amplitude and there are fewer trough-peak pairs.

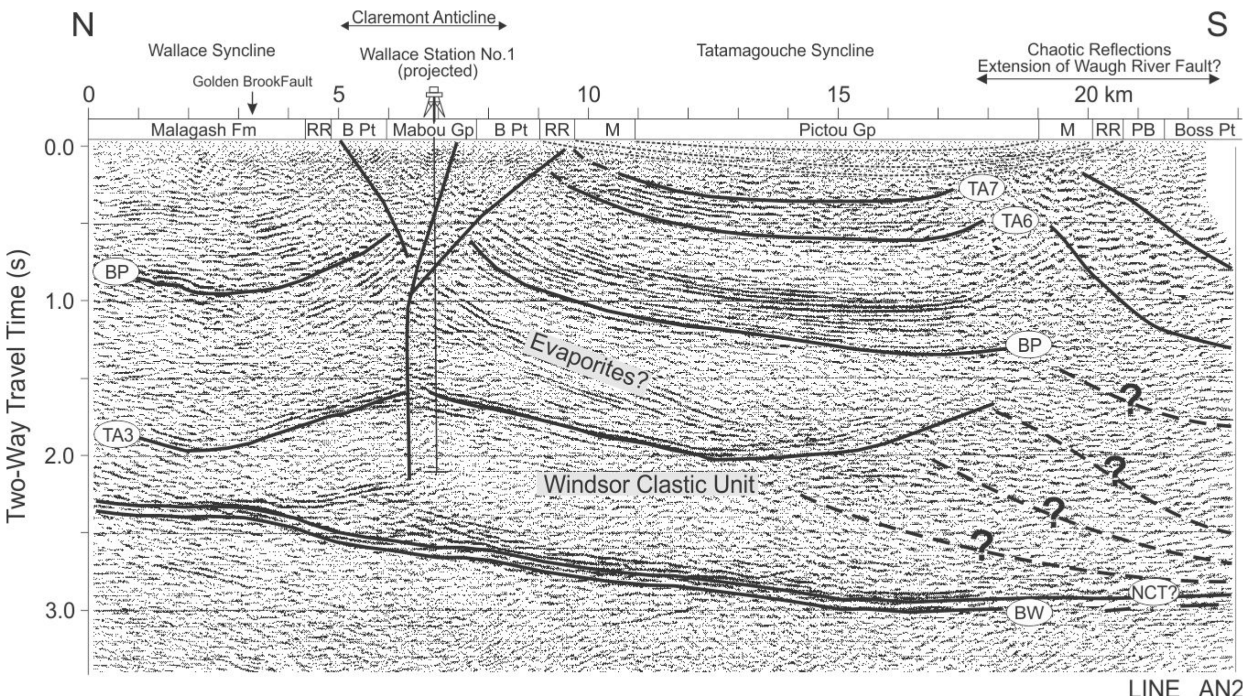


Figure 6: Interpreted seismic profile AN2 from the Tatamagouche Syncline. See text for discussion. Seismic data is subject to licence agreement with Repsol Canada.

There are no boreholes in the Cumberland Basin that intersect the BW horizon. The Wallace Station No.1 well penetrated a 0.6 s thick, low energy, seismic unit that immediately overlies horizon BW and its associated reflections (Figs. 6 and 7). Windsor Group rocks were encountered at a shallow depth in the well (MacDonald, 1973), and according to Ryan and Boehner (1994), drilling was terminated in the Windsor Group, since typical basal Windsor Group lithologies were not encountered in the well. Therefore, horizon BW must correspond to Windsor Group or older rocks. Seismic reflection mapping in the Gulf of St. Lawrence (Durling and Marillier, 1993b; Atkinson et al., 2019), demonstrated that a high amplitude reflection package, very similar to the reflection package associated with horizon BW, correlates with basal Windsor Group strata. In addition, two-way time measurements on horizon BW occur at comparable depths to basal Windsor Group reflections in the Northumberland Strait (Durling and Marillier, 1993a; Atkinson et al., 2019). Therefore, horizon BW is interpreted as a 'near base of Windsor Group' seismic event. The BW horizon generally corresponds the “W” seismic marker interpreted by Waldron and Rygel (2005) and Waldron et al. (2013).

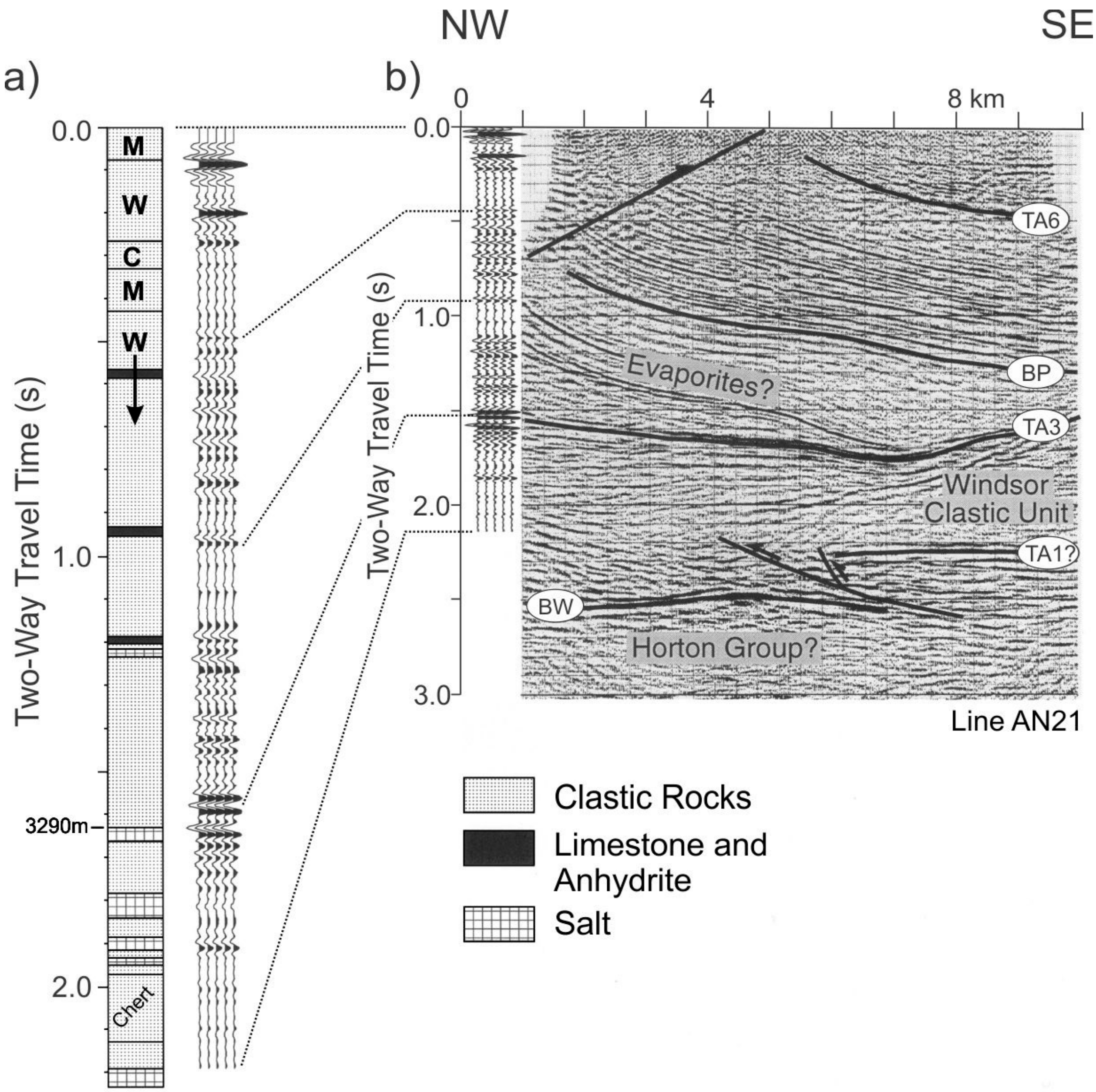


Figure 7: Well tie between the Wallace Station No.1 well and seismic line AN21. The surface well location is about 750 m southwest of the end to the seismic profile (Fig. 5). The synthetic seismogram was generated using LandMark’s “Syntheseis” software using the borehole compensated sonic log. A simplified stratigraphy is shown to the left of the synthetic; a more detailed stratigraphy is shown in Figure 3. Abbreviations: M – Middleborough Formation; W – Windsor Group (undivided); C – Claremont Formation. Seismic data is subject to licence agreement with Repsol Canada.

Base Boss Point Horizon (BP)

In all of the major synclines of the Cumberland Basin, at approximately 1 second depth, a thick interval of low to high amplitude continuous to discontinuous reflections is observed (Figs. 6 and 7). These reflections are best imaged in the Tatamagouche and Athol synclines and are poorly imaged in the Amherst Syncline. The base of this reflection package is identified as horizon BP.

The BP horizon corresponds to an abrupt change in reflection character from low amplitude reflections below to relatively higher amplitude reflections above horizon BP (Figs. 6 and 7), which may include more than 10 reflections (Fig. 7). The top is gradational, with reflectivity decreasing upward. In the eastern Tatamagouche Syncline, the reflections are generally lower in amplitude and fewer in number than elsewhere in Cumberland Basin. The package may, in this area, display a sharp upper contact with the overlying lower energy package. Locally in the Tatamagouche Syncline, the reflection package overlying horizon BP is unconformably overlain by younger rocks.

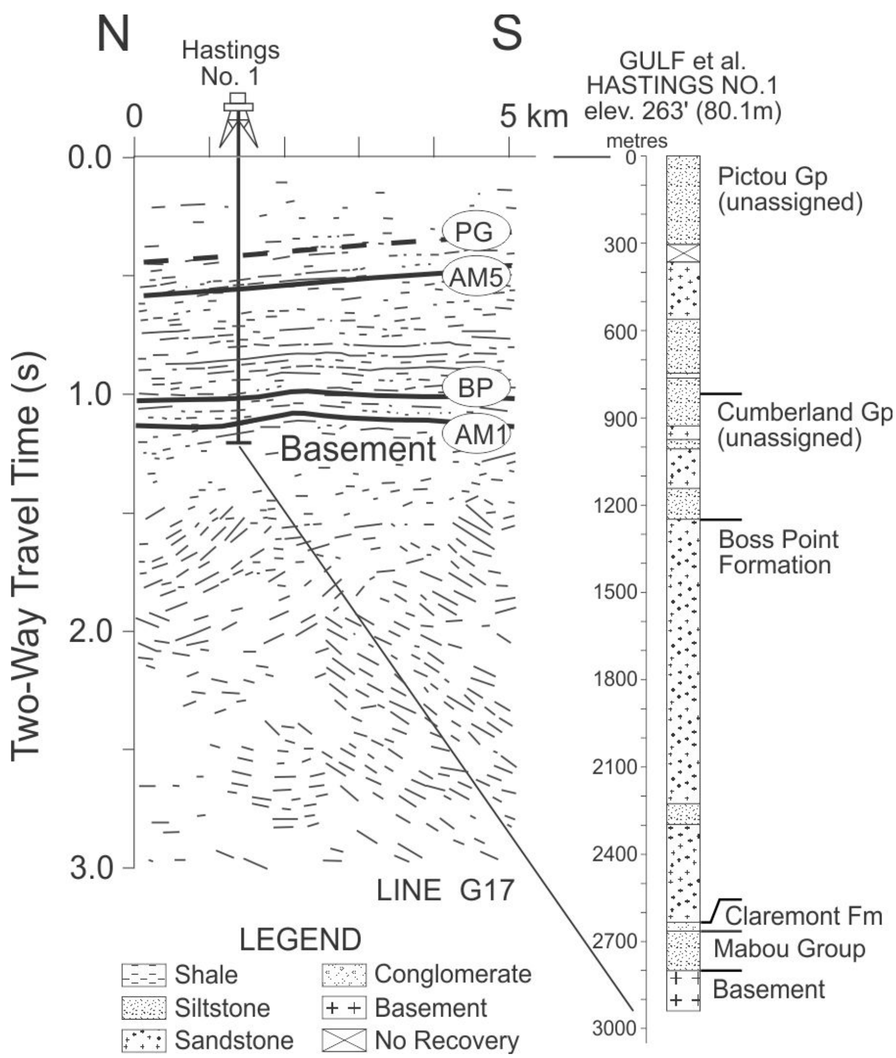


Figure 8: Correlation of the Hastings No.1 well with a line drawing of seismic profile G17. Time to depth relationships were established using the BHC sonic log. See text for discussion.

In the Athol and Tatamagouche synclines, horizon BP can be traced to surface exposures where it correlates with the base of the Boss Point Formation (Cumberland Group). In the Amherst Syncline, the Boss Point Formation does not outcrop a due to an overlying thick blanket of Pictou Group strata. Horizon BP was identified in the Amherst Syncline through correlation with the interpreted base of the Boss Point Formation in the Hastings No.1 well (Fig. 8).

Base Pictou Group Horizon (PG)

Horizon PG is recognized in only the Amherst and Tatamagouche Synclines. It was mapped at the base of a broad band of low to high amplitude, continuous to discontinuous reflections, similar

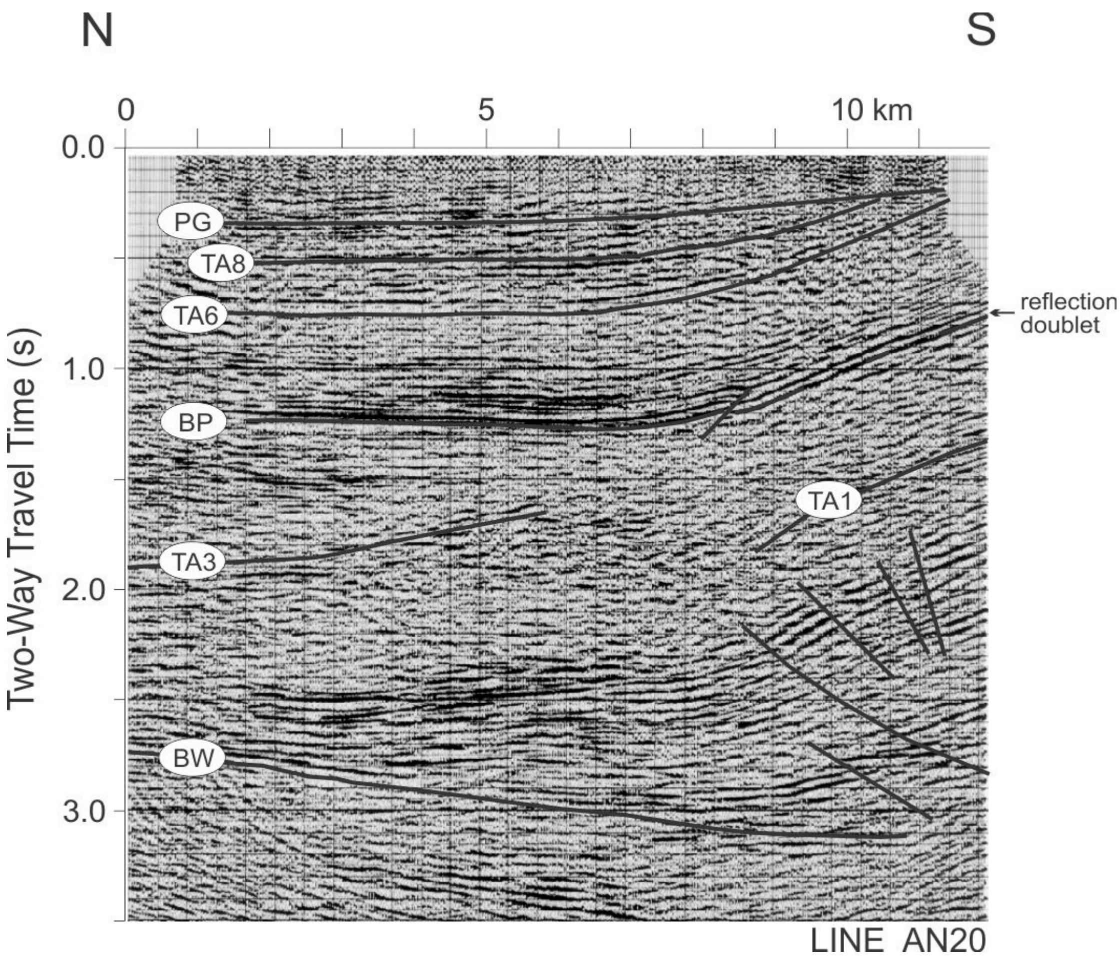


Figure 9: Interpreted seismic profile AN20 from the Tatamagouche Syncline. This profile shows the PG horizon unconformable on older strata at the southern end of the profile. The reflection doublet which occurs in this area is also shown and is correlated with the BP horizon. The line representing the BP horizon is dashed at the southern end of the profile to permit observation of the reflection doublet. The TA1 horizon identifies the top of Fountain Lake Group (FLG) volcanic rocks and ties with the Scotsburn No. 2 well. The relationships on this profile suggest that the FLG volcanic rocks overlie the BW horizon. A thrust fault (not indicated) may be present just above the BW horizon, which would account for the inverted stratigraphy. Seismic data is subject to licence agreement with Repsol Canada.

in character to the BP reflection package. Locally, horizon PG lies with marked angular unconformity on folded (Fig. 9) or steeply dipping older strata. In the eastern Tatamagouche Syncline, the horizon coincides with the base of the Pictou Group in outcrop and in the TF-86-1 borehole (see Fig. 1 for location). An obvious top to this package was not observed. The PG horizon was not recognized in the western part of the Tatamagouche Syncline where it is interpreted to lie within the surface noise on the seismic profiles (see figure 6, for example).

Horizon PG was identified in the Amherst Syncline through a well tie with the Hastings No.1 well (Fig. 8) where it correlates with the interpreted base of the Pictou Group in the well. The horizon locally coincides with the bottom of a package of discontinuous reflections (Fig. 10). Similar to the Tatamagouche Syncline, horizon PG may unconformably overlie folded older strata as observed on the north end of figure 10.

Horizons in the Amherst Syncline

Basement (AM1)

Metamorphic basement rocks comprising quartzite and chlorite schist were encountered at the base of the Hastings No.1 well (Figs. 3 and 8). These rocks are overlain by siltstones and shales of the Mabou Group (Souaya, 1975). At the well location, the sediment-basement contact corresponds to a change from incoherent and chaotic reflections at depth to horizontal, continuous to discontinuous reflections with variable amplitude. A strong reflection is not observed at the sediment-basement interface (Fig. 10) and it is difficult to trace on some seismic data. Horizon AM1 is mapped on an elevated basement block identified as the Hastings Uplift (Howie, 1986), which occurs between the Beckwith Fault and the axial trace of the Amherst Syncline (Fig. 1).

Base Windsor (BW)

See "Regional Seismic Horizons" above.

Top of Windsor Group Salt (AM3)

Horizon AM3 was mapped only north of the Hastings Uplift. It corresponds to the base of a reflection package with variable amplitude and continuity that overlies an interval comprising low amplitude, chaotic reflections (Figs. 10 and 11). The latter are interpreted as Windsor Group salt. Note that a “jump tie” between the northern ends of seismic data in figures 10 and 11 was used to facilitate the interpretation.

Base Boss Point Horizon (BP)

See "Regional Seismic Horizons" above.

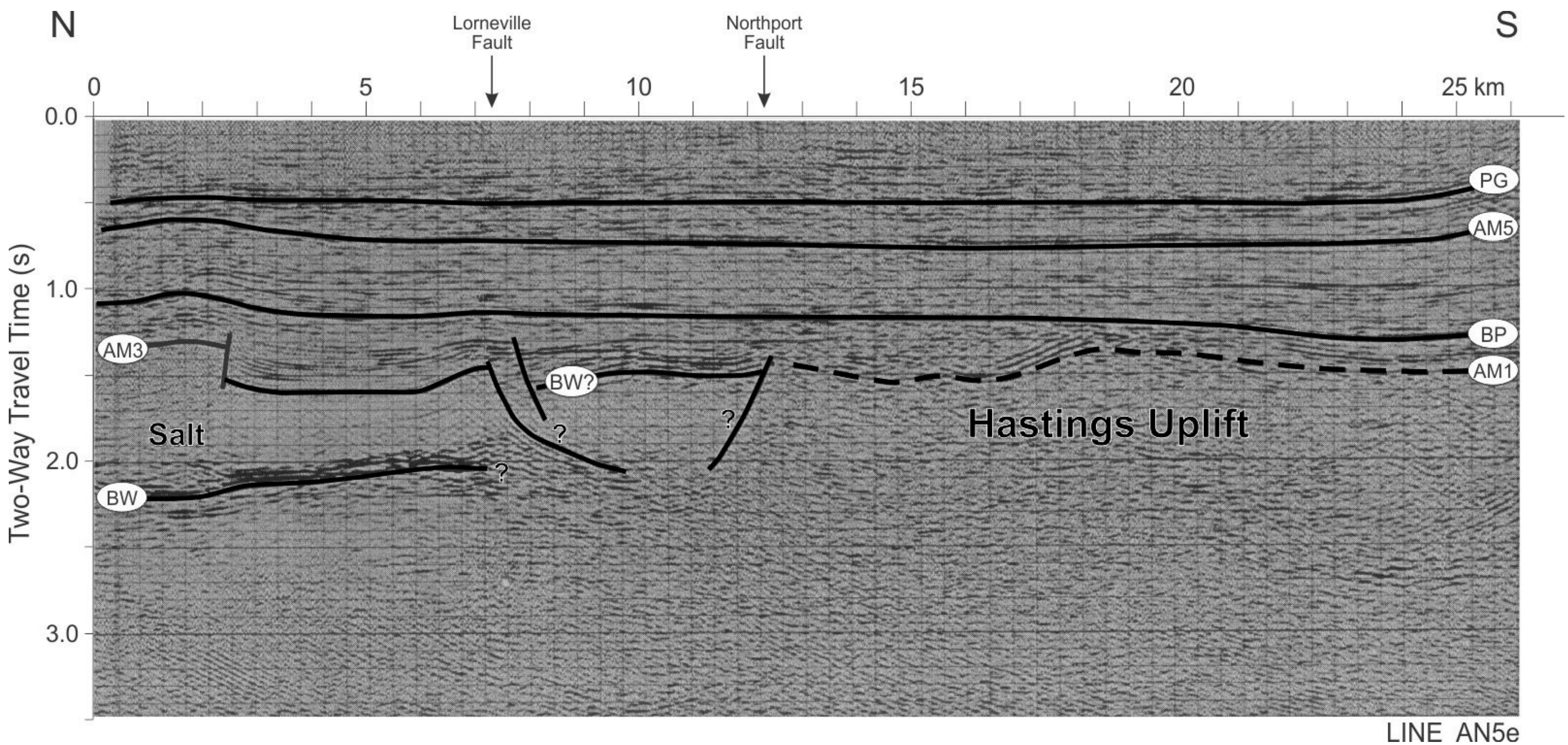


Figure 10: Interpreted seismic profile AN5e from the Hastings Uplift area. See text for description of the seismic horizons. Seismic data is subject to licence agreement with Repsol Canada.

Horizon AM5

Horizon AM5 correlates with the interpreted top of the Boss Point Formation in the Amherst Syncline (Fig. 8). It locally corresponds to the base of a series of 2-3 moderate to high amplitude reflections (Fig. 10); however, in most areas reflection amplitudes are rather low (Fig. 11). Strata above AM5 and below PG change thickness laterally suggesting tilting of older strata, perhaps associated with evaporite flow.

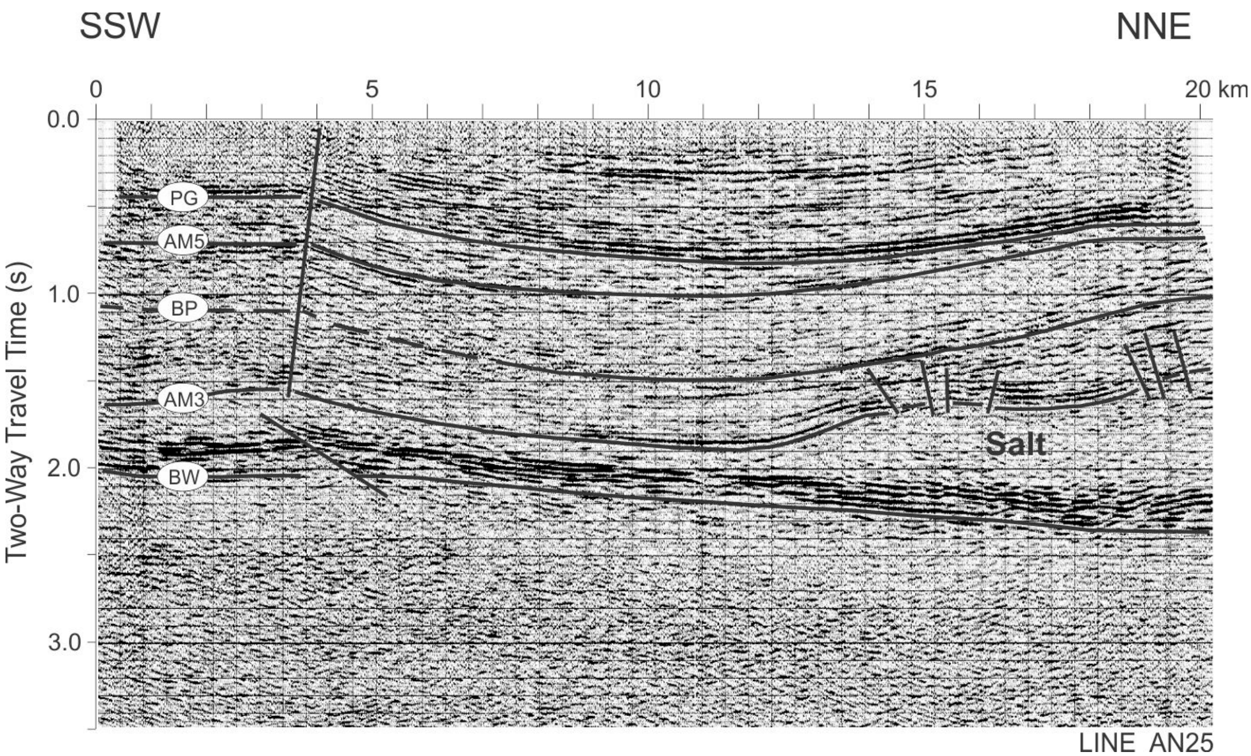


Figure 11: Interpreted seismic profile AN25 from the Hastings uplift area. The seismic horizons are described in the text. A salt layer is interpreted below horizon AM3. Seismic data is subject to licence agreement with Repsol Canada.

Base Pictou Group Horizon (PG)

See "Regional Seismic Horizons" above.

Horizons in the Athol Syncline

Base Windsor Horizon (BW)

See "Regional Seismic Horizons" above.

Base Boss Point Horizon (BP)

See "Regional Seismic Horizons" above.

Coal Horizons (CFB, No.2, and R)

Three coal horizons were mapped in the Athol Syncline: Forty Brine - Chignecto, No.2 Seam and the Rodney Seam. They were adapted from Bromley and Calder (1988), who used seismic reflection data to study the seismic character and distribution of the Late Carboniferous coals in the Athol Syncline. Figure 12 shows the reflection character of the coal strata in the Athol Syncline. The Forty Brine - Chignecto and the No. 2 seams are indicated. The Rodney seam occurs only in the Springhill area, and lies about 200 m above the No.2 seam.

The coal horizons comprise very high amplitude, continuous to discontinuous reflections. In the Athol Syncline, the reflections decrease in amplitude laterally, apparently indicating lithologic change (Waldron and Rygel, 2005). Bromley and Calder (1988; p. 10) interpreted the weak reflections beneath the coal horizons as conglomerate rocks of the Polly Brook Formation, whereas Waldron and Rygel (2005) show the Polly Brook Formation transitional with the Joggins Formation.

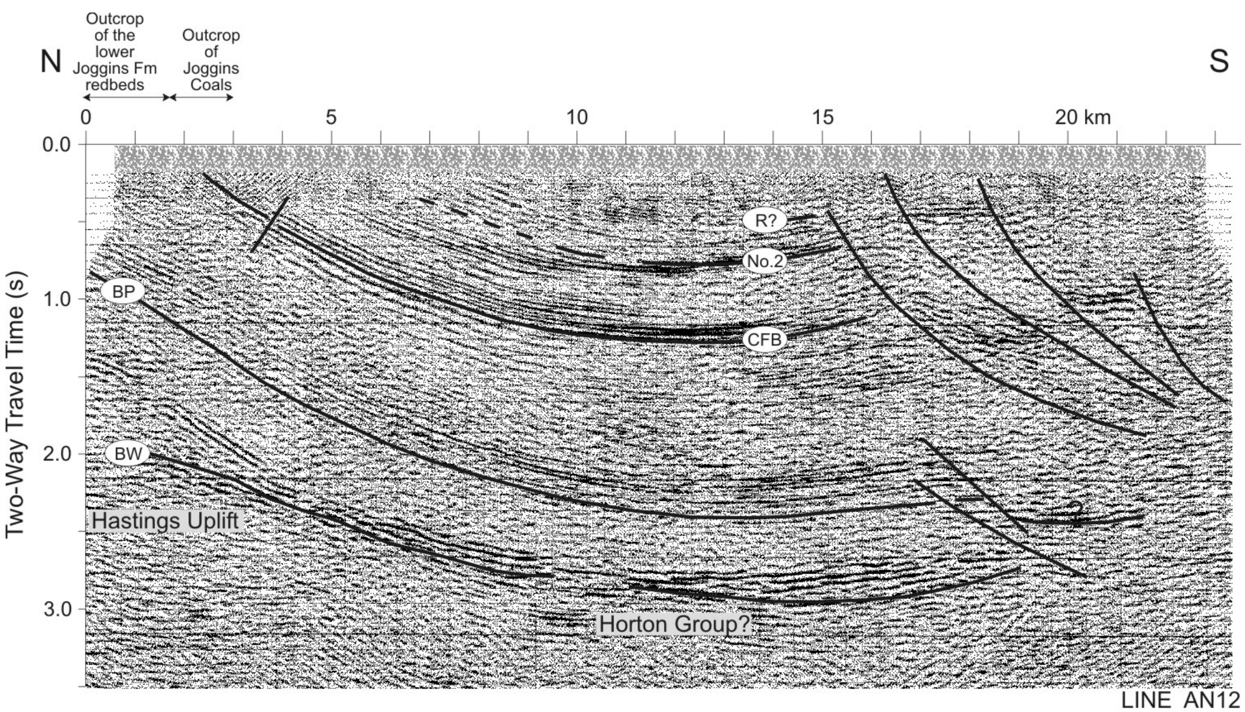


Figure 12: Interpreted seismic line AN12 from the Athol Syncline. The coal horizons (Chignecto-Forty Brine, No.2 and Rodney seams, respectively) are described by Bromley and Calder (1988). The Rodney seam (R?) is not known to occur on this seismic profile, but it is shown here to illustrate its stratigraphic position relative to the others. Seismic data is subject to licence agreement with Repsol Canada.

Horizons in the Tatamagouche Syncline

Top of Fountain Lake Group Volcanic Rocks (TA1)

Rocks assigned to Fountain Lake Group (FLG) were encountered in the Scotsburn No.2 well (Fig. 3). In the upper 625 m, mafic volcanic rocks, interbedded with minor red sandstones and siltstones (Diamond Brook Formation) were encountered; these are underlain by felsic pyroclastic rocks, mafic volcanic rocks, and rhyolite, interbedded with minor clastic rocks (Byers Brook Formation). A synthetic seismogram (Durling, 1996) shows that these rocks give rise to numerous high amplitude reflections, which are described as the high amplitude seismic facies (Fig. 13). Horizon TA1 marks the boundary between sparsely distributed and discontinuous reflections above from the high amplitude seismic facies below. An image of the seismic data used to make the line drawing of line C22 (Fig. 13) may be viewed in figure 4 of Durling (1996).

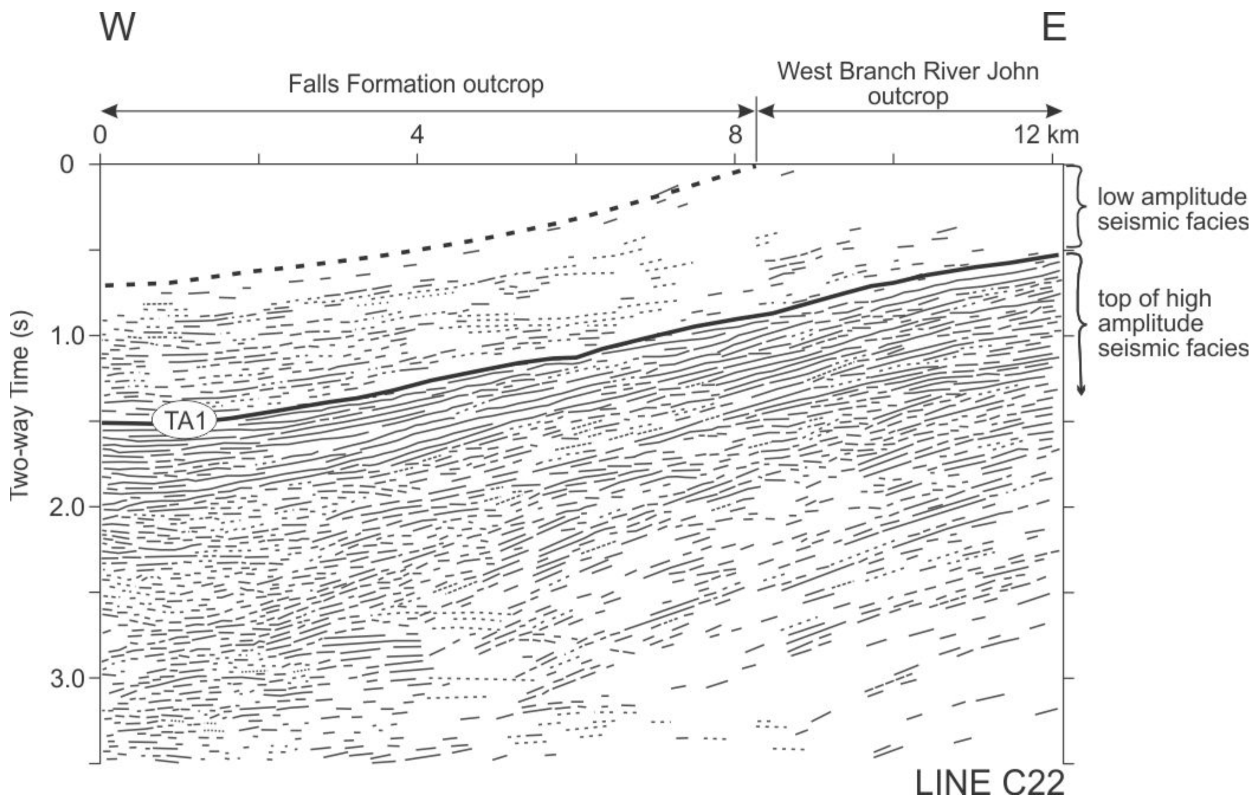


Figure 13: Line drawing of seismic profile C22 from the Scotsburn Anticline area. A seismic image of line C22 is presented in Figure 4 in Durling (1996). See text for discussion.

The top of the high amplitude seismic facies can be traced with confidence in the eastern part of the Tatamagouche Syncline and the Scotsburn Anticline (Durling, 1996), mainly due to the strong contrast in seismic response between it and the overlying rocks. Horizon TA1 was mapped in the sub-surface in an east-west direction for about 55 km and up to 17 km in a north-south direction (Fig. 14). It was recognized in the subsurface as far south as the surface trace of the Waugh River Fault

(Fig. 14), where horizon TA1 underlies basement rocks of the eastern Cobequid Highlands (Durling, 1996). These relationships demonstrate over thrusting in the area (Piper and Pe-Piper, 2001).

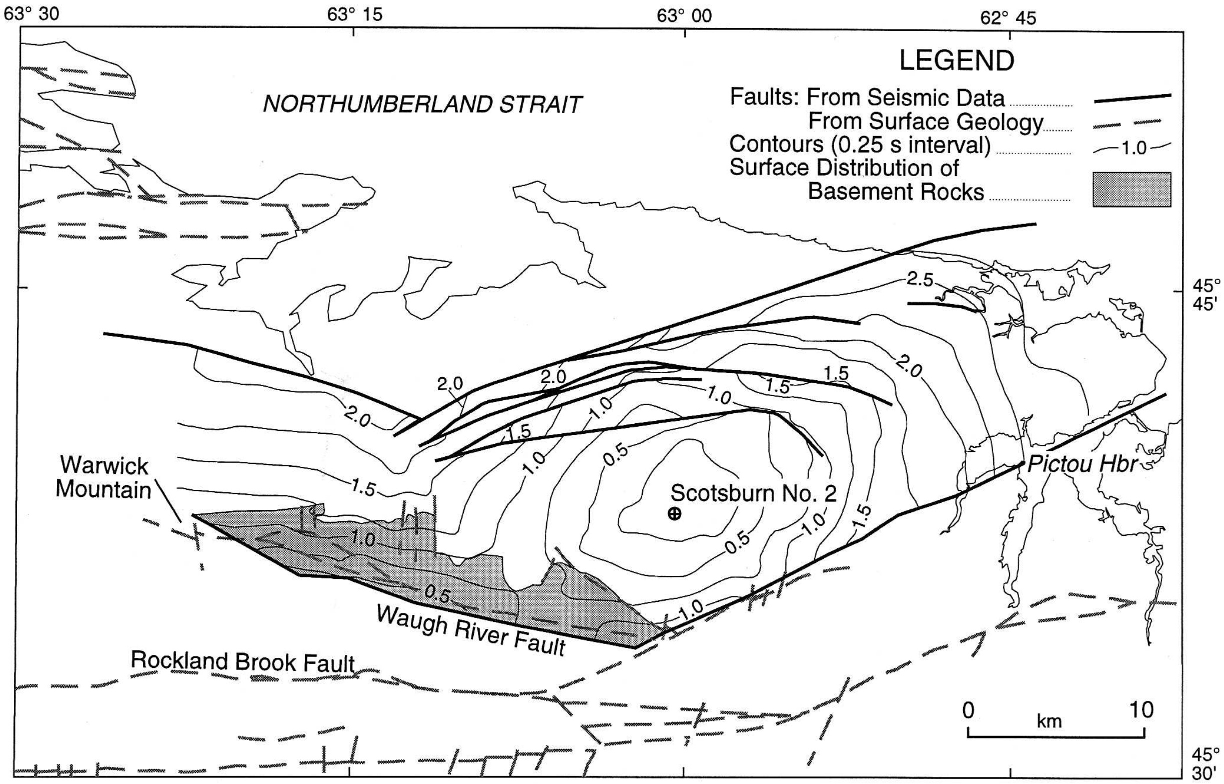


Figure 14: Time structure map on horizon TA1 (from Durling, 1996).

Overlying horizon TA1 is a seismic unit comprising low amplitude, discontinuous reflections (Fig. 13). Durling (1996) described this seismic unit as the low amplitude seismic facies of the FLG. Where this is traced to the surface it corresponds to the mapped distribution of the West Branch River John and Mackay Brook formations (Keppie, 2014). The Falls Formation overlies the West Branch River John formation in the vicinity of line C22 (Fig. 13), where the Falls Formation corresponds to a similar seismically transparent zone. There is very little difference in seismic response between these rock formations and seismic mapping of these units was not possible.

Base Windsor Horizon (BW)

See "Regional Seismic Horizons" above.

Top of Windsor Group Clastic Unit (TA3)

A series of 2-3 high amplitude reflections occur in the western Tatamagouche Syncline at 1.5-2.0 s two-way travel time (Figs. 6 and 15). These reflections, identified as TA3, overlie a thick (0.8 s; 1600 m) low energy interval compriing discontinuous, very low amplitude reflections.

Locally, the reflections above TA3 downlap onto it (Fig. 6), and TA3 truncates the reflections below it (Fig. 7). This reflection package is unique to the western Tatamagouche Syncline and it is not observed elsewhere in the Cumberland Basin. Furthermore, the reflection and the underlying low amplitude seismic unit are not limited to the Tatamagouche Syncline, but they extend north of the Claremont Anticline and beneath the Wallace Syncline (Fig. 6).

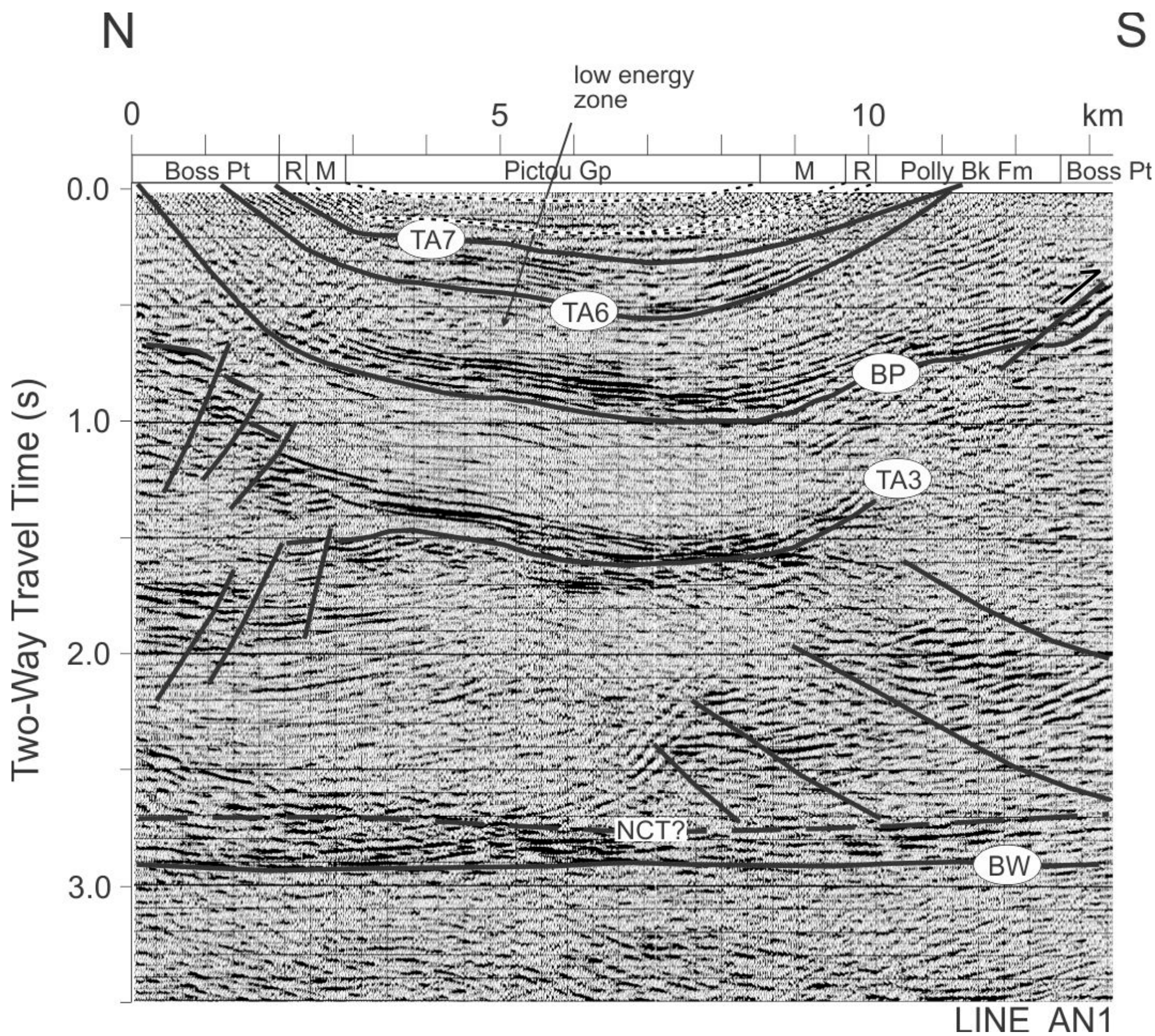


Figure 15: Interpreted seismic profile AN1 from the Tatamagouche Syncline. See text for discussion of seismic horizons. Seismic data is subject to licence agreement with Repsol Canada.

The TA3 horizon was intersected in the Wallace Station No.1 well (Figs. 3 and 7). It corresponds to shale and salt at about 3290 m and it is correlated with the strata of the Windsor Group (Marillier and Durling, 1995). The low energy unit below the TA3 horizon (Fig. 6) corresponds to salt, shale, siltstone, and minor conglomerate. The upper part of this unit (3290-3980m, Fig. 3) comprises interbedded salt and clastic rocks. A chert layer, dated by macrofossils as equivalent to the lower Windsor Group (MacDonald, 1973), occurs between 3980-4267 m (approximately 2.0-2.1 s; Fig. 7). These data establish that part of the low energy package correlates with the lower Windsor Group. It is reasonable to suggest, in the absence of a significant seismic boundary (i.e. a reflection indicative of typical base Windsor Group limestone and anhydrite), that all of the low energy package between the TA3 and BW horizons (Figs. 6 and 7) represents Windsor Group, in agreement with Ryan and Boehner (1994). This unit is interpreted as a clastic unit contemporary with the lower Windsor Group.

The Windsor clastic unit thins northward from 1.2 s thick (2200 m) near the Cobequid Highlands to about 0.4 s (760 m) north of the Claremont Anticline (Fig. 6). The northernmost limit of the Windsor clastic unit observed in this study is at the end of line AN2 (Fig.6) in the Wallace Syncline area (Fig. 1). Line C44x images the subsurface north of the Oxford Fault (Fig. 5). Interpretation of this line (see Appendix) suggests that the Windsor clastic unit may be transitional northward with Windsor Group limestone and evaporite rocks.

Intra-Conglomerate Reflection (TA4)

A series of peak-trough-peak high amplitude reflections are identified on two seismic lines (C28x and C28y; Fig. 5) on the Scotsburn Anticline. These reflections occur within the low energy seismic facies overlying horizon TA1 (Fig. 13). The area where the TA4 horizon could be mapped is limited to the northeast plunging axis of the Scotsburn Anticline (Fig. 14).

The reflections can be traced down dip (using lines AN17, AN18, and AN10; see Fig. 5 for locations) where reflections typical of the Windsor Group are observed on seismic line C34. The Windsor Group reflections were identified on line C34 by reflection character and jump correlation from Windsor Group events mapped in Northumberland Strait (Durling and Marillier, 1993a and 1993b; Atkinson et al., 2019). The TA4 reflections correlate with reflections at the stratigraphic level of the base of the Windsor Group, stratigraphically below interpreted salt and the highest Windsor Group reflections.

Subsequent to the completion of the seismic data analysis for this report in 1996, four seismic lines were acquired by Vintage Petroleum in 2003 in the area where the TA4 reflections are observed. Figure 16 shows a line drawing for line VIN-01 (see Fig. 5 for location). Line VIN-01 provides a direct tie between C28y and C34 and supports the interpretation that the TA4 reflections correlate with strata within the Millsville conglomerate and can be traced down-dip to correlate with reflections interpreted as Windsor Group. Some reflections below the TA4 horizon converge down dip and merge with the BW horizon (see arrows in Fig. 16). The interpretation of top of Windsor Group reflections is indicated by the abbreviation ‘TWG’ and the dashed horizon marker.

Base Boss Point Horizon (BP)

See "Regional Seismic Horizons" above.

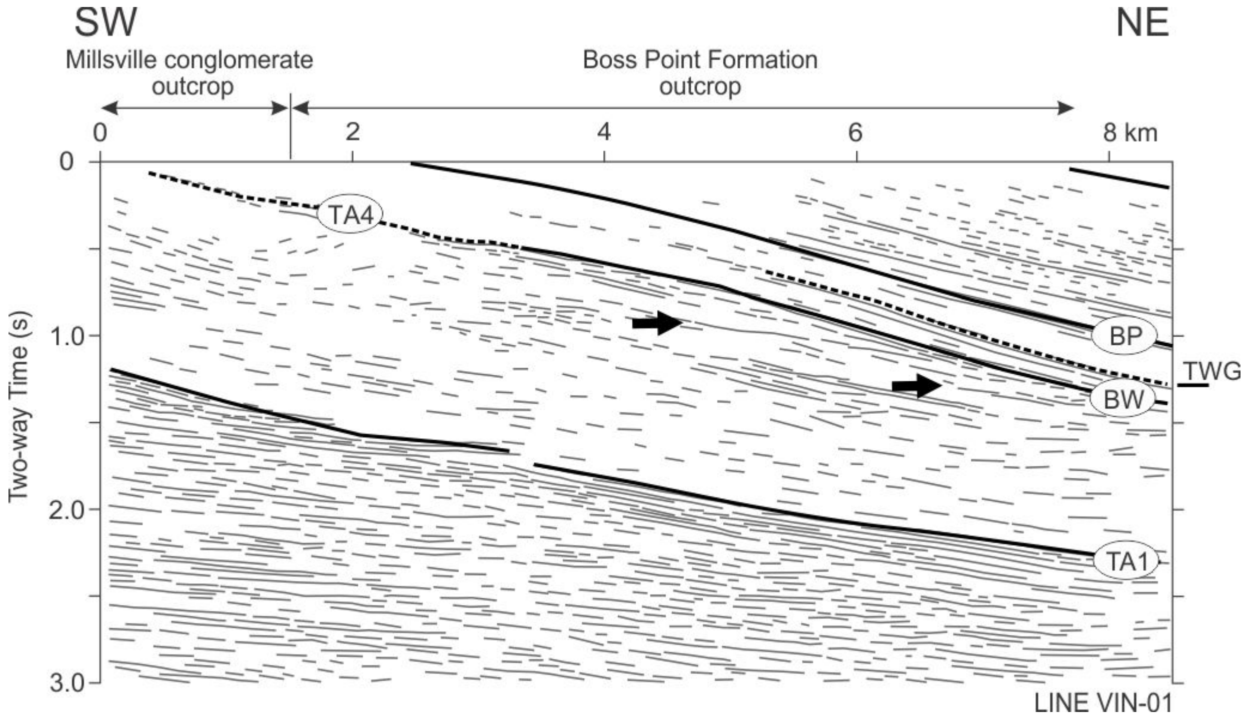


Figure 16: Line drawing of seismic profile VIN-01 from the Scotsburn Anticline. Abbreviation 'TWG' indicates top Windsor Group reflections. See text for discussion of seismic horizons.

<u>Top of Low Energy Zone (TA6)</u>

The high amplitude reflections directly overlying the BP horizon (Figs. 15 and 6) transition upward into a low energy zone characterized by discontinuous to chaotic reflections. The top of the low energy zone has a sharp to gradational contact, associated with an increase in the number of reflections within an upper high reflectivity package. Horizon TA6 was picked at the top of the low energy zone at the occurrence of the first high amplitude reflection. The TA6 horizon is locally truncated by overlying reflections, especially along the southern limb of the syncline (Fig. 15).

Correlation of horizon TA6 with surface geology is problematic as shown in figure 15. On the southern limb of the syncline horizon TA6 correlates to strata mapped as the Polly Brook Formation, whereas on the north limb it correlates with rocks mapped as Boss Point Formation. See Horizon TA7 below for a more fulsome discussion.

<u>Horizon TA7</u>

The TA7 horizon is recognized in the western part of the Tatamagouche Syncline. It was mapped at the top of an interval of high amplitude, discontinuous reflections (Fig. 6) that may pinch-out toward the south (Fig. 15). Horizons TA7 and TA6 form the upper and lower boundaries, respectively, of the upper high amplitude reflection package in the western part of the Tatamagouche Syncline. This high amplitude reflection package was not recognized elsewhere in the basin.

Correlation of the high amplitude reflection package between horizons TA6 and TA7 to surface geology was attempted using Line AN1 (Fig. 15). On the north end of the line the reflection package correlates with the upper part of the Boss Point Formation mapped on the north limb of the Tatamagouche Syncline (Fig. 1). Mapped contacts may be suspect in this area as outcrop exposures are very sparse (Ryan and Boehner, 1994). The reflection package does not outcrop on the southern margin of the Tatamagouche Syncline; however, horizon TA7 can be traced to the surface where it subcrops within the middle part of the mapped distribution of the Polly Brook Formation. Therefore, the correlation of this reflection package is uncertain. The Polly Brook Fm is laterally equivalent to the Joggins Fm (Ryan and Boehner, 1994) and the high amplitude reflection package between horizons TA6 and TA7 may represent a lateral transition from Polly Brook conglomerates to lithologies more typical of the Joggins Formation (Fig. 15).

Base Malagash Horizon (TA8)

In the eastern Tatamagouche Syncline, the TA6 horizon is identified at the occurrence of the first high amplitude reflection above the low energy zone (8-14 km markers on Line 32x, Fig. 17), consistent with its definition in the western Tatamagouche Syncline. Correlation of this horizon from profile to profile is dependent on recognition of similar seismic facies, since strike lines were not available during this study in some parts of the syncline. Up dip the TA6 horizon is truncated and over-stepped by the TA8 horizon (Fig. 17) forming an unconformity. Horizon TA8 on the WSW end of line 32x occurs in the same stratigraphic position as horizon TA6 as it is currently defined (i.e. at the top of the low energy zone). This represents a significant interval of erosion or non-deposition.

No drill holes intersect the TA8 horizon; surface relationships where used to identify the horizon. On River John (Malagash reference section), surface mapping (Ryan et al., 1988) shows the Malagash Formation to lie with angular discordance on the Boss Point Formation. There is a change in dip from less than 15^{o} in the Malagash Fm to more than 30^{o} in the Boss Point Fm across their common contact. Similarly, the TA8 horizon oversteps older strata to lie on reflections from the Boss Point Formation (Fig. 17). On this basis, the TA8 horizon is tentatively correlated with the base of the Malagash Fm. Support for this interpretation is provided by line C32y (not presented; discussed in Appendix). Jump correlation of the TA8 horizon from C32x (Fig. 17) to C32y was used to correlate horizon TA8 up-dip along line 32y with outcrop of the base of the Malagash Formation in the vicinity of the Scotsburn Anticline.

In the western part of the Tatamagouche Syncline (Line AN2 and westward), surface mapping (Ryan and Boehner, 1994) indicates that the Malagash Fm occurs in the shallow subsurface. Based on bedding attitudes, the apparent two-way travel time for horizon TA8 was calculated, and it is estimated to occur within the near-surface noise of the seismic reflection data (Fig. 15). Since the horizon cannot be mapped with confidence in this area, the horizon was mapped as a phantom horizon (a horizon traced on the seismic data where reflections may be lacking, but its location is assumed based on reflections above it or below it, or both).

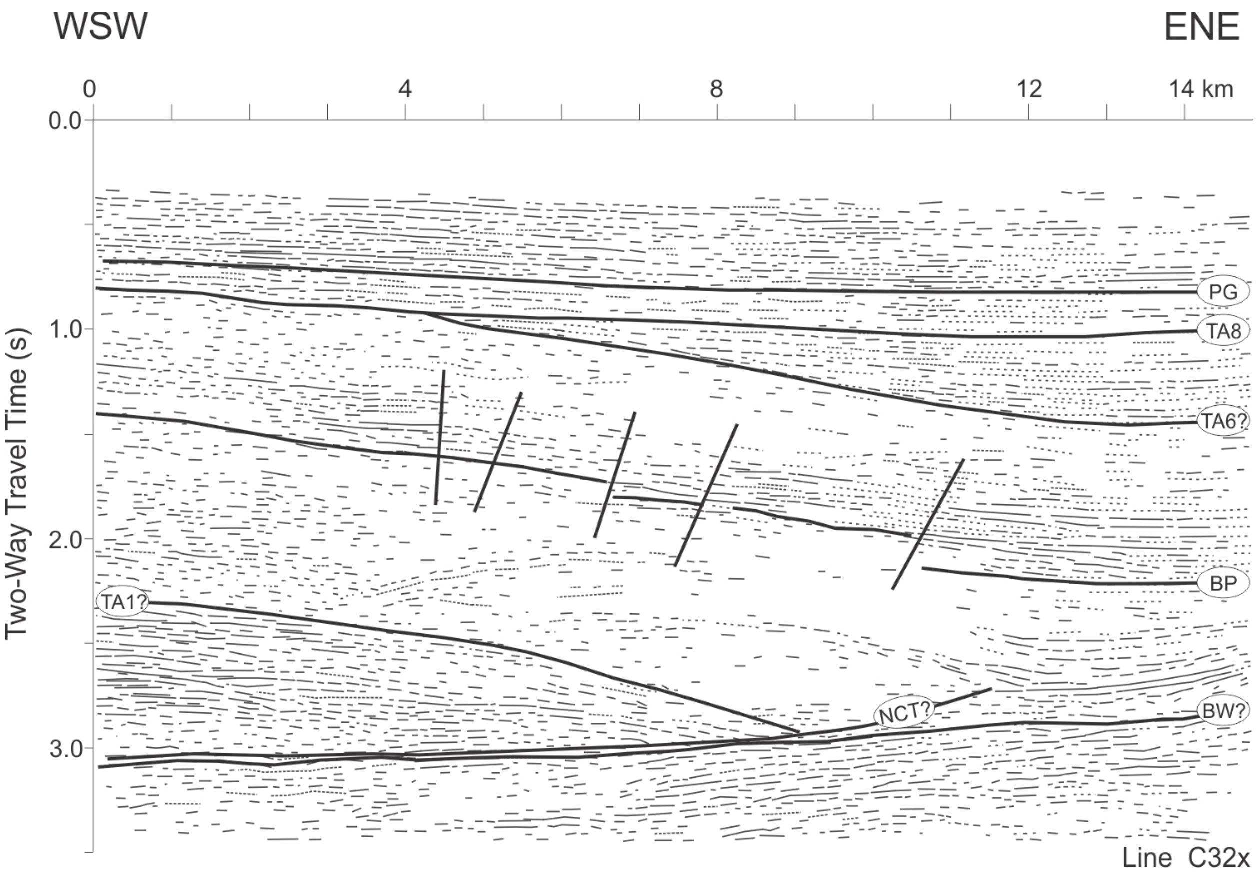


Figure 17: Line drawing of seismic profile C32x from the eastern Tatamagouche Syncline. See text for discussion.

<u>New Glasgow Formation</u>

In the eastern part of the Tatamagouche Syncline, a wedge of reflections occurs between horizons TA6 and TA8. Reflections within the wedge of strata show onlap onto horizon TA6. These reflections can be traced up-dip where they correlate with surface exposures of the fine-grained member of the New Glasgow Formation (Chandler, 1998). These reflections occur in a similar stratigraphic position to those between horizons TA6 and TA7 in figure 15, but the amplitudes are lower and the reflections are less continuous (Fig. 17) in the interpreted New Glasgow Formation (Chandler, 1998). In the absence of a high amplitude reflection package, and its interpreted top, Horizon TA7 was not interpreted in the eastern Tatamagouche Syncline, suggesting that the lithologies corresponding to the high amplitude reflections in the western part of the syncline were not deposited in the east.

Base Pictou Group Horizon (PG)

See "Regional Seismic Horizons" above.

Discussion of Seismic Horizons

The interpretation of seismic data in the Cumberland Basin has identified stratigraphic relationships which warrant further discussion: (a) a thick clastic unit of Windsor Group age in the Tatamagouche Syncline; (b) a reflection within the Falls and Millsville conglomerates that correlates with Windsor Group rocks; and (c) reflections in the western Tatamagouche Syncline that suggest the Joggins and/or Springhill Mines formations may be present there.

Windsor Clastic Unit

The Windsor Group clastic unit extends northward from the Cobequid Highlands to at least 6 km north of the Claremont Anticline (Fig. 6). A wedge of sediment interpreted as the Windsor clastic unit is observed on line C44x (see Appendix), which appears to extend northward to the southern limit of the Hastings Uplift. Therefore, the clastic unit underlies both the Tatamagouche and Wallace synclines, and possibly the Pugwash Syncline, as well (Fig. 5). Reflections on C44x suggest that it thins and possibly contains interbeds of Windsor Group evaporite rocks north of the Claremont Anticline.

Waldron et al. (2013) interpret seismic reflections in a similar stratigraphic position to the Windsor clastic unit as strata deposited in a salt withdrawal mini-basin. They proposed a model involving salt withdrawal and mini-basin development to explain the presence of the salt structures and synclines in the Cumberland Basin. The Windsor clastic unit extends north of the Claremont Anticline and underlies two potential mini-basins represented by the Wallace and Tatamagouche synclines. Further, structural dips data from the Wallace Station well indicate these strata are relatively flat (MacDonald, 1973) and may be less affected by salt tectonics (Waldron et al., 2013). Additional subsurface mapping is required to map the distribution of the clastic unit to assess its stratigraphic position and its relationship to salt diapirs and other structures in the eastern Cumberland Basin.

Based on seismic reflection character of horizon BW, the Windsor Group clastic unit is interpreted to lie on lower Windsor anhydrite and limestone (Major Cycle 1; Giles, 1981). Some reflections above horizon BW (at about 2.3 s near 6 km on figure 6) suggest that salt may have been present beneath the clastic unit and was subsequently squeezed out (consistent with the interpretation of Waldron et al., 2013). Reflections which convincingly suggest Windsor Group salt beneath the clastic unit occur on line AN4 (see Appendix), which is parallel to the Claremont Anticline (Fig. 5). The Wallace Station well (Fig. 7) encountered salt intervals in the upper part of the clastic unit.

Possible correlatives for the Windsor clastic unit include the Tennycape Formation (Giles, 1981), clastic rocks laterally equivalent to the Windsor Group included in the W4 and W5 units of McCutcheon (1981), and the Sydney River Formation (Boehner and Giles, 2008).

The clastic unit is overlain by high amplitude reflections which correlate with interbedded evaporite and clastic rocks typical of the middle part of the Windsor Group as identified in the Wallace Station well (Fig. 7). Waldron et al. (2013) correlate similar reflections to the Mabou Group. Additional subsurface mapping, and a re-evaluation of the Wallace Station well, is required to assess the stratigraphic assignment of these strata.

Falls Formation and Millsville Conglomerate

The Falls Formation and the overlying Millsville Conglomerate occur stratigraphically above fine grained redbeds (Donohoe and Wallace, 1982) assigned to the West Branch River John formation (Keppie, 2014), which contain Visean spores (Ryan and Boehner, 1990; 1994). The Millsville Conglomerate is unconformably (Chandler et al., 1994) overlain by the Boss Point Formation (Bashkirian). Therefore, the age of the Falls and Millsville conglomerates is constrained between the Visean and the Bashkirian (Fig. 2). Keppie (2014) shows the Millsville conglomerate to rest unconformably on the Falls Formation and older rocks.

The seismic observations presented in this report are consistent with the stratigraphic relationships described above. Reflections correlated with the Boss Point Formation overlie strata assigned to the Millsville conglomerate (Fig. 16). In addition, a reflection from the lower part of the Millsville Conglomerate (TA4) correlates with interpreted Windsor Group in Northumberland Strait. This suggests that the Millsville Conglomerate is Visean in age, at least in part, and is correlative with the Windsor Group. Based on surface geological mapping, the Falls Formation lies on redbeds with Visean spores (Ryan and Boehner, 1990; 1994; Keppie, 2014), which is consistent with the Windsor Group equivalent interpretation of the Millsville Conglomerate. Additional work is warranted to confirm these stratigraphic relationships.

The Falls, West Branch River John, and Mackay Brook formations overlie horizon TA1 (Figs. 13 and 16), which is interpreted as the top of Fountain Lake Group (FLG) volcanic rocks (Durling, 1996). Line AN20 (Fig. 9) shows the Windsor Group clastic unit (reflection poor zone below horizon TA3) overlying sub-horizontal high-amplitude reflections above the BW horizon (2.5 s depth; between 2 and 7 km; Fig. 9). The high amplitude reflections between horizons BW and TA3 are juxtaposed the faulted, north-dipping, high-amplitude reflections below horizon TA1 on the south end of the seismic line. These relationships may infer that the Falls Formation, and potentially the Millsville Conglomerate, as well, could be lateral equivalents of the Windsor Group clastic unit. These relationships may support an alluvial fan interpretation for the Windsor clastic unit.

Polly Brook Formation

The stratigraphy developed for the Cumberland Basin by Ryan and Boehner (1994) shows the Polly Brook Formation to be: (1) underlain by the Boss Point Formation, (2) laterally equivalent to the Joggins Formation and (3) overlain by the Springhill Mines Formation. The present study shows that, in the Tatamagouche and Athol Synclines, reflections correlated with the Boss Point Formation are overlain by low amplitude discontinuous reflections (low energy zone). In the Athol Syncline, low energy reflections overlie the Boss Point Formation and are correlated with surface outcrop of the non-coal-bearing portion of the lower part of the Joggins Formation (Fig. 12). In the Tatamagouche Syncline, similar low energy reflections overlie the Boss Point Formation (Fig. 15). The similarity of seismic character and stratigraphic position suggests the two reflection packages could be equivalent. Therefore, the low energy reflections in the Tatamagouche Syncline, which overlie the Boss Point reflection package, may be correlative with the lower part of the Joggins Formation. The low energy reflections in figure 15 can be traced southward to outcrop where they are correlated with the Polly Brook Formation. To the north, the low energy zone correlates with the Boss Point Formation; note that outcrop is sparse in this area. The rocks imaged between horizons TA6 and TA7 correlate with the upper part of the Boss Point Formation in the north and pinch-out within exposures of the Polly Brook Formation in the south. Given that the Polly Brook Formation is laterally equivalent to the Joggins Formation and overlain by the Springhill Mines Formation, the Springhill Mines Formation may be present, albeit thin in the Tatamagouche Syncline, represented by the high amplitude reflections occurring between horizons TA6 and TA7. Note that the high amplitude reflections occur only near the middle part of the syncline, which may have been a paleogeographic low during deposition.

STRUCTURAL GEOLOGY

Time structure maps were made for each of the regional horizons interpreted for this report (BW, BP, and PG; Table 2). The maps show the distribution of each horizon in the Cumberland Basin and highlight structural features that provide insight to the geological development of the basin. The map of each horizon is discussed in turn below.

Horizon BW Time Structure

The BW horizon was identified and mapped beneath all the major synclines in the Cumberland Basin (Fig. 18); however, it was not identified over the Hastings Uplift (Howie, 1986). The depth of the BW horizon ranges widely from 400 ms (600 m) to 3200 ms (7600 m). Offshore contours in figure 18 are taken from the base Windsor Group map of Durling and Marillier (1993a).

The BW horizon is locally faulted, and the fault patterns are different from those recognized from surface geological mapping (Fig. 1). Basement involved faults were recognized north and south of the Hastings Uplift and north and south of the Scotsburn Anticline. The structures in these two areas are discussed more fully below.

Scotsburn Anticline

In the Caribou River area (Fig. 18), the BW horizon displays a seismic character consistent with other parts of the Cumberland Basin and very similar to the base Windsor horizon identified in the Gulf of St. Lawrence (Durling and Marillier, 1993a and 1993b). South of Caribou River, the BW horizon can be traced up-dip toward the Scotsburn No.2 well, where it decreases in amplitude and fades into the low energy seismic facies of the Falls and Millsville conglomerates (Fig. 16). The limestone and evaporite rocks of the Windsor Group appear to be transitional with the clastic rocks of the Falls and Millsville conglomerates, as discussed above. This transition is observed approximately between the 1200 and 400 ms contours (Fig. 18).

The BW horizon is affected by a number of northeast striking faults in the Scotsburn Anticline area (Fig. 18). At the northern limit of the Scotsburn Anticline west of Caribou River, a south dipping, reverse fault is observed at the NW end of line C32y (see Fig. 5 for location). There are only two localities where this fault is clearly imaged and the orientation of the fault was inferred from the faults affecting the TA1 horizon (Fig. 14). High amplitude reflections from the FLG are clearly imaged in the hanging wall and are interpreted to lie with fault contact on the BW horizon. The fault heave appears to be small (estimated at a few hundred metres) but the throw is interpreted to be greater than 600 ms (1200 m).

Several small scale thrust faults occur southeast of Caribou River on the north limb of the Scotsburn Anticline (see description of lines AN10, AN17 in Appendix). The faults are closely spaced and are mapped as a single fault trace on figure 18. These low angle reverse faults show

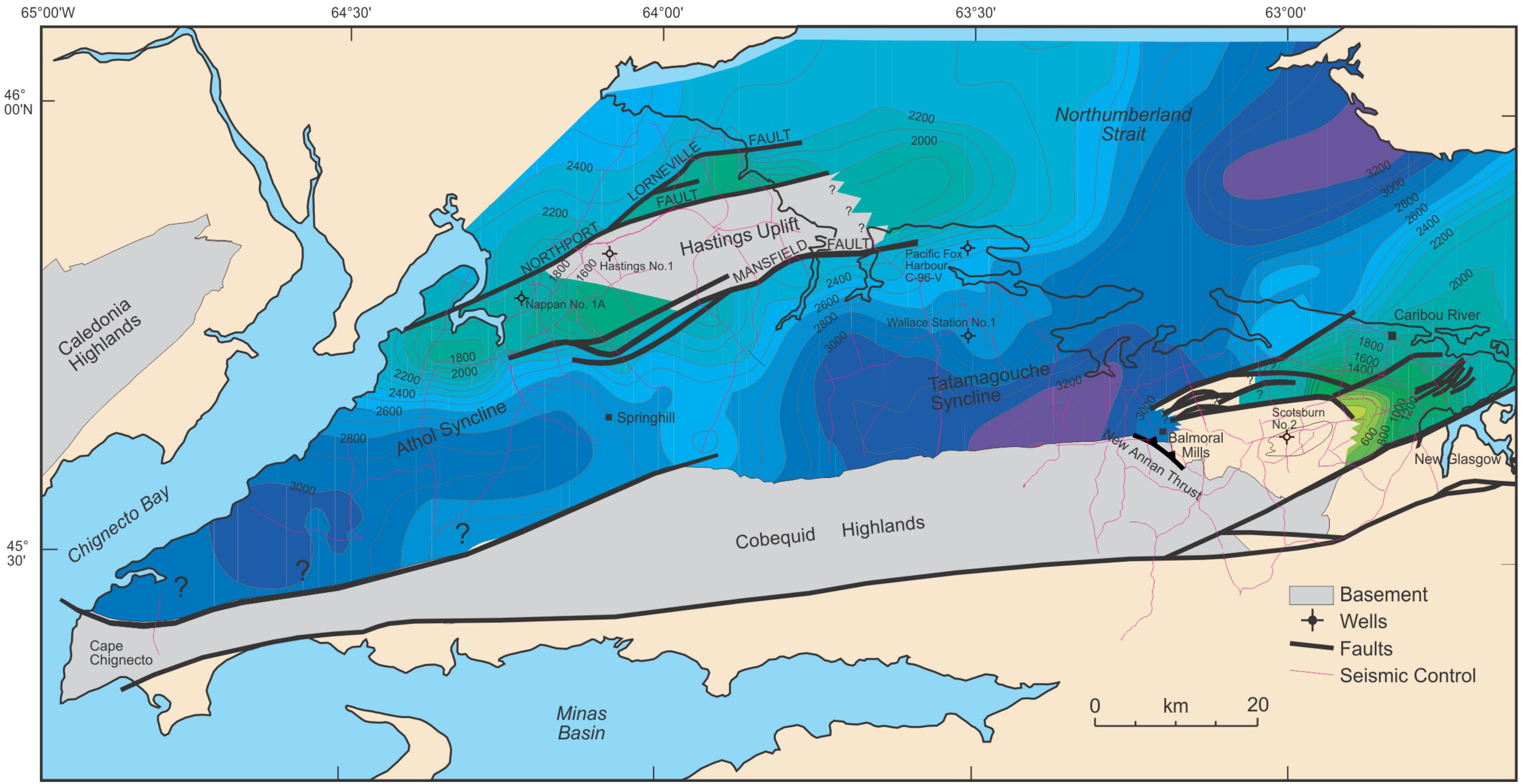


Figure 18: Time structure contours on the BW horizon. Contour interval 100 ms. See text for discussion.

south-over-north displacement and offset of up to 100 ms (200 m). The deformation appears to be limited to the BW horizon and does not affect strata above Windsor Group evaporite rocks.

The timing of fault movement is interpreted to be variable in the area. The youngest fault movement locally offsets the Boss Point Formation (Bashkirian); however, the Boss Point Formation oversteps many faults, suggesting the Boss Point Formation was deposited synchronous with the deformation.

A major fault is mapped on the southeastern limb of the Scotsburn Anticline and marks the southeast limit of the BW horizon in the area northwest of the town of New Glasgow. This northwest-dipping structure separates FLG and thick Falls and Millsville conglomerates to the northwest of the fault (thickness up to 2.0 s two-way time) from thin Carboniferous cover to the southeast (thickness up to 1.0 s two-way time). It is interpreted as the northeast extension of the Millsville Fault (Pe-Piper and Piper, 2002).

Hastings Uplift

Northeasterly striking faults bound the Hastings Uplift (Fig. 18). The northern boundary of the Hastings Uplift is marked by a structure identified as the Northport Fault; it separates reflections interpreted as top of basement (horizon AM1 on Fig. 10) from interpreted Windsor Group condensed section (horizon “BW?” on Fig. 10). The Windsor condensed section occurs between 8 km and 12 km along the seismic line and is represented by 4-6 high amplitude reflections underlain by incoherent reflections interpreted as basement. The absence of a typical BW event below the condensed section is key to this interpretation. Other seismic lines north of the Hastings Uplift show that reflections above horizon AM3 rest on salt, which is in turn underlain by the BW horizon. Also, note that reflections in the lower part of the “BW?” reflection package are higher amplitude than reflections interpreted above AM3 implying different stratigraphy. The condensed section appears to lack the thick salt interval between horizons BW and AM3 in figure 10.

The Lorneville Fault separates the Windsor condensed section on the south side of the fault from well-defined BW horizon and an overlying salt layer of variable thickness to the north (Fig. 10). Based on the distribution of horizons AM1 and BW, and the inferred strike of the Lorneville and Northport faults, the former appears to be a splay of the latter. The latest sense of movement on the Lorneville Fault is interpreted to be reverse (Fig. 10).

Some constraints for timing of fault movement are given by the distribution of the Windsor Group, by deformation recorded in the strata adjacent to the faults, and by unconformities in the area. The Windsor Group is not present in the Hastings No.1 well and is interpreted to thin onto the Hastings Uplift (see description of line G4 in the Appendix), suggesting the Windsor Group may not have been deposited, or was eroded, on the Hastings Uplift. The Lorneville and Northport faults are over stepped by the Boss Point Formation, which is not offset by these faults, but may be folded. Therefore, the faults pre-date deposition of the Boss Point Formation and post-date depositions of the Windsor Group. This limits the time of deformation to between middle Visean to Bashkirian (similar age range to deposition of Falls and Millsville conglomerates).

The southern boundary of the Hastings Uplift (Fig. 18) appears to correspond to several unnamed fault splays of a structure identified as the Mansfield Fault (Fig. 19). The fault splays are interpreted as north-dipping, basement-involved structures, in contrast to the south dipping Beckwith Fault that affects younger Carboniferous rocks (Fig. 19). The offset on the Mansfield Fault is greatest in the central portion of the Hastings Uplift (Fig. 18) and offset decreases to the northeast and

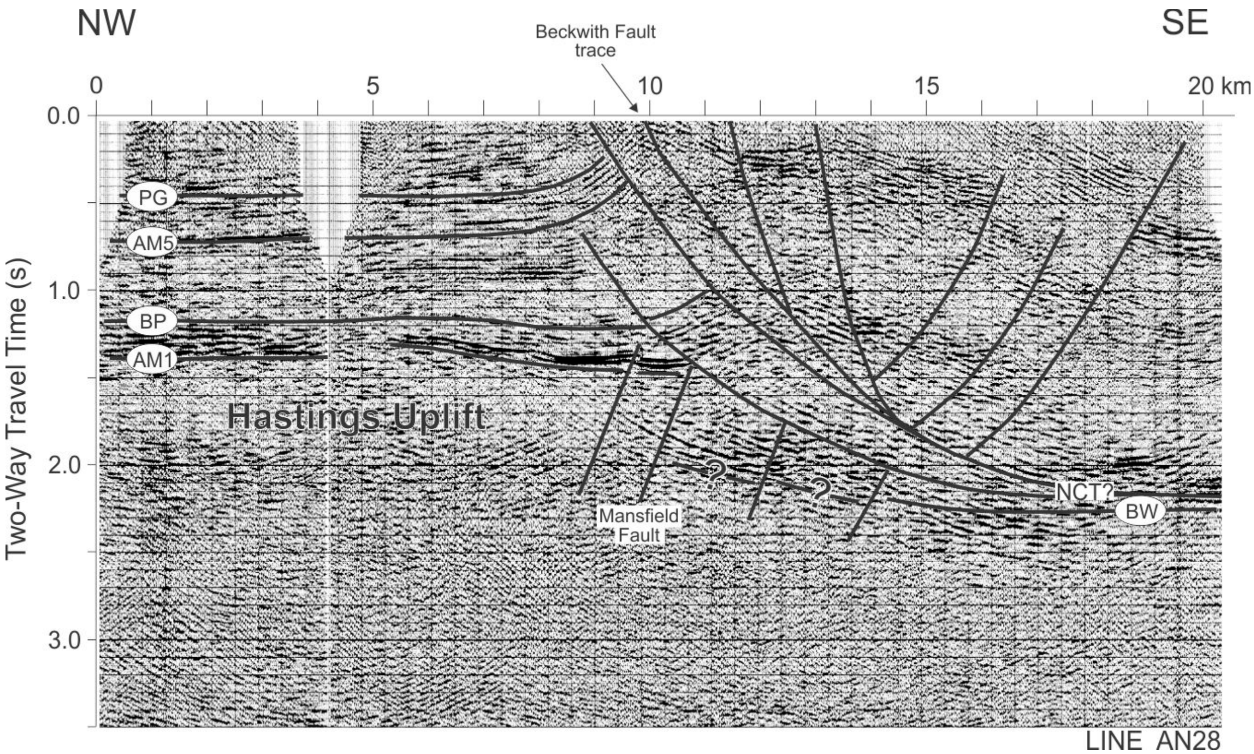


Figure 19: Interpreted seismic profile from the southern margin of the Hastings Uplift. The southern half of the profile crosses the deformed zone south of the Beckwith Fault. The seismic shows that this area is strongly deformed and any seismic correlations may be speculative. The northern half of the profile crosses the less deformed Amherst Syncline and Hastings Uplift. Seismic data is subject to licence agreement with Repsol Canada.

southwest. The Mansfield Fault is not mapped offshore in the Northumberland Strait (Durling and Marillier, 1993a; Atkinson et al., 2019). To the southwest, the fault appears to transition to a basement-involved fold in the area north of the Athol Syncline, where the uplift persists as a positive feature (Fig. 18) in the absence of observed faults (Fig. 12). The BW horizon is absent over the Hastings Uplift in the northeast, but is observed over the uplift in the southwest (Fig. 18). Waldron and Rygel (2005) interpret the north limb of the Athol Syncline to be supported by a salt structure in this area (see their figure 2A), whereas the regional grid of seismic lines interpreted for this report suggest it is supported by the southwestern extension of the Hastings Uplift (Fig. 12). Interpretations of lines G4 and G14 (see Appendix) confirm a shallow depth for the BW horizon, as opposed to the greater depth inferred by the salt structure interpretation of Waldron and Rygel (2005). Further mapping is warranted to resolve the differences in interpretation.

Horizon BP Time Structure

The BP horizon structure map varies in depth from 0 to 2600 ms two-way time (6000 m) and it is recognized in all of the major synclines in the Cumberland Basin (Fig. 20). A comparison of the reflections mapped during this study with reflections mapped by Waldron and Rygel (2005) in the Athol Syncline shows that their base Boss Point Formation stratigraphic boundary coincides with the same reflections used to map the horizon BP in this study. Similarly, the base Boss Point Formation mapped by Waldron et al. (2013) in the western Tatamagouche Syncline is the same as horizon BP. However, in the eastern Tatamagouche Syncline the base Boss Point Formation boundary identified by Waldron et al. (2013) is approximately 300 ms shallower than horizon BP mapped in this study. They mapped the upper boundary of a high amplitude reflection interval, whereas in this study, horizon BP correlates with a reflection near the base of the same high amplitude reflection package, consistent with the definition of the BP horizon elsewhere in the Cumberland Basin. The emphasis in the present study was to identify seismic facies that could be mapped throughout the basin. Further, the BP horizon mapped in this study is consistent with mapping in the Gulf of St. Lawrence (Atkinson et al., 2019), where the top of the Mabou Group (base of the Boss Point Formation) is overlain by higher amplitude reflections. The differences in seismic interpretation may be attributed to the location, distribution and quality of seismic data used in the different studies. Since this report presents a review of seismic mapping completed in 1996, further work is required to reconcile the differences in stratigraphic interpretation.

The main structural features delineated by the BP horizon structure map include the broad low relief area over the Hastings Uplift, the Beckwith Fault, and the structurally complex area between the Beckwith Fault and the Cobequid Highlands. This structurally complex area south of the Beckwith Fault includes the Athol and Tatamagouche synclines (as well as several smaller synclines such as the Black River, Pugwash and Wallace synclines), and several salt diapirs. The structural character of the Cumberland Basin is significantly different north and south of the Beckwith Fault (Fig. 20).

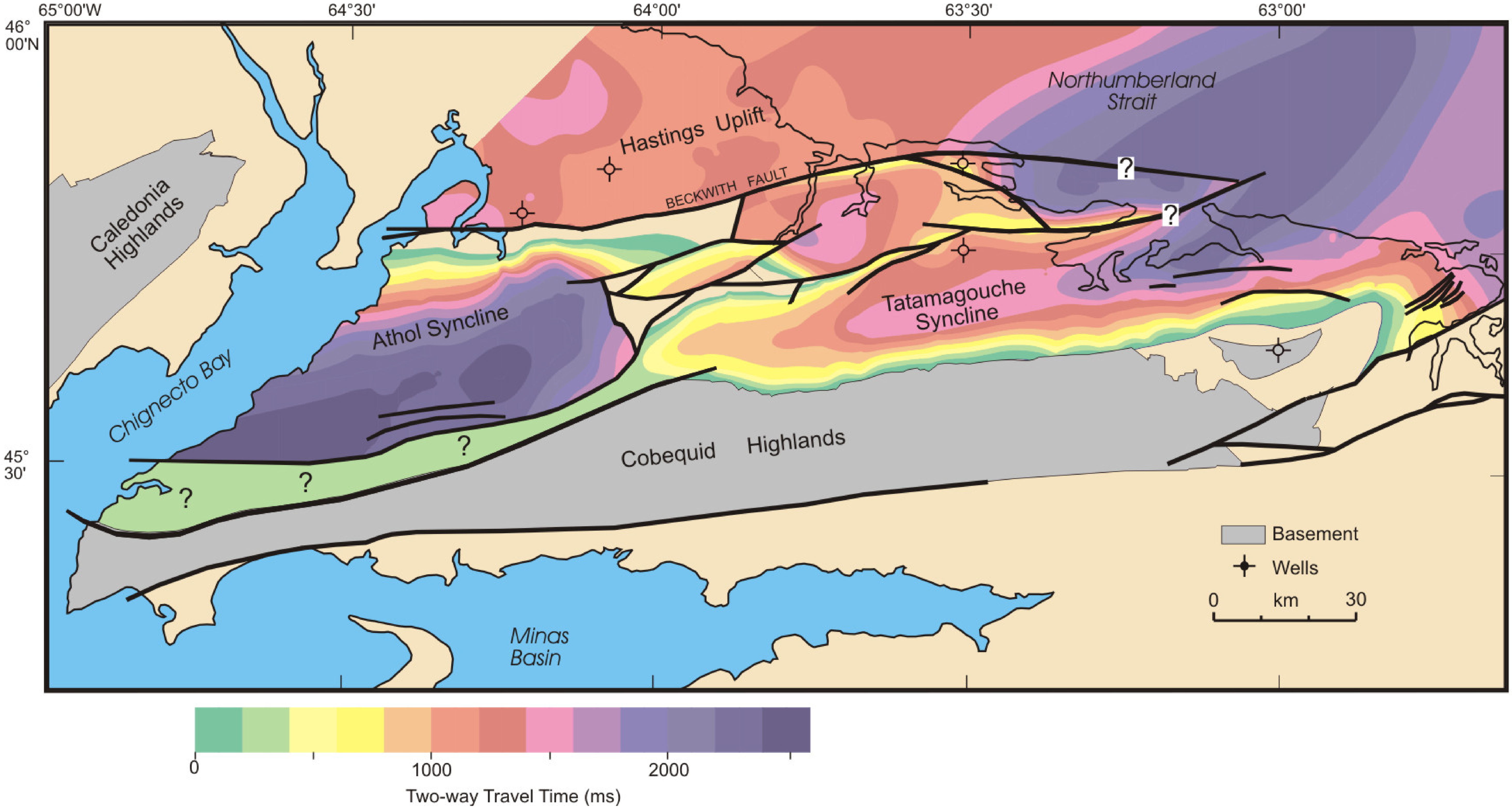


Figure 20: Time structure contours on the BP horizon. Contour interval 200 ms. See text for discussion.

Between the Beckwith Fault and the Tatamagouche Syncline (Fig. 20), the fault patterns from seismic mapping closely resemble those identified from surface mapping (Fig. 1). The structures identified as anticlines through surface mapping (i.e. Claremont and Minudie anticlines) appear to represent fault zones on the seismic reflection profiles (Fig. 6), which have been modified by evaporite deformation. In this sense, these features are evaporite structures (Waldron et al., 2013).

The Claremont anticline separates the Tatamagouche and Wallace synclines (Figs. 1 and 6). The anticline is roughly vertical and there appears to be no preferred offset of strata across it. It is, therefore, a candidate for a strike-slip fault (Sylvester, 1988). The Claremont structure does not appear to be basement-involved as suggested by Howie (1986), since the faults affecting the Claremont structure do not affect basal Windsor Group and older strata (Figs. 18 and 6).

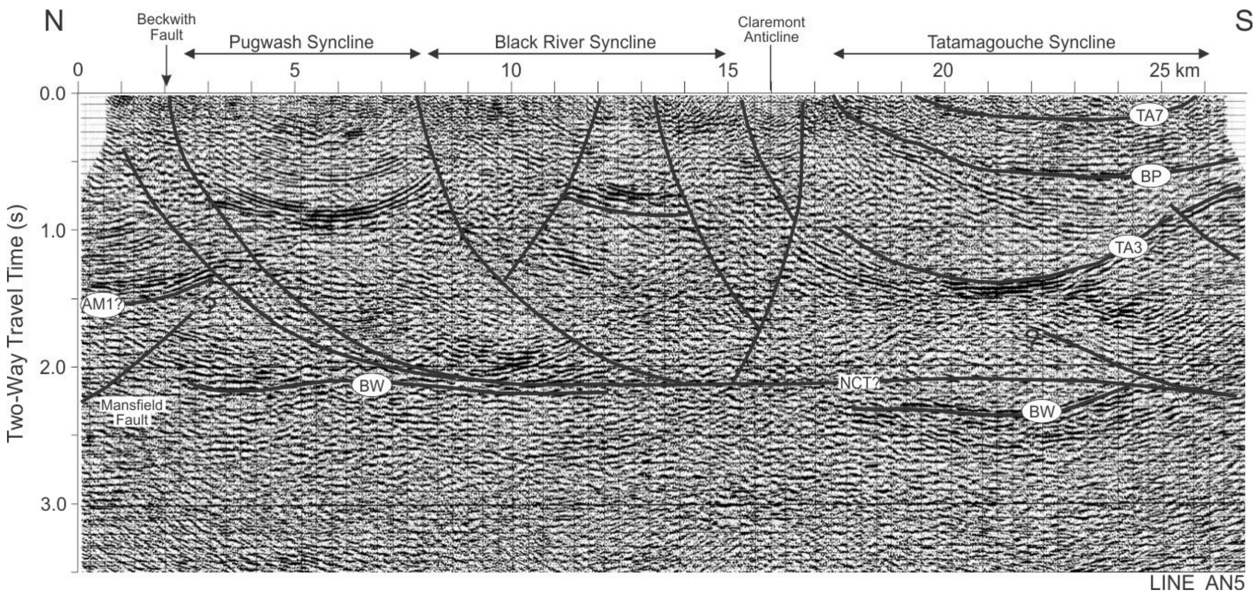


Figure 21: Interpreted seismic reflection profile across the deformed zone comprising the Pugwash, Black River and western Tatamagouche synclines. See text for discussion. Seismic data is subject to licence agreement with Repsol Canada.

The Beckwith Fault defines a major structural boundary in the Cumberland Basin. It is a moderately south dipping (about 40º in figure 19) reverse or thrust fault (Fig. 21). Vertical offset on the BP horizon on the western portion of the fault is about 1400 ms (2800 m), down to the north (Fig. 20). The Beckwith Fault merges with the Minudie Anticline (Fig. 1) in the western part of its trace.

The Minudie structure is a salt-cored fold, overturned to the north (Howie, 1986). The Beckwith Fault, being a southerly dipping structure, likely follows the south-dipping limb of the Minudie Anticline. J. Calder (N.S. Department of Natural Resources, pers. comm., 1995) noted that the coal horizons that outcrop on the south limb of the Minudie anticline (Figs. 1 and 12) are not associated with a basin margin facies. These rocks may have been thrust out of the basin along the Beckwith Fault. Cross sections through the Minudie structure (Howie, 1986) are consistent with north directed thrusting.

Horizon PG Time Structure

Horizon PG was mapped only in the Tatamagouche and Amherst synclines (Fig. 22). The horizon is generally mildly deformed, being affected by open folds. Locally, moderate to severe deformation is noted, especially deformation associated with the Beckwith Fault and the Claremont Anticline. This horizon is clearly much less deformed than the older strata suggesting that the main deformation in the Cumberland Basin largely pre-dates the Pictou Group.

North of the Beckwith Fault, the PG horizon is sub-horizontal in the northeast and is folded upward in the southwest. The syncline north of the Hastings No.1 well is only partly imaged on seismic and the contours in the northwestern part of the map are inferred based on surface geological maps in the Sackville area (St. Peter and Johnson, 2009). Southwest of the Hastings well, the PG horizon rises to surface and there is a divergence between the BP and PG horizons (Fig. 19). The divergence is interpreted as a depositional wedge, but the wedge may have a structural origin. If the wedge is depositional in origin, it may provide evidence for timing on the development of the Beckwith/Minudie structure. Additional work is warranted to study the nature of the wedge and its relationship to the Beckwith Fault/Minudie structure.

Discussion of Cumberland Basin Structure

The subsurface geometry of the Hastings Uplift (Howie, 1986) is mapped in this report (Fig. 18) and highlights that the Windsor Group is absent beneath the northeastern part of the uplift. Interpreted Windsor Group reflections decrease in amplitude from southwest (Minudie Anticline area; Fig.1) to northeast onto the Hastings Uplift as indicated on seismic line G4 (see description in Appendix; see Fig. 5 for location). These reflections suggest that at least part of this basement complex was a positive feature during the Visean. These observations suggest a complex geometry for the Cumberland Basin where some parts of the basin accommodated deposition of Windsor Group strata and other areas none. Further evidence is provided by the Falls and Millsville formations, which are likely correlatives of the Windsor Group, indicating coarse clastic deposition may have occurred in some areas whilst evaporite deposition occurred in others.

Waldron et al. (2013) postulate that part of the Cumberland Basin developed in a graben between the Cobequid Highlands and the Beckwith Fault. Based on the results presented in this report, the northern boundary of the graben is a deep basement-involved structure, herein named

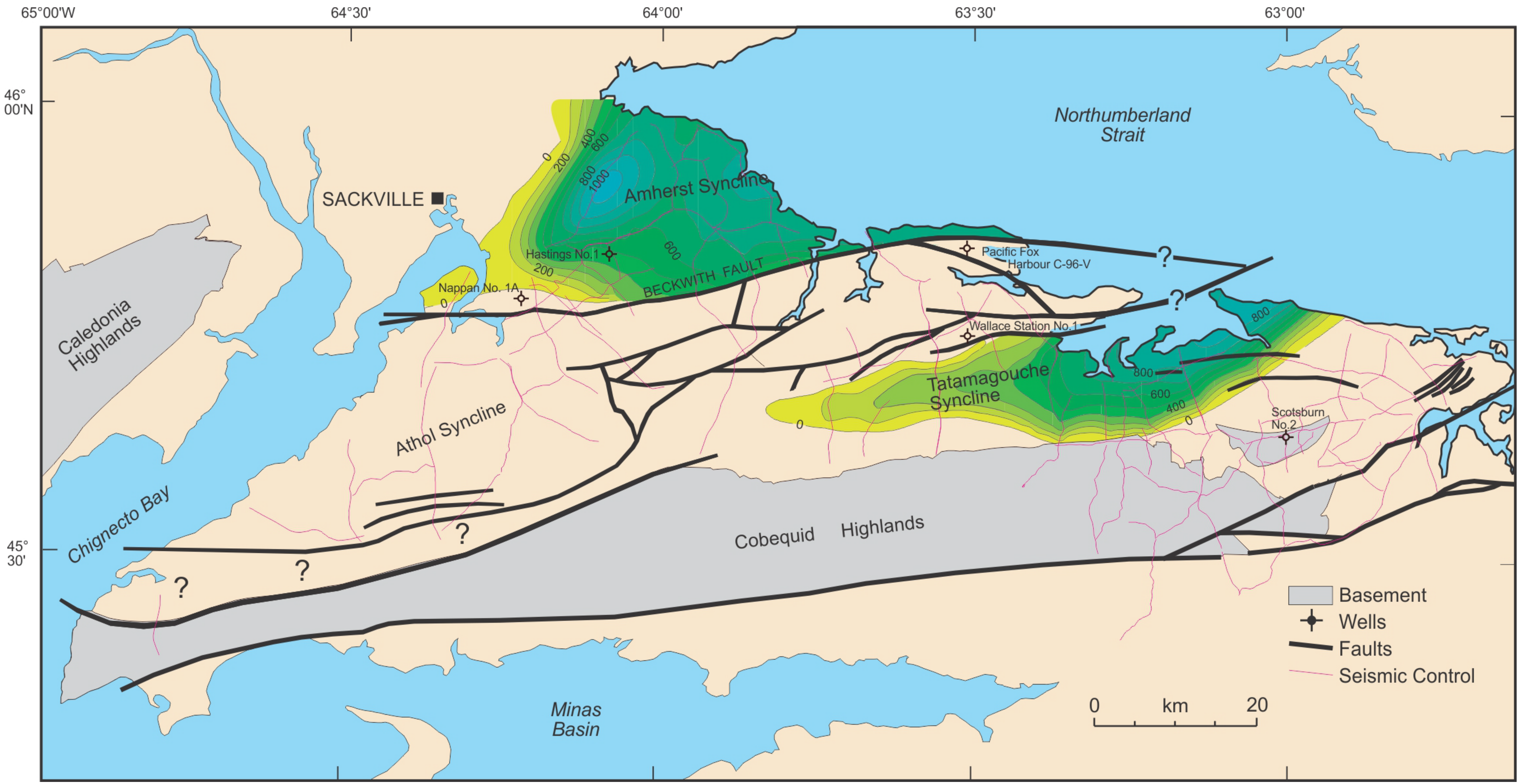


Figure 22: Time structure map on the PG horizon. Contour interval is 100 ms. See text for discussion.

the Mansfield Fault. This structure is poorly imaged, but seismic data suggest that it may be represented by more than one fault (Figs. 19 and 21). The boundary between the Hastings uplift and the deeper parts of the Cumberland Basin appears to be a north dipping, basement-involved structure that is distinct from the south dipping Beckwith Fault.

The timing of movement on the Mansfield Fault is not clear from the available seismic data. The timing of movement on this fault may be similar to the timing of faults on the northern margin of the Hastings Uplift, which predate deposition of the Boss Point Formation (pre-Bashkirian). As such, the timing does support the development of a graben that may have accommodated deposition of thick Windsor Group evaporite in the Cumberland Basin (Waldron et al., 2013).

Southern Margin of the Cumberland Basin

Very few seismic profiles in the Cumberland Basin cross the boundary between the Cobequid Highlands and the Cumberland Basin. Those seismic profiles that do cross this boundary are located in the eastern part of the basin and provide some insight into the structural relationships in that area. Piper et al. (1996) interpret the presence of thrust faults in the area west and southwest of the Scotsburn No.2 well (Fig. 18) on the basis of seismic reflection data and geological field evidence. They conclude that Precambrian, Silurian and probable lower Carboniferous rocks occur in the hanging wall of a thrust fault that they describe as the New Annan thrust (Piper and Pe-Piper, 2001). Field mapping (MacHattie and White, 2014) confirms that Precambrian and Silurian rocks occur at surface and seismic mapping by Durling (1996) indicates that the Fountain Lake Group (horizon TA1) underlies these rocks. Up to 5 km of horizontal displacement can be demonstrated where basement rocks were thrust northward in the hanging wall to overlie the Fountain Lake Group (horizon TA1) in the footwall (Fig. 14). Based on stratigraphic relationships, the age of thrusting was likely Late Tournaisian to Early Visean (Piper and Pe-Piper, 2001).

The overthrust relationships (Piper and Pe-Piper, 2001) are interpreted on seismic line C25 (Fig. 23). Stratigraphic control for part of this line is provided by borehole TF-86-1, in addition to field relationships. The stratigraphic boundaries identified in the borehole [B = Balfron (47.8-144 m), BP = Boss Point (144-338 m) and C = Claremont (338-785.5 m) formations (Ryan, 1986)] were plotted on the seismic line (Fig. 23), which is located about 700 m west of the borehole at its closest point (Shot Point 930). The Magdalen Basin velocity function (Durling and Marillier, 1993b) was used for depth conversion to two-way time. The base of the Balfron Formation in the well occurs within the surface seismic noise and it is not clear which reflection corresponds to this contact. The PG horizon was interpreted to coincide with the unconformity that truncates horizon TA8 (Fig. 23) in accordance with surface geological mapping. The base of the Boss Point Formation plots on the seismic profile 80 ms above a doublet reflection comprising continuous to discontinuous, high amplitude reflections. This reflection doublet is interpreted as the same reflection horizon that is correlated with horizon BP in figure 9. The Falls and Millsville conglomerates (identified as Claremont Formation in the borehole) correspond to a low energy, weakly stratified seismic interval. There is an apparent angular discordance between the reflections above and below the reflection doublet (BP horizon). Reflections below dip less steeply than those above such that the reflection doublet lies on increasingly older strata toward the basin centre. In other words, the top of the Falls and Millsville conglomerates is an erosional surface where the Boss Point Formation cuts down-section basin ward and toward the north. Note that up dip (Fig. 23) the interpreted reflections from the Falls and Millsville conglomerates are truncated by the New Annan thrust tectonite unit and the Cobequid northern margin fault (Piper and Pe-Piper, 2001).

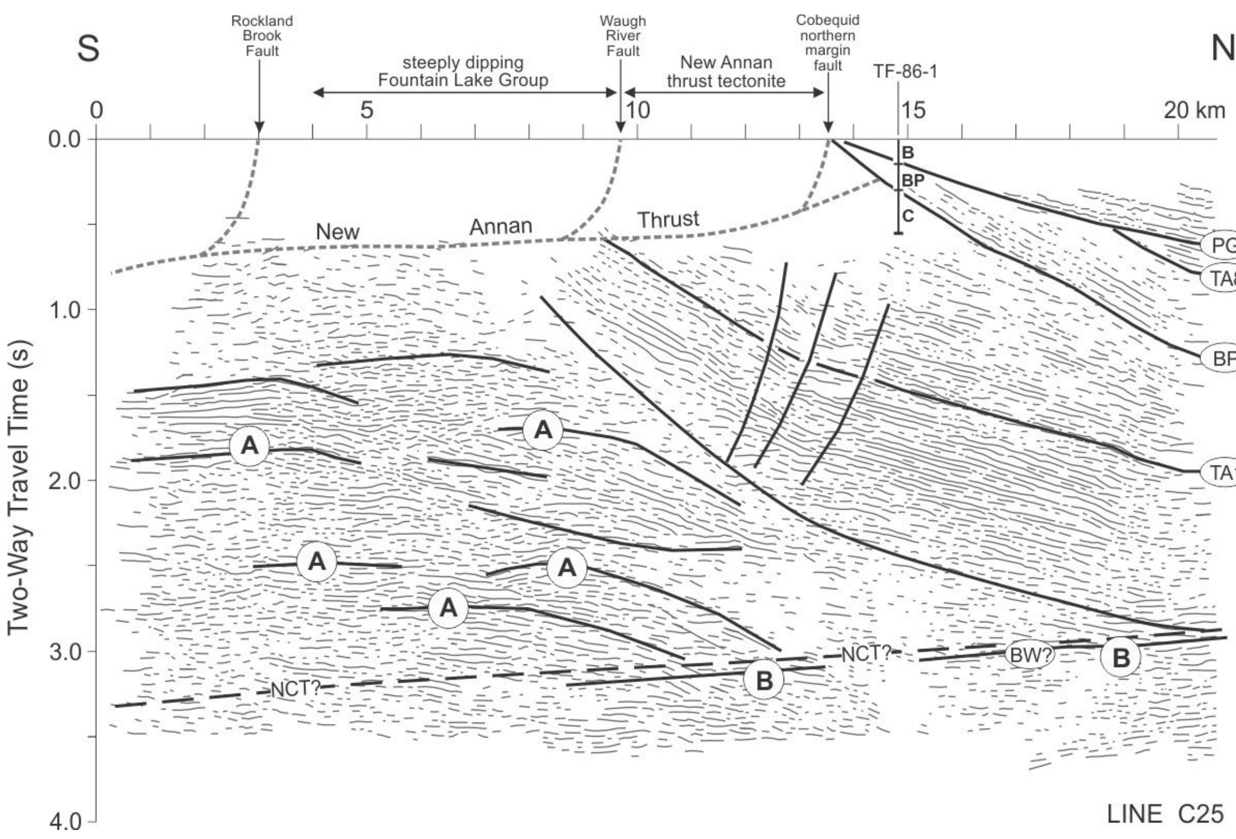


Figure 23: Line drawing of seismic profile C25 from the Cobequid Highlands and the southern margin of the Cumberland Basin. The New Annan thrust is redrawn from Piper and Pe-Piper (2001) to honour borehole TF-86-1. See text for discussion.

Figure 23 is representative of other seismic profiles in this area that cross the southern margin of the Cumberland Basin, which display the following features (Fig. 23): north-dipping Cumberland Basin strata (horizons BP, TA8 and PG), north dipping FLG reflections (TA1), horizontal to north dipping reflections of possible FLG affinity (reflections "A"), and sub-horizontal to gently south-dipping reflections (reflections “B”). The reflections labelled “A” in figure 23 form an antiformal shape reminiscent of a duplex thrust system (McClay, 1992). The sub-horizontal reflections labelled “B” are a probable southerly extension of the BW horizon, which dips uniformly toward the Cobequid Highlands (Fig. 18). These relationships place the Windsor Group structurally below the older Fountain Lake Group and suggest that the rocks above the BW horizon in figure 23 form the hanging wall of a major thrust that carried much of the eastern Cobequid Highlands northward.

Waldron et al. (2013) described a structure that they identify as the North Cobequid thrust (NCT) where the Windsor Group appears to extend beneath reflections mapped as Fountain Lake Group (see Waldron et al., 2013 figures 6 and 8). Durling (1996) described similar relationships. Seismic images of the southern margin of the Tatamagouche Syncline (Fig. 23) indicate overthrust relationships with horizontal shortening ranging from approximately 6 km (Waldron et al., 2013 Fig. 6E) to potentially 10 km (reflections “B” may be traced southerly to kilometer marker 9; Fig. 23).

The reflection patterns on figure 23 are analogous to structures observed in contractional settings that develop at mountain fronts (Vann et al., 1986). Mountain fronts typically involve a basinward dipping monocline (horizon TA1, for example) overlying complexly folded and thrust faulted mass of rock (reflections “A”) that is uplifted relative to the adjacent basin floor (BW horizon). Although the reflections observed in figure 23 may be interpreted as a mountain front, few thrust faults have been interpreted in this area, with the exception of the New Annan Thrust (Piper and Pe-Piper, 2001). Vann et al. (1986) describe four potential models to explain the range of deformation mechanisms at mountain fronts. Two options (sub-molasse detachments and backthusts) may be applicable to the northern margin of the eastern Cobequid Highlands.

In the backthrust model, the strata above the detachment fault are peeled upward to form a foreland dipping monocline as the deformed rocks wedge beneath and delaminate the foreland basin strata. The base of the monocline is a thrust (roof thrust), but of opposite vergence to the basal detachment thrust. Some thrust faults have been recognized in the Cobequid Highlands (Piper and Pe-Piper, 2001) that may be related to roof thrust development. A possible location for the roof thrust is at the base of the Boss Point Formation or within the Falls and Millsville conglomerate units. To date, no evidence for a roof thrust has been documented. However, tight folds on the West Branch River John immediately south of the angular unconformity at the base of the Millsville conglomerate could be evidence for a roof thrust fault.

In the sub-molasse detachment model, the detachment fault that carries the deformed rocks in the hanging wall continues basinward beneath undeformed basin strata (molasse). The undeformed basin strata and deformed hinterland rocks are carried together on the basal detachment fault that emerges some distance from the monocline in the form of faults and folds in the foreland. The incompetent Windsor Group salt provides an excellent weak layer within which a detachment fault may develop, and the Beckwith Fault may represent an emergent thrust fault. Waldron et al.

(2013) propose a model where the Tatamagouche Syncline is carried together with the Cobequid Highlands on the North Cobequid Thrust (NCT). Movement on the NCT is transferred to contractional deformation in the salt walls and diapirs. Alternatively, motion on the NCT could be carried northward to emerge as a thrust fault at the Beckwith Fault (Fig. 21).

The NCT is interpreted to place rocks of the Fountain Lake Group in the hanging wall upon Windsor Group strata in the foot wall (see figure 6 of Waldron et al., 2013). Based on their work, the NCT is interpreted in this report on lines AN1 and AN2 (figures 15 and 6, respectively), although observed reflection geometries suggest that the NCT may be interpreted on nearly all seismic profiles on the southern margin of the basin. Both seismic lines suggest that the whole of the Cumberland Basin fill, as well as the Fountain Lake Group, are in the hanging wall of the NCT. Further west, line AN5 (Fig. 21) spans the width of the Cumberland Basin, where the NCT is interpreted to continue beneath the Cumberland Basin within the Windsor Group evaporite as a detachment, which emerges as the Beckwith Fault.

The Beckwith Fault is a major southerly dipping structure that forms the boundary between the gently folded Amherst syncline and the complex structure and stratigraphy of the Cumberland Basin. The fault is downthrown to the north where a relatively thick succession of Pictou Group is preserved (approximately 800 m in the Hastings well; Fig. 3); the Pictou Group has been largely eroded south of the Beckwith Fault, except for the core of the Tatamagouche Syncline and isolated outliers in the Wallace and Pugwash synclines (Fig. 5). Strata of the Pictou and Cumberland groups are folded upward on the north side of the fault producing an apparent drag-fold (Fig. 19). In aggregate these relationships suggest that the Beckwith Fault is the product of significant contractional deformation, and potentially may be a major thrust fault. As such, the Beckwith Fault may be an emergent thrust (Vann et al., 1986) linked to the North Cobequid thrust (Waldron et al. 2013).

The preceding discussion describes the Beckwith Fault as it relates to the Tatamagouche and adjacent synclines in the eastern Cumberland Basin. However, a detachment can be inferred beneath the Athol Syncline based on its relationship to the Minudie Anticline, the western extension of the Beckwith Fault. Howie (1986) interprets the Minudie Anticline as a salt-cored structure that is overthrust to the north, which is consistent with the interpretation of seismic line G12 (see Appendix). The Minudie structure may be linked to a regional detachment that is rooted in detachment faults beneath the western Cobequid Highlands, in the same way that the Beckwith Fault may be linked to the North Cobequid thrust.

SUMMARY AND CONCLUSION

This report documents the results of seismic interpretations completed in 1996 in the Cumberland Basin, a mainly non-marine Carboniferous basin in northern Nova Scotia.

Approximately 1700 km of seismic data were analyzed, together with well information and geological map data. The seismic and well data were interpreted using a LandMark computer workstation.

Thirteen seismic horizons were identified and traced on the seismic data by establishing seismic stratigraphic units, which were subsequently correlated to lithostratigraphic units. Ten of the horizons were mapped only in limited areas, but three horizons could be mapped regionally. Time structure maps were made for these three horizons: BW, BP and PG.

The BW horizon is correlated with the base of the only marine evaporite unit in the basin, the Windsor Group. It is the deepest regional horizon mapped. The map of the horizon shows very little relief over most of the basin, with the exception of one large basement feature, the Hastings Uplift. Horizon BW was not recognized over the northeastern part of the uplift, suggesting the Windsor Group was removed by erosion or was not deposited. The horizon varies in depth between 400 ms (600 m) and 3200 ms (7600 m). It is affected by faults adjacent to the Cobequid Highlands and the Hastings Uplift.

The BP horizon is correlated with the base of the Boss Point Formation, a sand-dominated unit at the base of the Cumberland Group. This horizon outcrops on the flanks of the major anticlines and was mapped to depths of 2600 ms (6000 m). The horizon is highly faulted and folded in the southern part of the basin, but north of a major fault (Beckwith Fault), the horizon is essentially flat and not deformed.

The PG horizon is correlated with the base of the Pictou Group, comprising mainly red sandstones and shales. The horizon was mapped only in the Tatamagouche and Amherst synclines. It is gently folded and locally faulted. On the southern margin of the Cumberland Basin, the horizon rests with pronounced unconformity on older rocks.

Seismic stratigraphic analysis, combined with analysis of well and geologic data, resulted in the identification of notable stratigraphic relationships: a) a thick (up to 1600 m) clastic unit was recognized in the central portion of the southern margin of the Cumberland Basin. It is interpreted as Windsor Group equivalent; and b) seismic reflections were recognized associated with a thick succession of conglomeratic rocks on the Scotsburn Anticline that suggest the Windsor Group is transitional with the conglomeratic rocks. These reflections, together with unconformable relationships observed on the seismic data suggest the conglomeratic rocks (Falls and Millsville conglomerates) were deposited between the middle Visean and the Bashkirian.

Seismic lines that cross the southern margin of the Cumberland Basin and image parts of the basement complex to the south of the basin (Cobequid Highlands), show reflection patterns consistent with thrust faults at mountain fronts. The seismic data indicate that folded and faulted Cobequid Highlands was carried in the hanging wall of a major detachment fault, together with strata from the Cumberland Basin. This structure was described as the North Cobequid thrust by Waldron et al. (2013). The detachment is interpreted in this report to emerge along the Beckwith Fault. This deformation is suggested to post-date deposition of the Boss Point Formation and to pre-date the Pictou Group based on stratigraphic relationships.

Given that additional seismic data was acquired in the Cumberland Basin since 1996, future work should include an integrated interpretation of all available seismic data.

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APPENDIX: NOTES ON INTERPRETATION OF SEISMIC LINES

Interpretation notes of seismic lines described in this appendix are organized first by geographic area and then alphabetically.

AMHERST SYNCLINE

AN5E

High-amplitude, low-frequency reflections of the Windsor Group occur north of the Lorneville Fault. To the south of the fault on the Hastings Uplift, high amplitude reflections with a slightly higher frequency are recognized. These may correspond to the Windsor Group, even though Windsor Group rocks were not encountered in the Hastings No.1 well. Justification for correlating these reflections with the Windsor Group include the following: 1) similar reflection character north and south of the Lorneville Fault (i.e. similar lithologies on both sides of the fault; 2) Windsor lithologies recognized in outcrop in the Minudie Anticline; 3) possible Windsor reflections recognized at depth beneath the Minudie Anticline; 4) Windsor Group reflections occur on the eastern extension of the Hastings Uplift in Northumberland Strait. The three latter points suggest Windsor Group was deposited on at least part of the Hastings Uplift.

Windsor reflections south of the Lorneville Fault are divergent northward, suggesting thickening of the Windsor strata in that direction. At the location of the fault, there are several faults slices, and the Lorneville Fault could be termed a "fault zone". Rocks occurring immediately north of the Lorneville Fault are apparently deformed by the faulting. Their corresponding reflections curve upward adjacent to the fault, and reflections with the same character occur within some of the fault slices. To the north of the Lorneville Fault, up to 600 ms of Windsor and ?Mabou Group rocks are interpreted. These rocks are apparently truncated by the faulting. The basal Boss Point reflections, and reflections up to 200 ms below this horizon, are not offset by the fault.

AN25

Base Boss Point horizon is a phantom horizon between SP 5830 and 5900 due to poor quality of reflections at this level in this area.

AN30

High-amplitude discontinuous reflections between SP 7100-7200 at 1700-1900 ms are interpreted as basal Windsor Group reflections based on reflection character and continuity of reflections with interpreted Windsor reflections in the Athol Syncline.

AN31

Lorneville Fault interpreted at north end of profile based on Windsor reflections occurring at 2060 ms on line AN25 and basement reflections on AN31 at about 1450 ms. The apparent Horton Group rocks found south of the Lorneville Fault to the northeast of this line location (see AN5E, G9 and G6), appear to be absent in this area. North-dipping reflections within the 'basement' could, however unlikely, be representative of Horton or Fountain Lake group rocks.

The largest amount of throw on the Lorneville Fault appears to have occurred between Windsor Group deposition and Boss Point deposition. Offset and folding of Boss Point and younger strata indicates very late movement.

G4

Picks NE of the Beckwith Fault were established by line tie with G18 and the Hastings No.1 well. Picks SE of the Beckwith Fault were established using outcrop distribution and by ties with G14 and AN22. Beckwith Fault extrapolated into the subsurface from the location of the fault at the surface. The fault was interpreted to mark the change in character from steeply south dipping reflections above the fault to chaotic reflections below. The chaotic reflections likely represent salt or highly faulted and contorted sediments.

The confidence on the base Windsor Group pick between SP 365-500 is fair to good based on character and ties with AN22, AN30, and AN6. At SP 335, the amplitude of the interpreted base of the Windsor Group reflections decreases substantially. The decrease in amplitude may be due reflection truncation by faulting (less likely) or thinning of Windsor Group strata onto the Hastings Uplift (preferred interpretation).

G6

Similar relationships were observed on this line across the Lorneville Fault as on AN5E and G7/G8/G9. North dipping reflections beneath the Windsor Group south of the Lorneville Fault suggest tilting of the ?Horton Group prior to deposition of the Windsor Group. The Lorneville Fault dips more gently here than elsewhere; it has an almost nappe-like appearance. Late movement is suggested by the gentle folds in the Boss Point and younger strata north of the fault.

G7, G8, and G9

These three lines form a composite profile across the Lorneville Fault. These lines show similar geometry across the fault to AN5E (i.e. Windsor Group north and south of the fault and down to the north movement). The Windsor Group reflection package is thinner south of the fault on this line than on AN5E. The Windsor reflections also appear to be truncated, as if by erosion.

An apparent normal fault occurs at SP 175 on line G9. This fault may represent an early basin-bounding fault active during Horton Group deposition, and reactivated after Windsor Group deposition, as indicated by the offset on the U2 horizon. The age of the rocks corresponding to the U2 horizon is unknown, but they may correlate with the Mabou Group, since these rocks were interpreted in the bottom of the Hastings well.

G12

The base Windsor reflection was identified (based on character) on the north end of the line and on AN12 adjoining the south end of the line. No obvious base Windsor Group reflection was recognized over the middle part of the line (i.e. Hastings Uplift). Based on other lines in the Amherst area, I believe that basal Windsor Group strata were initially deposited on this part of the Hastings Uplift. The basal Boss Point pick was made based on a jump correlation from line AN25. This occurs deeper than the total depth of the Nappan No.1A well. There were no obvious stratigraphic breaks below the salt in the well to suggest the presence of the base of the Boss Point Formation.

The Lorneville Fault was interpreted on this line near SP 190. This is a doubtful correlation, however, due to the small throw and the very different geometry of the fault as compared to the fault geometry to the northeast. Also, the Beckwith Fault – Minudie Anticline is a very dominant structure on this part of the line, and diffractions and ray path distortions may obscure geological relationships below this structure.

The Nappan No.1A was projected onto this line at about SP 155. This location was chosen so that the salt/sediment interface in the well at 1850 m, roughly corresponded to the boundary between highly deformed south dipping reflections in the Minudie structure and horizontal strata north of the structure. Thus, the well merely supports reflection correlations made based on the Hastings well and surface exposures north and south of the Minudie structure.

<u>G14</u>

Picks established by line ties with G12, G4, AN12, and AN22. The ties with G12 and G4 appear to be good, although ties with AN12 and AN22 are poor. Reflections on AN12 and AN22 occur at greater TWTs than corresponding reflections on G14. This is interpreted to be due to migration problems.

The base Windsor Group reflection is not imaged on this line. There is a character change corresponding to the level of the base Windsor on adjacent lines. Therefore, it is mapped as a phantom horizon based on ties with adjacent lines.

ATHOL SYNCLINE

<u>AN6</u>

Poor data line. Few reflections to interpret largely due to high degree of deformation in the area. Several faults mapped at the surface are interpreted (i.e. Beckwith, Little River, and Oxford). Deformation in the subsurface does not exactly correspond to the inferred surface trace of the Oxford Fault, but limited outcrop in the area allows some flexibility. Phantom horizons of the base Boss Point and Chignecto/40-Brine were interpreted between SP 1590-1690. These were extended from outcrop on the seismic profile using attitudes and weak reflections.

Base Windsor was mapped based on seismic character. It was recognized in the Athol Syncline as well as over the Hastings Uplift, although the reflections are poor over the uplift. A series of faults were interpreted in the transition zone between the uplift and the syncline. These faults are interpreted as the Mansfield Fault.

<u>AN12</u>

Base Windsor reflections are poorly defined, possibly due to deformation (salt tectonics or thrust faulting). Reflection truncations within the Windsor reflection at SP 2970-3000 suggest a possible fault. The Mansfield Fault may be indicated on this lin by the disruption of the Windsor reflection at SP 2860-2890. The BP horizon was correlated from surface and roughly coincides with the deepest high amplitude reflection above the Windsor Group. The Forty Brine-Chignecto coal seam, as picked on line L-1002, occurs near the top of the lower high amplitude reflection package. This is not consistent with other lines in the area, which show the 40 Brine-Chignecto to be near the base of that package. The other lines are tied to boreholes and form a grid that may be tied to outcrop at several locations. Line L-1002 is somewhat isolated from the other lines, and a fault (which appears as a flexure on L-1002) occurs between the high amplitude reflection package and outcrop. I projected the 40 Brine-Chignecto seam onto AN12 and it correlates with reflections near the base of the high amplitude package, which is more consistent with the other lines. All other coal horizons from Bromley and Calder (1988).

<u>AN13</u>

All horizons picked on this line are based on a line tie L-1008.

<u>AN14</u>

This line ties with AN13. Only the BW horizon and the No.2 seam could be mapped. Confidence on the BW horizon is fair to good, whereas the No.2 seam is fair to poor, mainly due to a lack of character similar to that found elsewhere in the Athol Syncline. The section appears to disrupted by extensive faulting. Most profiles in the Cumberland Basin show stratigraphic thickening toward the Cobequids, but this profile shows thickening <u>away</u> from the Cobequids.

<u>AN15</u>

There are very few, if any, quality reflections on this line. Deep reflections occurring at about 3000 ms are similar in character to Windsor Group reflections found elsewhere in the Cumberland Basin. There are four troughs in the series of reflections (Windsor Group usually has 3-6 troughs), and the frequency and amplitudes are the same as other Windsor Group reflections. They are overlain by a low energy zone (?Mabou Group), similar in thickness to the Mabou Group in other areas of the Cumberlend Basin. High amplitude reflections overlying the low energy zone (2100 - 2400 ms) may represent Boss Point strata, although their frequency is lower here than elsewhere in the basin. These reflections dip gently northward, whereas the Windsor reflections are roughly horizontal. Overall, this package of reflections is typical of the Windsor-Mabou-lower Boss Point seismic stratigraphy found in other parts of the Athol Syncline. It is odd, however, that these reflections are only recognized in the southern portion of the line, and an apparent north dipping fault truncates these reflections at about SP 3250.

Collectively, the reflections on the south end of the seismic profile could be regarded as Fountain Lake Group or basement reflections. This interpretation is considered less likely than the interpretation given above.

<u>AN22</u>

BW horizon was mapped based on reflection character, it is the deepest recognizable reflection on the profile. BP horizon was mapped as the deepest high amplitude reflection above the Windsor Group. Coal horizons taken from line L-1001 of Bromley and Calder (1988).

<u>AN30</u>

Details of the interpretation of this line north of the Beckwith Fault are described under the section titled Amherst Syncline.

Base Windsor horizon was mapped based on seismic character. The BP horizon was mapped from location of contact at the surface (SP 7131). Chaotic reflections occur between SP 7075 and 7110, where the a phantom BP horizon was mapped. For SP less than 7075, the base Boss Point horizon was mapped at the base of a high amplitude reflection package (as was done in Tatamagouche Syncline). The coal horizons (Forty Brine/Chignecto and No.2 Seam), were mapped by comparison with the results of Bromley and Calder (1988). Their lines L-1004, 5 and 6 were collected along the same road as AN30. The Mansfield Fault is identified near SP 7080, and is represented by several small faults. The amount of throw is clearly recognizable.

TATAMAGOUCHE SYNCLINE

<u>AN9</u>

Line ties between Chevron profiles and line AN9 were extremely difficult. The migration version of AN9 was used to locate the locations of faults only and the structure stack was used for horizon mapping. Faults were interpreted to affect the FLG, the Windsor Group and possibly the Boss Point Fm. Individual faults (seismic character suggests some exist) in the Boss Point and younger strata could not be recognized. Faults are not indicated on geological maps. The structural stack section of AN9 was used to correlate reflections because reflection amplitudes and continuity are better preserved and the amount of mistie between AN9 and the Chevron data was much less than with the migration section.

Top of Windsor Group honours the seismic data, but at SP 2305 the reflection quality decreases and I may have skipped to the next higher reflection. The pick ties with both C81y and C32y, however. Base of the low energy zone not well defined, but it is present. Base of New Glasgow was ghosted in (based on line ties, outcrop and the "base low energy zone" horizon) since no coherent reflections occur at this level.

<u>AN10</u>

Several possible thrust faults were interpreted. Odd reflection geometries may be suggestive of possible extensional faults between SP 2750-2780. Top Windsor Group reflection poorly defined between SP 2668-2692. The bases of the low energy zone and the New Glasgow Fm cannot be interpreted on this line. Reflections at all depths become discontinuous east of SP 2770.

<u>AN17</u>

The BP horizon was tied from lines C28x and C32y. This horizon was found to correlate with chaotic reflections and was ghosted-in. Probable Windsor Group reflections were identified from C32y, but they thin to zero or are truncated by faults. The "intra-conglomerate" reflection corresponds to the top of a package of high amplitude discontinuous reflections that appear to correlate with the interpreted Windsor Group reflections on C32y. Potential thrust faults cut this reflection package at SP 3534.

<u>AN18</u>

AN18 does not tie well with C81y and C32y. The stack copies tie a little better, but not as well as I would like. Some problems recognizing the same high amplitude events on different profiles.

<u>C34</u>

Reflections between the Windsor Group and the base of the Boss Point have very high amplitudes on the south half of the line, which closely resemble Windsor reflections in amplitude, continuity, and frequency. The Boss Point Fm has lower amplitudes, and less continuous reflections. A strong doublet reflection occurs near the top of the Boss Point, which is overlain by the low energy zone. A gradual increase in reflectivity occurs up section, with occasional high amplitude low frequency reflections occurring. These may represent channel sand bodies? The bases of both the Malagash and the New Glasgow were projected from surface. The contact of the New Glasgow occurs south of the line and was projected trigonometrically. The base of the New Glasgow again occurs within the low energy zone.

<u>C44x</u>

There is a good line tie between C44x and line AN2. The BP horizon is more or less horizontal and can be traced from the line tie northward to SP 2780 where there is a fault. The BP horizon is down-to-the-north across the fault with an offset of approximately 200 ms. Horizons BW and TA3 can be traced to SP 2900, at the southern limit of the Hastings Uplift. There is lower confidence on the TA3 horizon than the BW horizon; however, a wedge of strata interpreted as the Windsor clastic unit is recognized between the line tie and SP 2900. This unit is weakly stratified, suggesting possible interbeds of evaporite rocks, and it thins northward from approximately 450 ms at the line tie to about 200 ms at SP 2900. The Beckwith Fault subcrops near SP 3000.

Scotsburn Anticline

Seismic reflections corresponding to Boss Point strata mapped at the surface are characterized by fairly continuous high amplitude reflections. The top of this reflection package is marked by a stratigraphic discontinuity (reflection BP1). This seismic horizon does not coincide with the top of the Boss Point mapped at the surface. Immediately overlying this horizon, is a seismically transparent zone up to 200 ms in thickness. The top of this unit coincides with the surface location of Boss Point - New Glasgow contact (reflection BP2). A similar situation occurs on lines C34 and C81y where a high amplitude reflection package is overlain by a low energy zone. Reflectivity in the low energy zone gradually increases up section, and the base of the New Glasgow Formation occurs within the low energy zone. It is clear from the seismic that the base of the low energy zone has some stratigraphic significance.

AN1

Picks on this line were made consistent with picks made on lines AN2 and AN3 (i.e. Polly Brook projected 10^{o} and is unconformable on older rocks, thicknesses of Malagash and Pictou consistent with other lines).

AN2

Type section for pre-Pictou strata of the Tatamagouche Syncline. Malagash and Pictou horizons are phantom horizons based on outcrop and surface attitudes.

AN3

Base of Polly Brook Fm was projected from surface outcrop. One outcrop (which occurs within 1000 m of the profile) records a dip of 24^{o}. All other attitudes measured for the Polly Brook Fm in the Tatamagouche Syncline are less than 15^{o}. An estimated mean for Polly Brook bedding dip is about 10^{o}. In addition, the Polly Brook everywhere dips more gently than the Boss Point Fm (dips range from 23^{o}-68^{o}), suggesting an angular discordance between these two rock units. Therefore, the base of the Polly Brook Fm was picked at the unconformity at SP 700, time 450 ms, which is approximately 10^{o} down dip from the base of the Polly Brook Fm mapped at the surface.

The top of the low-energy zone is not apparent on this line, but it was picked assuming a similar thickness of strata as on line AN2. The Malagash and Pictou events were picked using outcrop, bedding attitude, and boreholes BP-10 and 11 as a guide.

AN5

SP 1260-1420: seismic picks poorly constrained by outcrop geology, no boreholes, and unique seismic character to the Tatamagouche Syncline. The BP horizon was chosen at the base of the high amplitude reflections at about 750 ms, SP 1360. These appear very similar to Boss Point reflections elsewhere in the Tatamagouche Syncline. The wedge of reflections immediately below the Boss Point are not assigned to any rock unit. The Base of the Polly Brook was arbitrarily chosen and is consistent with depths of Polly Brook on AN1.

AN20 and AN27

The base of the Malagash Formation was picked at the top of the upper reflective package, based solely upon a reasonable thickness of strata for the Malagash Fm.

AN21

Based on 1) depth of base Windsor reflections on AN2 and AN20; 2) seismic character of base Windsor reflections; 3) similarity of seismic character of events on AN21 and AN20 above the base Windsor event; and 4) similar structural relationships, I conclude that the base Windsor extends below the thrust fault and the reflections above the thrust fault are the same as those above the base Windsor on AN20.

C5y

C5y is a very poor quality profile, mostly because of the severity of faulting on this line. All horizon picks were determined from surface contacts and a tie with line C32y. The mismatch of picks from these two sources is interpreted in terms of reverse or thrust faulting. It appears that rocks as young as Westphalian B (New Glasgow Fm) were affected by the faults.

Jump Correlation of Lines C32y and C32x

The eastern and western parts of the Tatamagouche Syncline were mapped by different geologists. To ensure consistent horizon identification on the seismic data, the surface geological contacts from the eastern and western parts of the syncline were tied using the seismic data. Unfortunately, the adjacent end points of two key seismic profiles (C32y and C32x), which were required to correlate horizons across the syncline, are separated by about 3400 m. Since the jump correlation between these two lines was not straightforward, and the correlation has significant implications for the stratigraphy of the Tatamagouche Syncline, some explanation is required.

The seismic stratigraphy of the two lines is sufficiently different to establish some doubt regarding the validity of correlations made solely on the basis of seismic character. Furthermore, jump correlations made on the basis of seismic character alone indicate a consistent mistie on all horizons of about 150 ms between the two lines. To facilitate correlation, two assumptions were made: 1) seismic horizons at depth were parallel to the dip of rocks measured at the surface; and 2) significant changes in thickness of strata were limited to the Boss Point and New Glasgow Formations, since these units show changes in thickness in the vicinity. The top of the Boss Point Formation appears to be a major unconformity on line 32x.

Lines C32y and C32x were extrapolated to a point where they intersect. C32x is a strike line and the dip was assumed to be horizontal. C32y is oblique to the true dip direction and an apparent dip was calculated for this line. The apparent dip was used to constrain the jump correlation. Horizons were correlated from youngest to oldest. Horizons were identified using outcrop data and boreholes NT-15 and TF-86-1.

The jump correlation, as established in this study, is consistent with the geological mapping for the Balfron, Malagash, and upper part of the New Glasgow Formations. Seismic reflections at the level of the lower part of the New Glasgow Formation and the Boss Point Formation on line C32y are quite different from reflections on C32x. The "Boss Point" is characterized by fairly continuous high amplitude reflections, the top of which is marked by a stratigraphic discontinuity (reflection BP1). This seismic horizon does not coincide with the top of the Boss Point mapped at the surface. Immediately overlying this horizon, is a seismically transparent zone up to 200 ms in thickness. The top of this unit coincides with the surface location of Boss Point - New Glasgow contact (reflection BP2). A similar situation occurs on lines C34 and C81y where a high amplitude reflection package is overlain by a low energy zone. The top of the low energy zone coincides with the surface mapped contact of the base of the New Glasgow. But it is clear from the seismic that the base of the low energy zone has some stratigraphic significance. At least two interpretations are possible: 1) reflection BP1 corresponds to the top of the Boss Point Formation, suggesting the surface contact be moved 1000 m east along line C32y. Sparse outcrop data would permit such an interpretation. 2) Reflection BP2 corresponds to the top of the Boss Point Formation, and the seismically transparent unit consists of up to 270 m of one homogeneous lithology, most probably sandstone. The latter interpretation is preferred since the New Glasgow and younger strata have the same seismic character on both lines, and the top 200 ms of strata in the Boss Point Formation on line C32y has the same seismic character as on line C32x.