University of Alberta

Development and Structure of the Kennetcook-Windsor Basin, Nova Scotia, Atlantic Canada

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science

Department of Earth and Atmospheric Sciences

Fall 2011
Edmonton, Alberta

To my parents, who taught me the humanistic secrets to explore myself.

Abstract

The Kennetcook-Windsor basin is a part of the large composite Maritimes Basin in Atlantic Canada. Subsurface seismic data indicate a very complex basinal history in terms of syn-depositional deformation and superimposition of numerous episodes of fault reactivation in the basin. Faults mapped and correlated at the tops of basement, the Horton Bluff, and the Cheverie formations can be subdivided into six categories. On the basis of interpretation of seismic reflection geometries and fault modeling, at least six episodes of deformation are suggested in the Kennetcook-Windsor basin. Flower structures mapped in the subsurface clearly indicate a strike-slip setting that remained active during the entire history of the basin. Structural collapse features represented by high-angle chaotic seismic reflections within the Windsor Group indicate evaporite withdrawal that played a key role in the creation of accommodation space for the Pennsylvanian sediments in the basin.

A two-way-time (TWT) structure map at the top of basement shows tilted fault-blocks stepping down to north and northeast. The TWT maps at the tops of the Horton Bluff and the Cheverie formations show a structural low in the central area and rising in the northeast, west, and south. However, the structural low on the top of the Cheverie Formation is narrower and indicates that the faults in the northeast were inverted more than those mapped on the top of the Horton Bluff Formation. Comparison of the thickness maps of the Horton Bluff and the Cheverie formations indicate an overall thickening in the north and northeast.

Episodic dextral strike-slip movement on the basin-bounding fault (Minas Fault) controlled the basement architecture and the development of the basin. Probably oblique movement (SW-NE) on the local subsurface faults caused compartmentalization of the tilted fault-blocks within the Horton and Windsor groups.

Acknowledgements

I am grateful to Dr. John Waldron, my thesis supervisor, for his kind guidance and support for the completion of this study. I always found him ready to help out even during busy times. I am greatly indebted to him for his timely help and useful advice for the last two and half years. During our field trip to Nova Scotia, he setup a very comfortable base camp at Noel and provided the best facilities to carry out work in a logistically difficult area.

I thank my department for providing support in the form of teaching and research assistantships during my studies. Thanks are due to Triangle Petroleum Corporation, USA, and Elmworth Energy Corporation (Canada) for providing well and reprocessed seismic data and financial support for this project. I especially thank Dr. Peter Hill and Anne Grau at Triangle Petroleum Corporation for giving encouraging feedback on the seismic interpretation results. I thank Schlumberger for providing *Petrel 2010*, seismic-to-simulation software, for the interpretation of seismic and well data. I really appreciate Valery Companiytsev at our department who provided software-related technical support especially the installation and trouble-shooting of Petrel software. I also thank Nova Scotia Department of Natural Resources for providing well reports and mudlogs.

Lastly, I am very grateful to my wife who encouraged me to start studies at the University of Alberta. Her endless love and cooperation always provided me backup to face the challenges during the course of this project.

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1. Introduction

The Kennetcook-Windsor basin represents the southern part of the large (approximately 148, 000 km^2; Wilson and White, 2006) composite Maritimes Basin developed during the Acadian orogeny in Atlantic Canada (Figure 1.1). The Maritimes Basin preserves upper Paleozoic sediments which were deposited between the Late Devonian and Permian (ca.385 – 295 Ma) (van de Poll et al., 1995; Gibling et al., 2008; Hibbard and Waldron, 2009) in a series of interconnected depocentres (Gibling, 1995). A generalized stratigraphic column for the Maritimes Basin, showing the principal stratigraphic units, is shown in Figure 1.2. The Maritimes Basin is filled by mainly non-marine sedimentary rocks but includes a thick pile of Mississippian marine carbonates and evaporites (Windsor Group) in lower part of the succession.

This research project focuses on an area of intense deformation in the southern part of the Maritimes Basin that extends south of the Cobequid-Chedabucto Fault, a boundary between Avalon and Meguma terranes recognized in the earlier Paleozoic history of the Canadian Appalachians (Figures 1.3 & 1.4). This terrane boundary represents a major transform fault zone that contains deformed Carboniferous sedimentary rocks (Waldron, 2004; Waldron et al., 2010). Structures (folds, normal and reverse faults, axial planar cleavage, en echelon veins and boudins) within this deformed zone have excellent exposures along the southern coastline of Cobequid Bay between Cheverie and Selma (Figure 1.4).

Much of the coastal area between Cheverie and Tennycape (Figure 1.4) has exposed highly deformed Tournaisian Horton Group rocks (Figures 1.2 & 1.5) which have been divided into a lower Horton Bluff Formation (grey lacustrine unit) and an upper Cheverie Formation (red and grey fluvial unit) (Bell, 1929; Gibling, 1995). The type sections of both formations exposed in the western and eastern banks of the Avon River (Figure 1.5) show very mild deformation (dips are less than 30^o) in contrast to the coastal sections between Cheverie and Tennycape, few kilometers northeast of the type sections (Roselli, 2003), which contain intensely folded and faulted Horton Group rocks. This contrast in deformation and structural style observed in the coastal sections is interpreted to result from the allochthonous nature of the Horton Group rocks, in the Cheverie and Tennycape areas, which have been transported to southeast (Boehner, 1991; Waldron et al., 2007; Waldron et al., 2010).

1.1. Regional geological setting

The Lower Paleozoic and older rocks that form the basement to the Maritimes Basin have been grouped into Humber, Dunnage, Gander, Avalon and Meguma zones (Figure 1.3). The Gander, Avalon and Meguma zones are regarded as the fragments of Gondwana that accreted to Laurentia during Appalachian orogenesis (Williams, 1995). Boundaries between these accreted terranes remained active during the history of the Maritimes Basin and caused transtension and transpression in the depocentres (Waldron et al., 2007). Much of the Mississippian and Pennsylvanian strata of the basin overstepped these terrane boundaries (Waldron, 2004; Gibling et al., 2008). Post-collisional convergence between Gondwana and Laurasia, intermittent connections between depocentres, and episodes of varied subsidence and inversion along the basin-bounding faults, all contributed to the geological history of the basin (Gibling et al., 2008).

Geophysical data reveal the Maritimes Basin as a deep basin containing numerous depocenters (Hibbard and Waldron, 2009; Gibling et al., 2008). Its central part contains a minimum of 12 km (Sanford and Grant, 1990; Gibling et al., 2008; Hibbard and Waldron, 2009) of late Paleozoic strata near the Magdalen Islands (Figure 1.1). The Maritimes Basin sediments on land also include thick, fault-bounded Late Devonian – Early Mississippian volcanics and sedimentary rocks below the Visean evaporite unit (Hibbard and Waldron, 2009; Gibling et al., 2008). These observations suggest several kilometres of Late Devonian – Mississippian subsidence and thinning of the underlying Appalachian crust during the history of the basin (Hibbard and Waldron, 2009).

1.2. Previous Work

1.2.1. Regional review

Bell (1927) discussed Carboniferous stratigraphy of the Maritimes Bain in relation to climatic and tectonic events. He subdivided the entire Carboniferous strata into Horton, Windsor, Riversdale, Cumberland, lower Stellarton, and upper Stellarton series on the basis of lithological characteristics and faunal assemblages. He argued that the Carboniferous strata in the Maritime Provinces were deposited in numerous subsiding linear basins that were intermittently separated by linear uplifted areas of erosion. The thick alluvial deposits preserved in the basin indicate progressive rising in the neighbouring of the subsiding basins. He suggested an isostatic nature of the crustal movements during the deposition of the Carboniferous strata. The rhythmic repetition of similar facies (e.g. coal beds, paleosol horizons, sandstones with erect tree stems) indicate that the subsidence in the basin was not continuous but was variable.

Belt (1968) documented the origin and evolution of the Maritimes Basin in the context of post-Acadian rifting. Carboniferous sediments of northern Appalachians are thick and highly deformed in narrow regions of southeastern New Brunswick, northern Nova Scotia, and central Newfoundland, and a region of thick strata (the Fundy basin, Figure 1.3) is interpreted as a complex rift valley bounded by high-angle faults and surrounded by relatively stable platforms . He interpreted that major longitudinal faults dip towards the rift basin and classified NE-SW striking faults as strike-slip and dominantly E-W striking as normal or reverse faults. He suggested that the strike-slip, extensional, and compressional deformation documented simultaneously in the northern Appalachians could only be explained in the context of strike-slip tectonics.

Howie (1984, 1988) proposed a horst-and-graben tectonic model for the development of the Maritimes Basin. He supported the conclusion of Howie and Barss (1975) who suggested that about 9 km of upper Paleozoic sediments were deposited over a faulted basement in downwarped areas (local depocentres of Belt, 1968; Boehner, 1991; Gibling, 1995).

Bradley (1982) speculated on the subsidence in the Late Paleozoic basins developed in the northern Appalachians. He applied McKenzie (1978) model that illustrates the subsidence history of many rifted sedimentary basins in terms of an initial rift phase followed by thermal subsidence during subsequent cooling of the lithosphere. Bradley (1982) postulated that up to 9 km of clastic sediments were deposited in interconnected depocentres which suffered two stages of subsidence within a right-lateral transform fault zone.

Fyffe and Barr (1986) documented the petro-chemistry of Carboniferous volcanic rocks in New Brunswick. They hypothesized a model in which the Maritimes Basin developed in a failed rift along the margin of the Late Paleozoic Rheic Ocean.

McCutcheon and Robinson (1987) proposed a foreland basin model for the Maritimes Basin, in which the basin developed as a consequence of Acadian continental collision. They proposed their model on the basis of variation in thickness, facies correlation and faunal assemblages. They considered rapid initial subsidence and subsequent slow but more widespread subsidence during the evolution of the basin.

Gibling (1995) compiled a detailed account of the upper Paleozoic rocks of

Nova Scotia. He proposed that syn-depositional motion on transcurrent faults and associated thrust zones, halokinesis, and extensional tectonics during Atlantic opening played a significant role in the distribution and deformation of stratigraphic units within the Maritimes Basin. Gibling et al. (2008) have suggested that a series of post-Acadian extensional and compressional episodes which led to widespread or more local subsidence and inversion have affected these depocentres.

Waldron and Rygel (2005) documented the role of evaporite withdrawal in the preservation of Pennsylvanian sediments in the Cumberland basin of Nova Scotia, a depocenter within the Maritimes Basin. They supported their hypothesis with the help of seismic interpretation and showed some minibasins developed due to withdrawal of Visean Windsor Group evaporites.

Hibbard and Waldron (2009) have suggested that dextral NE – SW strike-slip displacement is responsible for the subsidence of the Maritimes Basin beneath the Gulf of St. Lawrence (Figure 1.1). They have observed that at most places the timing of strike-slip motion is poorly constrained. However, field observations in southern New Brunswick (Figure 1.1) suggest that the significant displacements were Mississippian. On the basis of stratigraphic relationships, they have proposed a Late Devonian – Early Mississippian plate kinematics involving a significant component of dextral strike-slip motion along the entire eastern margin of Laurentia.

1.2.2. Local review

Bell (1921) concluded his detailed work on the Mississippian stratigraphy of the Horton-Windsor district. He described and mapped the Horton and Windsor rocks around the Avon River (Figure 1.5) in the northwestern part of the Minas Basin. He suggested that the terrestrial fluvial environment and the source area for the *Horton series* (the Horton Bluff and the Cheverie formations) were similar during deposition. However, channelling, mud-cracking, fresh feldspars, little altered biotite, and oxidized iron contents are dominant in the Cheverie Formation and differentiate it from the underlying Horton Bluff Formation. This indicates that the climatic influence was the main controlling factor of the chemical and the textural characteristics of the sediments. In the type section, he subdivided the Horton Bluff Formation into a basal feldspathic arenaceous member and an upper argillo-arenaceous shale member that contains abundant Ostracode and fish scales at different levels. Whereas, the Cheverie Formation, in the basal part (~ 92 m), is composed of gray arkose grits with minor amounts of chocolate argillaceous and arenaceous shale and local beds of micaceous and arenaceous greenish black shale. The upper part of the formation is dominantly purple-red argillaceous and arenaceous shale with local thin beds of greenish micaceous shale. Bell (1921) described the *Windsor series* comprising three or probably four horizons of gypsum and anhydrite (~ 50 feet each) separated by brick-red argillaceous shale of varying amounts and fossiliferous limestone with minor thin beds of dolomitic sandy shale and calcareous algal bands. He estimated that the gypsum and anhydrite may make up to 10 percent of the total thickness of the *Windsor series*. Bell (1921) subdivided the Windsor strata into subzones A, B, C and D on the basis of faunal assemblage and the lithological characteristics. He proposed that shallow water, probably high temperature, and varying salinities were controlling the deposition of the Windsor rocks in the area.

Fyson (1964) described the folded Carboniferous rocks, mainly a shale-siltstone succession, exposed between Cheverie and Walton. He interpreted that the main folds are asymmetric, face towards southeast and plunge at low angles. Their axial planes mostly dip northwest. The cross folds plunge steeply and are S-shaped with their axial planes dipping south. However, at Rainy Cove (Figure 1.5) adjacent to the S-folds, inverted folds with intermediate plunge are also present. On the basis of field observations, Fyson (1964) classified the fold generations into three classes. The first generation of folds comprises the main gently plunging folds that have their axial planes dipping dominantly northwest. The second generation of folds consists of the inverted and other folds that have low and intermediate plunge angles and axial planes dipping south. The third generation of folds include steeply plunging cross folds that have axial planes dipping south. Fyson (1964) interpreted that the folds which have variable plunge angles but nearly parallel axial planes were generated by a single episode of deformation.

Fyson (1967) interpreted that the main folds in the Carboniferous rocks follow the Acadian structural trends and are overturned in the direction of sediment thickening. He suggested that the subsidence caused by the movement along the normal faults during Carboniferous period was succeeded by gravity gliding that controlled the generation of the main folds. He described cross folds that are oriented north to north-northeast in the Carboniferous strata, nearly parallel to late Acadian cross folds that formed near the strike-slip faults within the basement rocks.

Clifton (1967) identified the solution-collapse and cavity fill in the lower part of the Windsor Group in the Minas Basin. He described a limestone breccia called the Pembroke breccia that is composed primarily of fragments and is present only near the surface. This breccia laterally grades into unbrecciated evaporite-limestone succession. Clifton (1967) interpreted that collapse followed by the solution caused initial brecciation of the limestone beds. Further solution and weathering produced cavity fillings in the laminated limestone underlying the breccia. He suggested that these breccias depositionally are not part of the Windsor Group and postdate the late Paleozoic deformation in the basin.

Keppie (1982) mapped the study area and correlated major lineaments in relation to Carboniferous tectonics. He interpreted a south-dipping thrust in the northeastern part of the Kennetcook-Windsor basin and named it the Kennetcook Thrust.

Boehner (1991) suggested an overall transpressive-thrusting model for the Kennetcook-Windsor basin on the basis of subsurface seismic interpretation. He interpreted that the southeastern margin of the basin is a major high angle fault (2300 m apparent dip-slip) and the northern margin is a thrust fault, the Kennetcook thrust, which transported deformed Horton Bluff and the basal Windsor Group sediments to the south. Boehner (1991) proposed that the localized small-scale thrust faults that have scattered outcrops in the basin could potentially be the splays of a large thrust system.

On the basis of sedimentological and diagenetic characteristics, Lavoie et al. (1995) distinguished two types of breccias present in the lower part of the Windsor Group in the study area. The first type is composed of an early synsedimentary breccia related to slope failure and underlies the Macumber Formation. The second type, a karstic breccia, is related to late subaerial exposure of the carbonate succession of the Windsor Group and is included in the Pembroke breccia. These breccias host base-metal mineralization (e.g. Fe, Zn, Pb, Cu sulphides and barite) in the Cheverie and Walton areas (Figure 1.5).

Martel and Gibling (1996) described the stratigraphy and tectonic history of the Horton Bluff Formation in the Minas Basin. They subdivided the Horton Bluff Formation into four formal members on the basis of palynology, lithostratigraphy and environments of deposition. The basal Harding Brook member of late Devonian to Tournaisian age is a braided fluvial sandstone and conglomerate unit with minor shale, which unconformably overlies the Meguma Supergroup. The middle to upper members the Curry Brook, Blue Beach and Hurd Creek members are shale and sandstone packages of Tournaisian age and were deposited under fluvio-lacustrine, lacustrine, and fluvio-lacustrine conditions respectively. Martel and Gibling (1996) interpreted that the Horton Bluff Formation was deposited in a half-graben bounded by the Cobequid-Chedabucto fault to the north of the Minas Basin. Lacustrine shales within the formation indicate a regional extensional phase and subsequent rapid subsidence during which coarse alluvial deposits were restricted to the basin margins.

Moore et al. (2000) did detailed geological mapping (1: 50 000) in the Wolfville-Windsor area. They mapped the Kennetcook Thrust just south of Walton and showed it extending to the southwest and juxtaposing the Windsor rocks with the Horton Group. Moore et al. (2000) inferred the surface trace of the Kennetcook Thrust on the basis of their field observations in the Cheverie-Windsor area.

Kontak (2000) documented a small base-metal occurrence and a mafic dyke within the Horton Bluff Formation in the Cheverie area (Figure 1.5). Dating ($^{40}Ar/^{39}Ar$ whole rock) indicates that the emplacement of the mafic dyke occurred at about 315 Ma and provides the maximum age of the mineralization. On the basis of field observations, Kontak (2000) suggested that an episode of ductile deformation occurred prior to the emplacement of this mafic dyke in the Horton Bluff sediments.

Waldron et al. (2007) have interpreted localized episodes of both transtension and transpression associated with dextral strike slip motion along Meguma-Avalon boundary (Cobequid Chedabucto Fault, Figure 1.1). They documented numerous oblique contractional structures which developed in a dextral transpression regime.

Waldron et al. (2010) have documented late Paleozoic transpression near the southern margin of the Maritimes Basin. Just northeast of Cheverie (Figure 1.5), they observed highly deformed lower Windsor Group rocks that indicate a thrust-sense decollement which has emplaced Horton Bluff formation on top of lower Windsor Group rocks (Figure 1.5). Previous work by Keppie (1982), Boehner (1991), and Moore et al. (2000) have documented this near-surface thrust, named the Kennetcook Thrust, and mapped it at different places. Waldron et al. (2010) have suggested a number of splays of the Kennetcook Thrust which was previously mapped by above mentioned authors. They (Waldron et al., 2010) have interpreted that these thrusts are probably linked at depth and form a thrust system (Kennetcook thrust system). Horton Group rocks may thus have transported from the central zone of transpression along the Cobequid-Chedabucto Fault (Figures 1.1 & 1.3) by gravitationally driven spreading in the shallower parts of a positive flower structure.

Recently Murphy et al. (2011) have summarized the late Paleozoic history of the Minas Fault Zone (MFZ) that represents an intra-continental transform fault in the Canadian Appalachians. This history involved several episodes of oblique dextral movement and played a key role in the development of numerous basins along its strike. On the basis of field observations they suggested that the active tectonics along this regional transform boundary in the southern part of the Maritimes Basin resulted in magmatism, regional fluid flow and mineralization. Murphy et al. (2011) identified numerous step-overs and fault segments within the Minas Fault Zone. Local zones of transpression and transtension affected the Carboniferous rocks and transported them to the north and south of the MFZ.

Extensive geological field work in and around the Kennetcook-Windsor basin has already been done for the exploration of natural resources. Various parts of the study area have been mapped by the Geological Survey of Canada, Nova Scotia Department of Natural Resources and Gunnex Limited (Weeks, 1948; Boyle, 1957; Stevenson, 1958; Bell, 1960; Crosby, 1962; Giles and Boehner, 1982; Ferguson, 1983; Moore, 1986; Moore and Ferguson, 1986; Moore 1993, 1994, 1996; Moore and Cormier, 1994; Donohoe and Grantham, 1989; Moore et al., 2000; Naylor et al., 2005).

Various geological maps by Geological Survey of Canada, Department of Mines and Technical Surveys and Nova Scotia Department of Natural Resources are available at 1: 63, 360, 1: 50,000 and 1: 10,000 scales. However, all maps differ in terms of distribution of stratigraphic units and structural interpretation. Detailed geological maps (1: 10,000) by Moore and Cormier (1994), R. G. Moore (1993, 1996) and Naylor et al., (2005) do not cover the area between Walton and Selma (Figure 1.5) which needs detailed work to resolve the structural/stratigraphic ambiguities on the existing maps. For instance, surface outcrops of Late Tournaisian Cheverie Formation (Figure 1.2) just south of Tennycape and in area between Walton and Selma (Figure 1.5) have not been mapped. Similarly the triangular fault bounded outcrop of Windsor Group rocks (Figure 1.2) in the Selma area (Figure 1.5) needs detailed geological investigations. Results of the geological reconnaissance between Walton and Selma are discussed in detail in chapter 2.

1.3. Objectives of this project

This project focuses on the main aspects of the deformed Carboniferous rocks in the Kennetcook-Windsor basin (Figures 1.5) to resolve the distribution of stratigraphic units and structural complexity of Horton and Windsor group rocks. Integration of the surface geology with the subsurface seismic and well data (Figure 1.5, tables 1 & 2) is the main method used to understand the basin development and examine the roles of dextral strike-slip, transtension and transpression, and salt tectonics in the deformation and preservation of the Carboniferous rocks immediately south of the Cobequid-Chedabucto Fault (Figures 1.1 & 1.3).

The following methods are used to help delineate the geometry of deformation, relative timing of the subsurface faults, folds and their relationship with the large dextral strike-slip component along the basin bounding faults: Subsurface fault interpretations;

correlations and mapping at the top of basement, the Horton Bluff Formation, the Cheverie Formation and the Windsor Group; Time structure maps at the top of basement, the Horton Bluff and the Cheverie formations; and the thickness maps of the Horton Bluff and the Cheverie formations. Results of the subsurface seismic interpretation, stratigraphic and drilling information from the available wells data (table 2, Figure 1.5) will add valuable information to the understanding of the depositional and deformation history in the basin.

Rock exposures and stratigraphic sections in the Kennetcook Basin are relatively sparse so geological fieldwork, collection of surface data between Walton and Selma area (Figure 1.5), and integration with subsurface seismic data was a major task during the course of the project.

1.4. Dataset for the project

1.4.1. Seismic reflection data

About 280 line kilometres of moderate to good quality 2D seismic reflection data and 64 km^2 of 3D seismic reflection data (table 1, Figure 1.5) are available for this project in the Kennetcook-Windsor basin. Triangle Petroleum Corporation generously provided this seismic reflection data. The 2D seismic dataset comprises five vintages that were acquired during 2000, 2001, 2002, 2007 and 2009. The 3D seismic volume acquired in 2007 covers a relatively small area in the Kennetcook-Windsor basin (Figure 1.5).

The seismic reflection dataset exhibits excellent subsurface geometries and structures which were interpreted in detail during the course of this study. Overall the subsurface reflection data is good except where the highly deformed basal Windsor evaporites are exposed on the ground surface which has affected the imaging quality of the subsurface rock units.

1.4.2. Well dataset

Wireline data from 9 exploratory wells (Figure 1.5, table 2) were also made available by the Triangle Petroleum Corporation for this study. This dataset helped well-to-seismic tie and regional well log correlations, which were used for horizon interpretations in the subsurface. Nova Scotia Department of Energy, Halifax was kind enough to provide the mudlogs for the lithological descriptions of the ditch cutting samples collected during drilling. These mudlogs were originally created by Edwin

Macdonald Geoconsulting Ltd, New Glasgow, NS. Stratigraphic intervals within the Horton, Windsor, and the Cumberland groups were made and correlated on the basis of lithological information from the mudlogs.

1.4.3. Field dataset

Structural data were collected during coastal and inland traverses in the study area during summer 2009. This dataset added confidence in identifying different rock units and their distribution in the study area.

The Horton Group rocks (Horton Bluff and Cheverie formations) are exposed in the north and south of the Kennetcook-Windsor basin. In the type section across the Avon River (Figure 1.5) the Horton Bluff Formation shows regular bedding and gentle dips (9^o – 25^o) towards SE and NE. Small scale fault-propagation folds and ramp anticlines are present in the fine-grained sandstone beds. Overall the whole package is mildly deformed as indicated by gentle dips. The Cheverie Formation, a coarse alluvial deposit, is also exposed in the Avon River. The grey and reddish brown colour and the, mildly calcareous, arkosic and micaceous nature of the sandstone beds clearly distinguish the Cheverie Formation from the underlying Horton Bluff Formation, and these criteria were used in the field to distinguish both formations.

The Windsor Group rocks are well exposed in Cheverie, Kennetcook, Cogmagun, and Shubenacadie rivers sections and show intense deformation. Due to the soluble nature of the evaporites, anhydrite and halite, the inland exposures of the Windsor Group rocks are sparse and could be traced only in the brooks or as indicated by sink holes (water ponds). Variable dips (30^O – 70^O) of the gypsum, limestone, siltstone and mudstone beds oriented in different directions indicate structural collapse features that resulted from the evaporite withdrawal.

Coastal sections between Cheverie and Tennycape (Figure 1.5) have exposed intensely deformed Horton and Windsor Group rocks which have high angle bedding (40^o – 70^o). Tight, asymmetric to overturned folds, mostly with sharp hinges, indicate intense deformation. Curved axial traces observed and variable plunge angles (9^o – 40^o) in the Rainy Cove and Walton area (Figure 1.5) show overprinting of multiple generations of folds. Mylonitic fabric observed in the Whale Cove (just few hundred metres east of Walton) along the faulted contact between the Cheverie and the Macumber formations, shows intense shearing in the area.

1.5. Approach

1.5.1. Geological fieldwork

This research project involves general reconnaissance and structural data collection of well exposed sections along southern coast of Cobequid Bay (Figures 1.4 & 1.5). Stratigraphic and structural data were collected between Walton and Selma, and plotted on the orthophoto maps (1: 10,000) and analysed stereographically to correlate with the surface trends. Further supplement to this geological work would update the existing available geological maps.

1.5.2. Seismic interpretation

Available seismic data in the Kennetcook-Windsor basin (Figure 1.5, table 1) were loaded in the *Schlumberger Petrel 2010.2* seismic software for the interpretation of structural and stratigraphic features of the key units which have regional significance in the basin. Most of the visible reflection geometries within every stratigraphic unit were picked to delineate the subsurface structure and stratigraphic features. Time slices within and near the top of basement, the Horton Bluff Formation, the Cheverie Formation and the Windsor Group were generated to correlate these structural and stratigraphic features.

Subsurface fault interpretations, correlations, and mapping at the top of basement, the Horton Bluff Formation, the Cheverie Formation and the Windsor Group were done prior to generating time structure maps. Interpreted faults were correlated and converted into fault sticks for an accurate 3D model prior to generating fault pillars which gave the flexibility to shape and extend faults in three dimensions. Truncation, merging and branching of faults were done in the 3D fault model before horizon surfaces were generated.

Geological field investigations and subsurface drilling data were used to establish time-depth relationships to tie wireline curve signatures with the seismic reflections (details in chapter 3). Thus stratigraphic tops picked in the wells were interpreted on the seismic data by producing regional composite transects.

Stratigraphic drilling well data (table 2, Figure 1.5) in conjunction with the seismic data added valuable information to the understanding of the depositional and deformation history in the basin. Key seismic reflections identified on the basis of well-to-seismic tie were correlated with the surface geology in the study area. The basal part of the Horton Bluff Formation that comprises coarse alluvial sediments represents bright dipping reflections. The base of these bright reflections is interpreted as the top of basement. The seismic reflections below the interpreted top of basement are discontinuous, chaotic and mostly show diffractions possibly due to poor migration. The top of the Horton Bluff Formation is picked along a seismic reflector above which gently inclined reflections within the basal part of the Cheverie Formation are dipping. Below this seismic reflection, Horton Bluff sediments represent very regular and nearly continuous reflections. The top of the Cheverie Formation is interpreted at the base of a package of bright reflections which represent the basal part of the Windsor Group (Macumber limestone). Below these bright reflections, seismic data show gently dipping geometries which probably show prograding wedges in the Horton Group. Top of the Windsor Group is interpreted where the chaotic, discontinuous, and high angle inclined reflections are truncated by a very gently dipping to nearly a flat reflector. Reflections above and below this seismic event show angular relationship and represent a regional unconformity. Seismic reflections above this reflector are uniform and continuous and show mild deformation.

Fault and horizon modeling were quality controlled by revisiting individual seismic lines. Time structure maps and thickness maps were generated after an acceptable 3D fault model and the subsequent pillar gridding in the *Petrel 2010.2*. Time structure maps at the top of basement, the Horton Bluff and the Cheverie formations and thickness maps of the Horton Bluff and the Cheverie formations were generated to delineate the geometry of the basin, relative timing of the subsurface faults, folds and their relationship with the large dextral strike-slip component along the basin-bounding faults. Results of the subsurface seismic interpretation are presented in chapters 4 and 5.

1.5.3. Subsurface Stratigraphic Analysis

Geological strip logs and drilling data were analysed to correlate the stratigraphic units across the basin. Subdivision of drilled sections into different intervals is established for this project on the basis of lithologic variations picked from the ditch cutting descriptions and net-to-gross (N/G) ratios in each of these intervals (where possible). Tops of the stratigraphic units were picked and in some wells were revised on the basis of lithological information. Intervals identified in the Horton Bluff Formation were correlated with the member subdivisions (e.g. Harding Brook, Curry Brook, Blue Beach and Hurd Creek) of Martel and Gibling (1996).

1.6. Results

Detailed seismic interpretation in the Kennetcook-Windsor basin helped delineate subsurface structural geometries, systematic fault correlations and mapping at the top of key horizons (e.g. the basement, the Horton and Windsor groups) which have regional significance in the study area. This subsurface mapping added valuable information to categorize the faults and their behaviour through the history of the basin. At least six episodes of deformation could be marked across the entire history of the study area which represents the southern part of the Maritimes Basin.

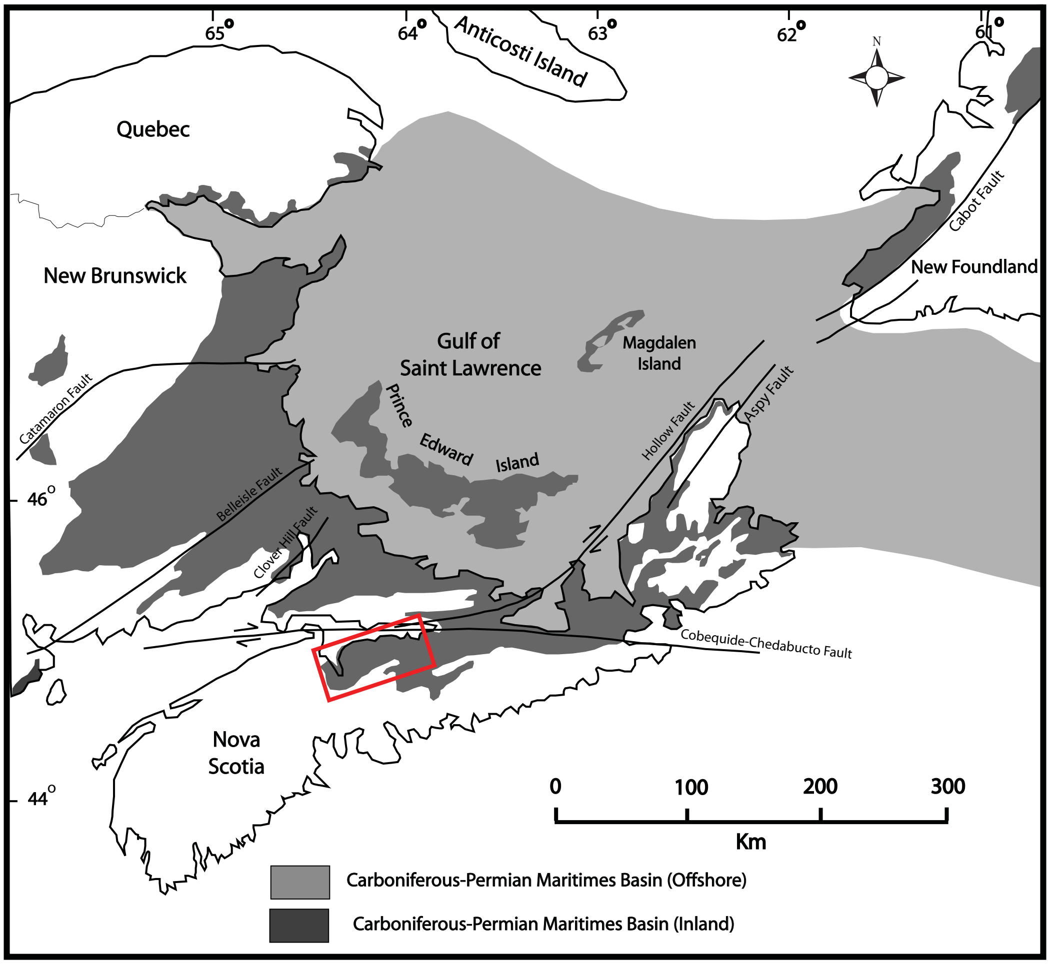


Figure 1.1: Schematic map of Atlantic Canada showing the Carboniferous Maritimes Basin. Red rectangle shows the location of the study area, NW Nova Scotia.

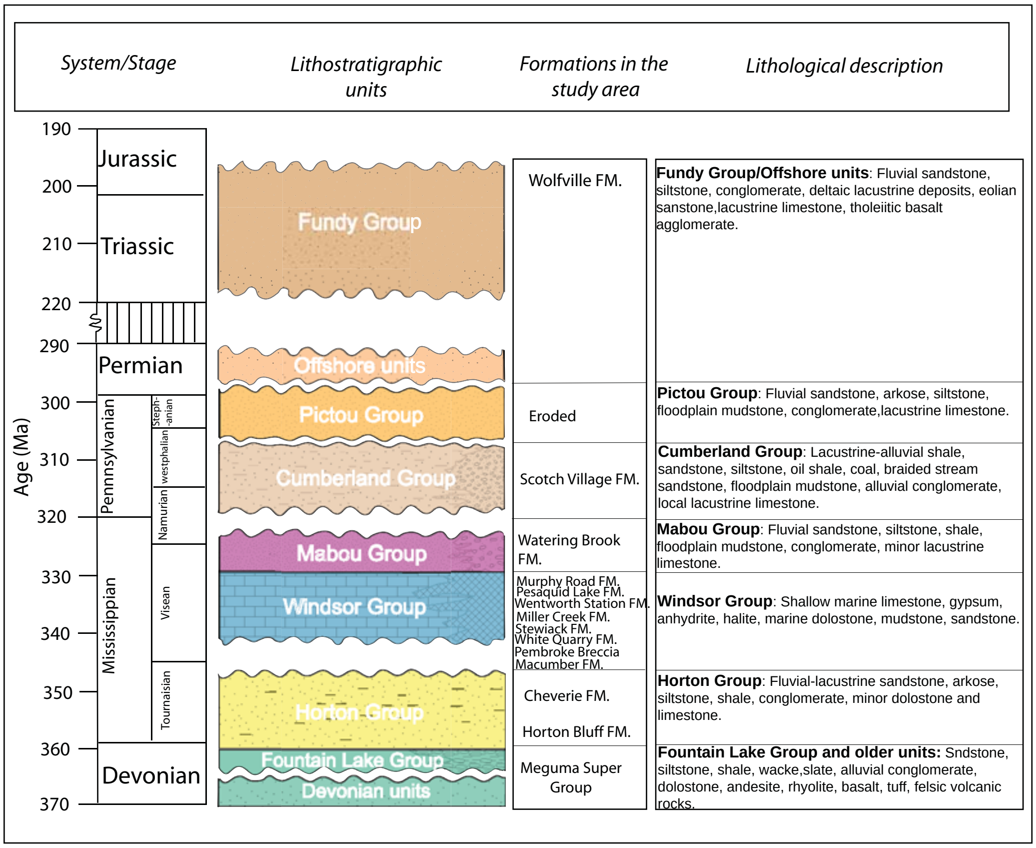


Figure 1.2: Stratigraphic column of the study area, Kennetcook-Windsor basin.

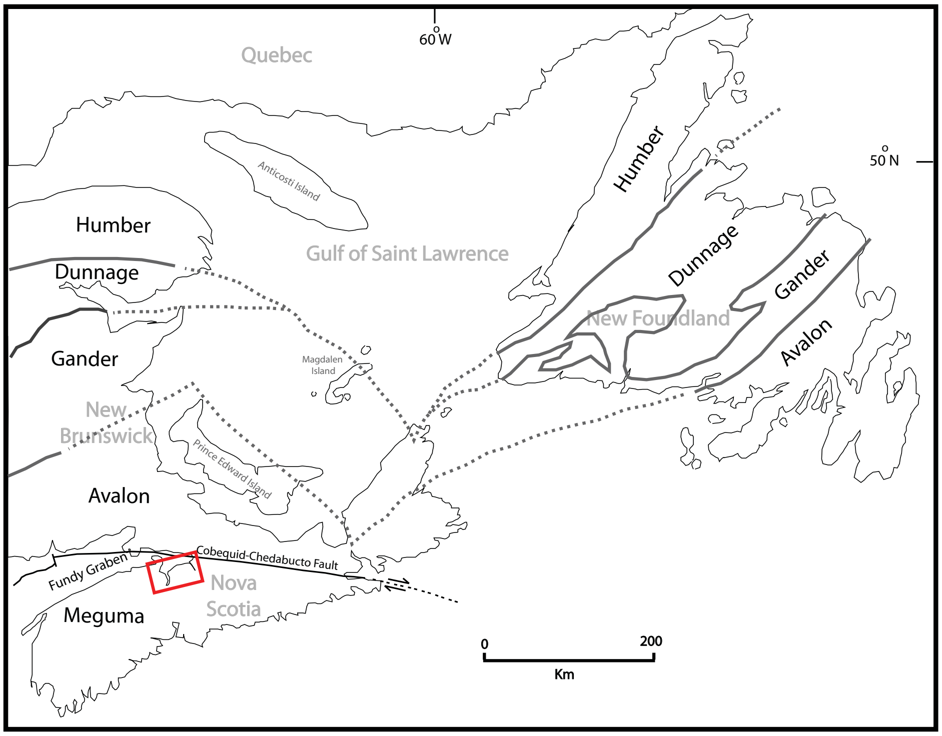


Figure 1.3: Subdivisions of the Northern Appalachian orogen into different zones. Red rectangle shows the location of the project area, NW Nova Scotia. Modified from Waldron et al. (2007).

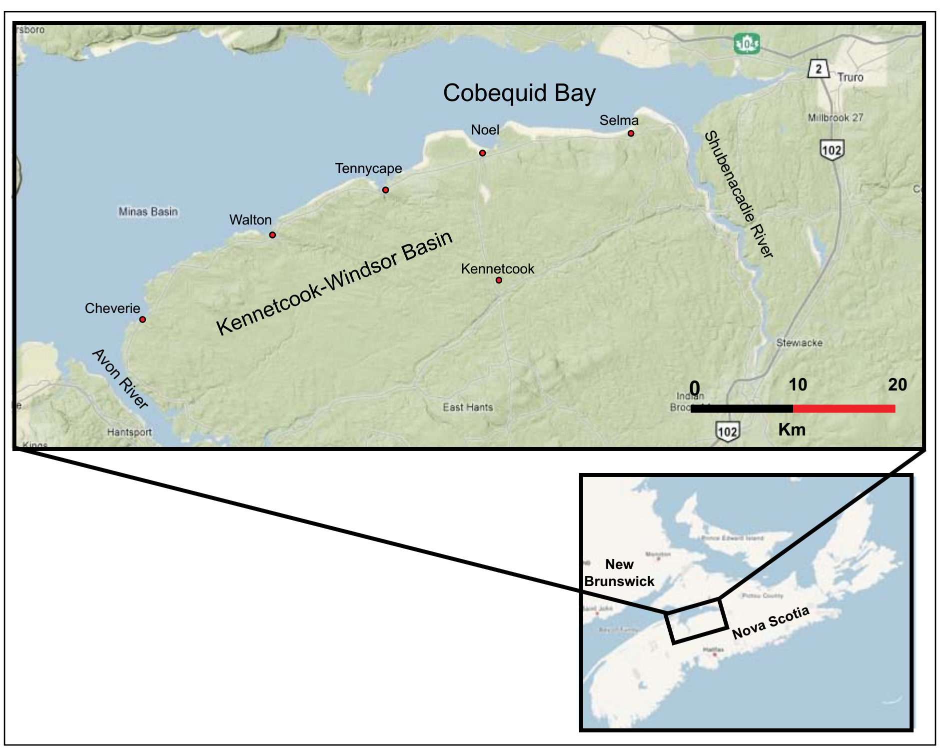


Figure 1.4: Location map of the study area, Kennetcook-Windsor basin, NW Nova Scotia.

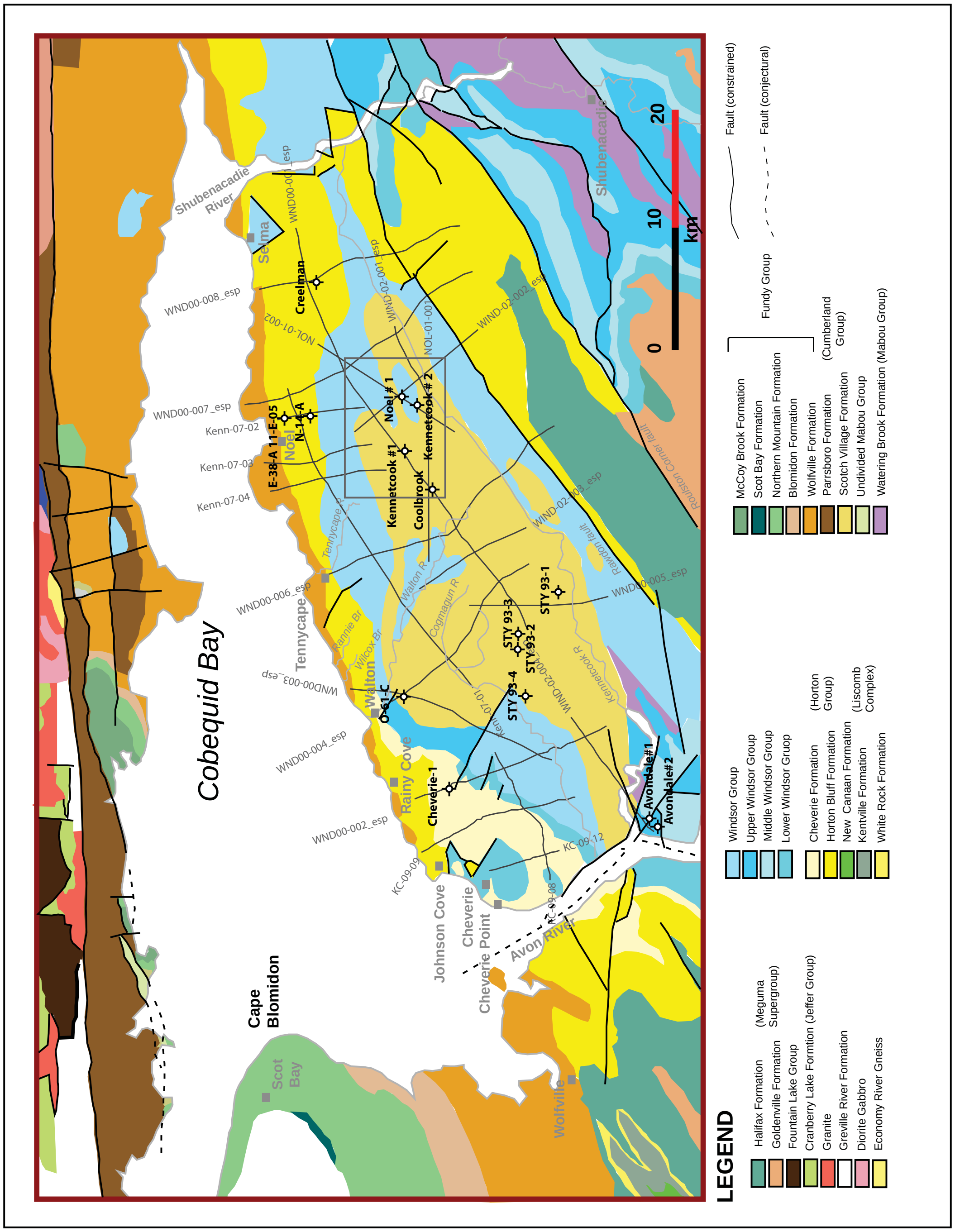


Figure 1.5: Geological map with seismic coverage and exploration wells drilled in the study area.

2D sesimic data

Survey	Operator	Line Name	km	Shotpoint (sp)		Data Type	Source
				first	last		
Windsor (August 2000)	Northstar Energy	WND00 - 001	36	1017	3384	Filtered Pre-stack Migration	Dynamite
		WND00 - 002	16	1111	2200	Filtered Pre-stack Migration	Dynamite
		WND00 - 003	17	1050	2185	Filtered Pre-stack Migration	Dynamite
		WND00 - 004	16	1001	2035	Filtered Pre-stack Migration	Dynamite
		WND00 - 005	11	1001	1732	Filtered Pre-stack Migration	Dynamite
		WND00 - 006	22	1001	2488	Filtered Pre-stack Migration	Dynamite
		WND00 - 007	21	1225	2620	Filtered Pre-stack Migration	Dynamite
		WND00 - 008	18	1070	2260	Filtered Pre-stack Migration	Dynamite
Noel (September 2001)	Northstar Energy	NOL - 01 - 001	13	101	755	Filtered Pre-stack Migration	Dynamite
		NOL - 01 - 002	13	101	741	Filtered Pre-stack Migration	Dynamite
Windsor (July 2002)	Contact Energy	WIND - 02 001	7	101	460	Filtered Pre-stack Migration	Dynamite
		WIND - 02 002	13	101	730	Filtered Pre-stack Migration	Dynamite
		WIND - 02 003	10	101	600	Filtered Pre-stack Migration	Dynamite
		WIND - 02 004	12	101	678	Filtered Pre-stack Migration	Dynamite
Kennetcook (Nov 2007)	Triangle Petroleum Corp	Kenn - 07 -01	27	97	1910	Filtered Migrated Stack	Dynamite
		Kenn - 07 -02	7	111	601	Filtered Migrated Stack	Dynamite
		Kenn - 07 -03	9	86	676	Filtered Migrated Stack	Dynamite
		Kenn - 07 -04	9	101	701	Filtered Migrated Stack	Dynamite
Kennetcook (Oct 2009)	Triangle Petroleum Corp	KC - 09 - 08	11	106	828	Filtered Pre-stack Migration	Dynamite
		KC - 09 - 09	13	114	1011	Filtered Pre-stack Migration	Dynamite
		KC - 09 - 12	6	101	511	Filtered Pre-stack Migration	Dynamite

3D seismic data

Survey	Operator	Line Name	Area	sp line spacing	rec. line spacing	Data Type	Source
Kennetcook 3D (Oct-Nov 2007)	Triangle Petroleum Corp	Inline, Xline	64 sq.km.	420	300	Filtered Migrated Stack	Dynamite

Table 1: 2D and 3D seismic dataset available for the project.

Well Name	Company	Spud Date	Rig Released	Total Depth (m)	Status
Noel # 1	SOQUIP A.C.C	July 18, 1975	August 13, 1975	1447.80	Plugged & Abandoned
Coolbrook	Northstar Energy	February 19, 2001	April 14, 2001	1349.00	Plugged & Abandoned
Creelman	Northstar Energy	April 22, 2001	June 16, 2001	1407.00	Plugged & Abandoned
Cheverie # 1	Deven Canada	November 10, 2001	November 30, 2001	1394.00	Plugged & Abandoned
Kennetcook #1	Elmworth Energy	August 26, 2007	September 15, 2007	1385.00	Plugged & Abandoned
Kennetcook #2	Elmworth Energy	September 18, 2007	October 13, 2007	1935.00	Plugged & Abandoned
N - 14 - A/11-E-05	Elmworth Energy	July 7, 2008	August 20, 2008	2618.00	Suspended
O - 61 - C/11-E-04	Elmworth Energy	August 24, 2008	October 9, 2008	2955.00	Suspended
E - 38 - A/11-E-05	Elmworth Energy	October 22, 2008	November 11, 2008	1726.00	Suspended
Avondale#1	Northstar Energy	December 15, 1999	December 18, 1999	298.00	Plugged & Abandoned
Avondale#2	Northstar Energy	January 19, 2000	January 22, 200	210.00	Plugged & Abandoned

Table 2: Details of the wells available for the project.

2. Geological field results

The Kennetcook-Windsor basin lies to the south of the Cobequid-Chedabucto Fault Zone (CCFZ) in the northwestern part of Nova Scotia and contains deformed Carboniferous sedimentary rocks (Figure 1.1). Geological field work was carried out in the northern part of the Kennetcook-Windsor basin during July – August, 2009 (Figure 1.5).

A base camp at Noel was setup to access coastal and inland outcrops marked on available geological maps. Logistically, the area is approachable by a network of excellent roads. As this area is close to Cobequid Bay where the world's highest tides have been recorded, so tide table and weather forecasts were very helpful in planning daily traverses especially in the coastal areas. The field party comprised John Waldron (supervisor), Jennifer Noade (research assistant) and myself.

2.1. Objectives

The purpose of this field work was as follows:

1) Geological reconnaissance of the area between Walton to Selma/Maitland covered by the seismic profiles and exploration wells (Figure 1.5).

2) Recognise different formations on the basis of their lithological characteristics and distinguish them in the field.

3) Collect structural data, observations and interpretations to assist with interpretation of seismic data and regional structure.

2.2. Stratigraphy of the study Area

Carboniferous and Triassic rocks exposed in the study area can be described in terms of the following lithostratigraphic scheme developed over past few decades by many workers (Bell, 1929 & 1958; Barss and Hacquebard, 1967; Barss et al., 1979; Giles, 1981; Ryan et al., 1991; Gibling, 1995; Gibling et al., 2008).

2.3. Horton Group

The Late Devonian to Tournaisian Horton Group rocks are the oldest rocks exposed in the Kennetcook basin and rest unconformably on the Meguma Supergroup in the west around Windsor (Gibling, 1995; White, 2008; Waldron et al., 2010). Rocks of the Horton group consist of dark gray to black splintery shale, fine to medium-grained sandstone, siltstone, and minor thin beds of medium gray limestone. The type sections of the Horton Group formations are exposed along the east and west banks of the Avon River in the western part of the Kennetcook-Windsor basin (Figure 1.5).

The Horton group is divided into two formations which are mapable in the project area.

2.3.1. Horton Bluff Formation

The Horton Bluff Formation is composed of braided-fluvial sandstone and conglomerate, lacustrine-deltaic sandstone, siltstone and shale. The sandstone is light to medium gray, fine to medium grained and locally coarse-grained particularly in the upper part. The siltstone and shale are of medium to dark gray color. Martel and Gibling (1996) have divided the Formation into four members. The basal Harding Brook member contains a braided-fluvial sandstone and conglomerate package. The overlying Curry Brook member is a succession of fine-grained sandstone and siltstone alternating with dark gray shale. The Blue Beach member consists of coarsening and shallowing-upwards succession of sandstone and siltstone units with hummocky cross-stratification alternating with paleosol horizons (2 – 3 m thick) in the type section. The uppermost Hurd Creek member is composed of sandy deltaic packages alternating with thin beds of dark gray shale. Distinctive “glass sands” (historically used for glass-making) of good reservoir quality are found in the uppermost part of the Horton Bluff Formation (Moore, 1986).

The Horton Bluff Formation in the type section at Avonport (west bank of Avon River, Figure 1.5) has gentle dips (9^{o} – 25^{o}) towards the SE and NE. Small scale fault-propagation folds and ramp anticlines are present in the fine-grained sandstone beds associated with faults. Overall the whole package is mildly deformed as indicated by gentle dips.

2.3.2. Cheverie Formation

The Cheverie Formation consists of gray to reddish gray, maroon, red-brown shale and fine to medium grained gray, light maroon, and brown-red sandstone which is locally arkosic and micaceous. These shale and sandstone units locally alternate with dark maroon paleosols horizons 2 – 3 m thick as observed in the Cheverie Point section (Figure 1.5) where the total exposed thickness of the formation was measured as 183 m in this study. The gray and reddish brown colour and the mildly calcareous, arkosic and micaceous nature of the sandstone beds clearly distinguish this unit from the Horton Bluff Formation, and these criteria were used in the field to distinguish both formations.

2.4. Windsor Group

The Middle to Late Visean Windsor Group represents the only marine succession in the Maritimes Basin and has its type area in the western Minas Basin (Utting, 1978, Gibling, 1995). It consists of marine limestone, gypsum/anhydrite, halite and typically red-brown or maroon calcareous mudstone, sandstone, and subordinate shale.

In the Minas Basin, the Windsor Group is represented by nine formations mapped on available geological maps (Moore and Ryan, 1976; Moore and Ferguson, 1986; Moore et al., 2000). These formations include: the Macumber, White Quarry, Tennycape, Stewiacke, Miller Creek, Wentworth Station, Pesaquid Lake and Murphy Road formations. The upper part of the Windsor Group is not exposed east of Avon River up to Maitland. However, in the banks of the Shubenacadie River a variety of thick white, black, greenish gray, orange gypsum/anhydrite packages alternating with maroon sticky mudstone, siltstone, and occasional thin beds of limestone is exposed that represents the Windsor Group rocks. Naylor et al. (2005) have mapped these limestones, mudstone, and gypsum/anhydrite facies as the Carrolls Corner, McDonald Road and Green Oaks formations which are the lateral equivalent of the White Quarry-Stewiacke, Miller Creek-Wentworth Station, and Pesaquid Lake-Murphy Road formations.

In the study area, well indurated limestone breccia was found at the top of the Macumber Formation. This unit (2 – 3 m thick) contains gray and red-brown limestone, mudstone and evaporite clasts of varying sizes (~ 2 – 10 cm) embedded in a fine-grained calcareous matrix. This breccia unit is referred to as Pembroke Breccia and reported by many authors (Weeks, 1948; Hudgins, 1984; Giles and Lynch, 1994; Lavoie et al., 1995; Lavoie and Sangster, 1995). The genesis of these breccias has been a subject of debate on the basis of field observations and relationship with the underlying and overlying rocks. However, field investigations integrated with the subsurface seismic interpretation (chapter 4) suggest that secondary processess (e.g. dissolution and structural collapses) were responsible for the generation of these tectonic breccias.

In the area between Walton and Maitland (Figure 1.5), Windsor Group rocks mostly mapped as the Macumber Formation, Pembroke Breccia and White Quarry Formation have scattered outcrops in faulted contact with the Horton Group rocks. A brief lithological description of Windsor Group rocks seen in the area is given here for identification purpose.

2.4.1. Macumber Formation

The Macumber Formation is composed of thinly bedded, finely laminated medium gray, brown-red, maroon argillaceous and arenaceous limestone. The maximum measured thickness of the Macumber Formation is about 20 m (Moore, 1996). The Formation has sharp contact with the underlying Cheverie Formation and may contain some calcareous siltstone/shale beds in the basal part as observed in the Walton area just south of the highway bridge (Figure 2.1).

2.4.2. Pembroke Breccia

Brecciated limestones embedded in argillaceous/arenaceous limestone matrix are present at the top of the Macumber Formation and were observed in the Cheverie point, Johnson Cove, Walton, Tennycape River and Shubenacadie River sections (Figure 1.5).

2.4.3. White Quarry Formation

The White Quarry Formation consists of thick, massive gypsum and anhydrite with thin intercalations of limestone and some black shale in places as observed in the abandoned gypsum quarries southeast of Walton area (Figure 2.1). The formation contains a variety of white, black, orange, green and gray gypsum/anhydrite.

2.4.4. Tennycape Formation

The Tennycape Formation was named by Weeks (1948) but he did not designate a type section. The formation is not present in the Windsor Group type area; however, it is well exposed in the Tennycape River and is composed of splintery red, brown, or green arenaceous shale and yellowish mudstone (Williams et al., 1985).

Weeks (1948) has described the Tennycape Formation to overlie a lower sulphate bed that is a lateral equivalents of the White Quarry Formation. Moor and Ryan, (1976) described the Tennycape Formation as conformably overlying the Visean White Quarry Formation. Giles (1981) has defined the formation to overlie the Pembroke Breccia where the sulphate bed is absent in the Minas Basin.. It may be the lateral equivalent of the Miller Creek Formation in the Kennetcook-Windsor basin (Williams et al., 1985).

2.4.5. Stewiacke Formation

The formation comprises thick stratified halite (salt) and minor interbeds of anhydrite and gray-green and red siltstone (Moore et al., 2000). These deposits represent restrcited shallow marine saline enviroment of deposition. Due to soluble nature of the salt and anhydrite, the Stiwiacke Formation has not been well-established in the study area. Only one well Avondale#2 (Figure 1.5) drilled about 8 m of white to clear halite of the Stewiacke Formation.

2.4.6. Miller Creek Formation

The Miller Creek Formation is composed of interbeds of highly fossiliferous medium to dark gray limestone and white gypsum/anhydrite with minor gray-green siltstone and fine-grained sandstone (Moore et al., 2000). The formation represents cyclic shallow marine and restrcited saline environment of deposition. Bryozoan and brachiopod broken shells sometimes exhibit excellent geo-petal structures (cavities filled with sedimentary layers) which can be used to determine the right way up. This limestone has highly deformed outcrops along the south bank of the mouth of the Kennetcook River.

2.4.7. Wentworth Station Formation

This Formation contains gypsum/anhydrite, occasional interstratified thin beds of fossiliferous limestone, red and gray-green siltstone and fine-grained sandstone. The formation represents cyclic shallow marine deposits of evaporites, continental redbeds and marine carbonates (Moore et al., 2003). The Wentworth Station Formation has scattered outcrops just southeast of the junction of the Avon and the Kennetcook rivers in the western part of the study area. Lateral equivalents of this formation (McDonald Road Formation; Naylor et al., 2005) are also exposed along the Shubenacadie River.

2.4.8. Pesaquid Lake Formation

The Pesaquid Lake Formation comprises red, gray-green mudstone, siltstone and fine-grained sandstone with thin intercalations of marine limestone. This formation also represents cyclic continental redbed and shallow marine deposits. The formation has some scattered outcrops just south of Windsor town. The Pesaquid Lake Formation has similar lithological characteristics and is correlatable with the Green Oaks Formation that has been mapped along the Shubenacadie River by Naylor et al. (2005).

2.4.9. Murphy Road Formation

This formation is mainly composed of red, gray-green siltstone and fine-grained sandstone with thin beds of distinctive fossiliferous limestone and occasional thin beds of gypsum/anhydrite. The formation has widespread outcrops just east of the Windsor and along the Kennetcook River in the western part of the study area. The formation is closely correlatable with the Green Oaks Formation (Naylor et al., 2005) in the eastern part of the area along the Shubenacadie River.

2.5. Mabou Group

The Mabou group, Late Visean to Early Namurian, represented by the Watering Brook Formation, is exposed between Scotch Village and Brooklyn areas along the south bank of the Kennetcook River (Figure 1.5). The Watering Brook Formation was not examined in outcrops in the course of the project. The Mabou Group rocks are not exposed in the northeastern part of the study area.

Moore et al. (2000) have described a succession of gray, green-gray laminated mudrocks (calcareous shale, siltstone and fine-grained sandstone) in the upper part. Interbedded gypsum, anhydrite, and minor salt are present in the lower part. These lithologies represent restricted shallow marine and saline continental lacustrine environments of deposition (Moore et al., 2000).

2.6. Cumberland Group

The Cumberland Group in the Kennetcook basin is represented by Namurian to Middle Westphalian Scotch Village Formation. The Formation is poorly exposed even along the inland brooks. The geological map by Stevenson (1958) shows a widespread exposure of the Scotch Village Formation in a regional NE-SW trending synform. Cores from the diamond drillholes STY 93-1, -2, -3 and -4 in the Stanley area (region between Cogmagun and Kennetcook rivers, Figure 1.5) confirmed the presence of Scotch Village Formation (Boehner and Edgecombe, 1993).

The Formation contains gray to yellowish brown sandstones interbedded with gray to brown shales and contains some occasional thin coal and plant debris. Moore (1996) has interpreted this succession as continental fluvial floodplain. The Scotch Village Formation is interpreted to have an unconformable contact with the underlying Windsor Group rocks.

2.7. Fundy Group

The Fundy Group in the Kennetcook-Windsor Basin represents syn-rift sediments that were deposited in the Fundy graben during the early (mid-Triassic to Early Jurassic) break-up of central Pangea (Wade et al., 1996; Withjack et al., 2009). These rift-related sediments are included in the Newark Supergroup and have been divided into the following four formations in an ascending order: the Wolfville Formation; the Blomidon Formation; the North Mountain Basalt; and the Scots Bay Formation (Wade et al., 1996). However, Withjack et al. (2009) in their recent work have included the basal part of the Fundy Group in the Honeycomb Point Formation which is possibly of Late Permian age.

The Wolfville Formation, Middle to Late Triassic (Wade et al., 1996; Moore et al., 2000) has excellent coastal exposures in the northern Kennetcook-Windsor basin (Figure 1.5). The Formation consists of a variety of orange, red to brown, medium to coarse, in places very coarse sandstone, pebbly sandstone, conglomerate and minor shale (Wade et al., 1996). Channelized sandstones show large trough cross beds which gently dip north and north-northwest. Conglomerate beds are more frequent in the western part between Walton and the Avon River (Figure 1.5). The sandstones are moderately hard, poorly sorted and dominantly arkosic in nature. These sand bodies have been interpreted as alluvial fan, sand flat and braided river deposits (Wade et al., 1996; Moore et al., 2000). Semi-arid to sub-humid conditions prevailed during the deposition of the Wolfville Formation (Tarner, 1993 in Wade et al., 1996). Only the lower part of the formation (about 10-50 m) is exposed in the study area. However, the maximum thickness is estimated to be more than 3000 m in the Minas Basin (Wade et al., 1996).

Withjack et al. (2009) have documented two phases of deformation in the Fundy graben: syn-depositional extension; and the post-depositional inversion which uplifted the eastern part of the graben and caused considerable erosion of the Fundy Group. The extensional phase represents the inversion of the Acadian thrust system that was active during the Appalachian orogenesis in the Atlantic Canada and juxtaposed the Avalon and Meguma terranes (Wade et al., 1996).

The syn-rift sediments represented by the Wolfville Formation exhibit mild deformation and have an angular unconformable relationship with the underlying mildly to intensely deformed Carboniferous rocks in the study area. Offshore seismic data from the Cobequid Bay indicate that these syn-rift sediments thicken north and northeast and may host a valid petroleum system in the area (Withjack et al., 2009).

2.8. Stratigraphic/structural observations of the visited sections

During this short reconnaissance field investigation, most of the coastal sections which have had exposed Horton, Windsor and Fundy group rocks were visited.

Lithological descriptions and characteristic features of the rocks exposed at each station were noted. Structural data collected during the course of this field work were plotted on orthophoto maps available at 1: 10, 000 scale, and stereographic projections. The area from Walton to Maitland including the Shubenacadie River section was traversed to identify formations of the Horton, Windsor, Cumberland and Fundy groups. Some inland traverses along Cogmagun and Walton rivers, and Ross, Cool, Rannie and Wilcox books (Figure 1.5) were also made to visit the outcrops marked on existing Kennetcook, Bass River, and mineral assessment geological map sheets. Observations taken during these traverses are discussed in the following section.

2.8.1. Walton – Whale Cove

In Walton area, the Macumber, White Quarry, Cheverie, Horton Bluff and Wolfville formations were mapped (Figure 2.1). The Macumber/Cheverie contact is exposed just south of the highway 215 bridge built on the Walton River (Figure 2.1). The contact between Cheverie and Horton Bluff formations is obscured in thick vegetation along the left bank of the Walton River where it enters Cobequid Bay in the north (Figure 2.1). The Curry Brook and Blue Beach members (Martel and Gibling, 1996) of the Horton Bluff Formation are exposed in this section. However, due to intense deformation and vegetation cover at the mouth of the Walton River, it is difficult to mark a boundary between the members.

Cheverie and Horton Bluff formations dip steeply (60^o – 70^o) southeast on the left bank of the Walton River. On the right bank, dip angles are variable due to folding. The folds show variably overturned limbs and have asymmetry and variable fold wavelengths. The Wolfville Formation, in the coastal exposures, dips gently north-northwest and has angular unconformable contact with the underlying steeping dipping Horton Bluff Formation.

Due to intense deformation within Horton Bluff Formation, the attitude and orientations of beds are highly variable. Tight, asymmetrical and chevron folds have excellent exposures, occurring in antiform-synform pairs plunging moderately towards southwest. These fold pairs occur at a highly variable scale. Some multiple folds have curvilinear axial surfaces. Roselli (2003) and Waldron et al. (2007) have interpreted these folds as the earliest formed folds and classified them as F1/F2. This early generation of folds were overprinted by the later phase of F3 folds that have axial traces crossing the curved hinges of F1/F2 folds (Waldron et al., 2007). These folds have excellent exposures along the Rainy Cove – Walton section (Figures 2.2 & 2.3).

Highly deformed Horton Bluff Formation is exposed in the cliffs as well as on the shore and extends eastwards towards Whale Cove where it has faulted contact with the Cheverie Formation. Due to intense deformation and possible fault splays, the contact between Horton Bluff and Cheverie is not clear. Further east the Cheverie Formation has faulted contact with Macumber/Pembroke Formation that shows a highly brecciated zone with steep dips (Figure 2.4). Intense shearing has produced local mylonitic fabric in the Macumber Formation.

Moore and Cormier (1994) have shown repeated Macumber/Pembroke Breccia outcrops in multiple fault offsets around Whale Cove on their geological map of the Walton – Rainy Cove Brook Quadrangle. We did detailed investigations of these outcrops and traced them off-shore on the beach during a falling to low-tide interval and did not find any faulted repetition of the Macumber Formation and Pembroke Breccia. Only one small outcrop on the cliff-face extends off-shore towards Cobequid Bay.

Figure 2.5 shows a stereoplot (pi-diagram) containing poles to the bedding planes and the best-fit great circle which gives the trend and plunge of the mean fold axis 245-09 in this section. These gently southwest plunging folds are interpreted here the latest generation of F3 folds which were described by Waldron et al. (2007). It is difficult to constraint the timing of these F3 folds in the absence of any magmatic activity that could have intruded these deformed sediments.

2.8.2. Wilcox – Rannie Brooks area

Wilcox and Rannie brooks are located between Whale cove and Tennycape (Figures 1.5 & 2.6). Both brooks have good access under the bridges on highway 215. Light to medium gray, fine to medium grained sandstone alternating with siltstone and dark gray to black splintery shales exposed in these brooks are described here as the Curry Brook and the Blue Beach members of the Horton Bluff Formation. Both brooks have excellent exposures of the deformed Horton Bluff Formation which dips moderately (30^o – 40^o) to steeply (60^o – 70^o) northwest and southeast. Consistent dip direction over a considerable section shows that the Horton Bluff Formation is deformed by long wavelength folds. Some small-scale antiform-synform pairs within fine-grained sandstone and siltstone sequence were also observed along Wilcox brook.

A stereoplot (pi-diagram) shows that the trend and plunge of the long wavelength F3 fold axis is 210-24 (Figure 2.7) and indicates that the axis plunges slightly more steeply than that estimated for the Walton-Whale cove section (Figure 2.5) but the southwest plunging direction is consistent.

2.8.3. Tennycape

The Horton Bluff Formation is exposed at the mouth of the Tennycape River north of highway 215 (Figure 2.8). A fine to medium-grained sandstone-siltstone succession dips steeply (50^o-75^o) southeast, but some overturned beds have opposite dips towards the northwest. Northwards, the Horton Bluff Formation has angular contact with the overlying Wolfville Formation which dips very gently NNW and extends offshore (Figure 2.8). Light to medium gray, medium to coarse-grained, 2-3 m thick beds of sandstone have very distinct exposure at the mouth of the Tennycape River and could be described as the "glass sand" of Moore (1986). Lithological characteristics of the rocks and presence of the "glass sand" indicate that the uppermost, Hurd Creek member, of the Horton Bluff Formation is exposed at the mouth of the Tennycape River.

Just 15 – 20 m south of the highway bridge on Tennycape River (Figure 2.8), brown-maroon, arkosic, micaceous and fine to medium sandstone alternating with gray shale/siltstone is exposed along the left bank of the Tennycape River. We described and mapped this sequence of sandstone, siltstone and shale as Cheverie Formation and traced this succession southwards through scattered outcrop along the river meanders. Further south along the river, a small outcrop of Macumber/Pembroke limestone is exposed along a high cliff. Further upstream, thick vegetation has covered the outcrops of the Tennycape Formation, White Quarry gypsum/anhydrite, and other formations of the Windsor Group.

Horton Group rocks in the Tennycape area are moderately deformed as compared to Walton area. However an antiform-synform pair, asymmetric to over-turned and trending NE – SW, is present within the Cheverie Formation. These could be part of the larger-scale folds. The Horton Group in the Tennycape area probably represents the autochthonous sheet. A stereoplot (pi-diagram) shows the distribution of the poles to the bedding planes and the trend and plunge of the fold axis is 244-27 (Figure 2.9) which is comparable to that estimated for the Wilcox-Rannie brooks (Figure 2.7).

2.8.4. Selma-Maitland

This section covers an area between St. Anthony Park and northern Maitland along the coast at the mouth of the Shubenacadie River (Figure 2.10). Mostly along the coast, gently dipping Wolfville Formation is exposed which extends offshore towards the Cobequid Bay. Some scattered outcrops of Cheverie sandstone-siltstone alternating with maroon shale between St. Anthony Park and Selma were mapped during the course of this traverse. The Cheverie Formation in this area dips moderately (30^o – 60^o) towards

NW and then NE forming a long wavelength fold trending NE.

In the Selma area, around Selma River meanders (Figure 2.10), there are some scattered outcrops of fine to medium-grained, thick and massive, maroon and light gray micaceous sandstone that was mapped here as the Cheverie Formation. The overlying basal Windsor Group rocks (Macumber/ Pembroke, White Quarry etc.) were found absent in and around the Selma River mouth. However, south of the Selma River bridge on highway 215 (Figure 2.10), a small outcrop of greenish gray, maroon, mottled mudstone with some cross-cutting gypsiferous veins is present. This outcrop seems to the part of the Pesaquid Lake Formation (Windsor Group) as observed in the Shubenacadie River banks. However, north of this bridge, the Macumber Formation, Pembroke breccia and White Quarry gypsum have been shown as a triangular structural outlier on the Londonderry geological mapsheet (Weeks, 1948). This angular outcrop of the basal Windsor Group rocks is questionable as the Cheverie Formation sandstone has surface exposures in the area where the Macumber Formation and Pembroke breccia have been mapped previously.

A stereoplot plotted for the measured bedding planes in the Selma-Maitland section shows that the trend and plunge of the fold axis is 256-21 (Figure 2.11) comparable with that determined for the Tennycape section (Figure 2.9).

2.8.5. Shubenacadie River Section

This section was accessed through eastern and western traverses to observe the exposed geology along both river banks. During eastern traverse, Black Rock, Princeport, and Eagles Nest localities were visited (Figure 2.12). Mostly middle to upper Windsor Group rocks are exposed along the eastern bank of the river except at Black Rock and Eagles Nest where Macumber Formation/Pembroke Breccia and the Cheverie Formation are exposed respectively (Figure 2.12). North of the Eagles Nest, the topography is nearly flat with vegetation, probably due to soluble nature of gypsum/anhydrite and shales. This is confirmed by the excellent exposures of a variety of gypsum/anhydrite lithologies on the opposite side of the river. The rest of the section has exposed red-brown, maroon, greenish gray, moderately hard mudstone having local intercalations of siltstone, gypsum/ anhydrite and thin limestone beds in some cliff faces.

Naylor et al. (2005), on their geological map of the Truro area, have mapped a thick succession of red-maroon mudstone, siltstone, gypsum/anhydrite and thin beds of limestone. They have subdivided the whole section into the MacDonald Road, Green Oaks and Carrolls Corner formations. The Carrolls Corner Formation mapped by the

Naylor et al. (2005) is the lateral equivalent of the White Quarry Formation exposed in the Kennetcook-Windsor basin. Whereas, the thick succession of red-maroon mudstone, siltstone with minor beds of gypsum/anhydrite and gray limestone mapped in the Shubenacadie River banks is the lateral equivalent of the Pesaquid Lake and the Murphy Road formations.

At Eagles Nest (Figure 2.12), Cheverie sandstone is exposed, making a high cliff, and dips moderately (25^o – 35^o) towards NE. Further south towards Shubenacadie River bridge (Figure 2.12), again a succession of the middle to upper Windsor Group rocks comprising maroon mudstone, minor gypsum and limestone is exposed along the eastern bank. Naylor et al. (2005) have marked this sequence as undifferentiated Windsor Group rocks due to limited outcrop information. Our field observations show that this succession mapped as undifferentiated Windsor group rocks seems to be the lateral equivalent of intensely deformed Pesaquid Lake and the Murphy Road Formations exposed in the southwest of the Kennetcook-Windsor basin.

A stereoplot (pi-diagram) plotted for the bedding planes measured in the Shubenacadie River section shows the distribution of the poles to the bedding planes and the trend and plunge of the fold axis is 180-12 (Figure 2.13). This orientation of the fold axis shows that the shortening direction was east-west and is different from the orientation estimated in the Selma-Maitland, Tennycape, Wilcox-Rannie brooks and the Walton-Whale cove sections. However, this interpretation is nearly consistent with the orientation of the fold axes (SSW-NNE) in the St. Marys Basin (Stevenson, 1958; Naylor et al., 2005) and indicates that the Shubenacadie River section marks the structural boundary between the Minas and the St. Marys basins. Fold axes rotated more southwards at the eastern margin of the Minas basin. Figure 2.14 shows the overall distribution of the poles to the bedding planes that were measured during this field work.

2.9. Discussion and Interpretation

The Kennetcook basin in the NW Nova Scotia contains deformed Carboniferous rocks that have been periodically affected by the movement along E-W striking Cobequid-Chedabucto Fault (Waldron et al., 2007). Due to deformation along this regional fault boundary between the Avalon and Meguma terranes, Carboniferous rocks were distributed in distinctive structural domains across both sides of the fault (Waldron et al., 2007 & 2010).

Intensely folded coastal sections (e.g. Cheverie, Rainy Cove, Walton-Whale Cove and Tennycape) within the Horton Group rocks show a complex history of deformation in terms of fold interference patterns (Figures 2.2 & 2.3). Waldron et al. (2007) have documented at least three superposed folding phases that form the present day fold patterns. This deformation can be attributed to the dextral transpressive history of the major boundary between Avalon and Meguma (Waldron et al., 2010).

Highly deformed Horton Group rocks, east of Avon River, along the coastal exposures, are definitely allochthonous in nature and have been transported southward (Waldron et al., 2010) along shallow detachments as indicated by seismic and well (Cheverie-1) data (chapters 3 & 4). Many workers (Keppie, 1982; Boehner, 1991; Moore et al., 2000; Waldron et al., 2007) have discussed structural association of these allochthonous rocks and the surface expression of the thrusts. Waldron et al. (2010) recently have documented this deformation as related to a thrust system which they have termed the Kennetcook thrust system, relating the various splays discussed by the previous workers.

The Kennetcook thrust system contains shallow detachments within the Windsor Group evaporites and seems to extend southward to define the surface exposures of other parallel thrusts that join at depth to form the geometry of a positive flower structure (Waldron et al., 2010). Field observations and bedding attitude of the rocks between Tennycape and Selma have shown (Figures 2.8 & 2.10) that deformation along the Kennetcook thrust progressively diminishes towards the east along the coastal area and possibly the allochthonous rocks have been eroded away expsoing the autochthonous rocks.

Stereoplots (pi-diagrams) indicate that the axial traces dominantly strike NE-SW and the axial planes dip either NW or SE. In contrast, the diagram plotted for the Shubenacadie River section showed that the axial plane strikes nearly north-south and marks the eastern boundary of the Kennetcook-Windsor basin. Structural data have shown that there are two dominant strike directions for the bedding planes that are NE-SW and NW-SE where the latter is dominant in the Shubenacadie River section. These two strike directions are nearly parallel to the strike direction of the subsurface faults mapped at the top of the Horton Bluff and the Cheverie formations. Stereoplots also have shown that the latest folds F3 plunge gently (10^{o}-30^{o}) SW and have long wavelength.

The Fundy Group rocks exposed in the northern part of the study area represent the Mesozoic syn-rift sediments and mark the reactivation of the major Acadian thrust system. This extensional and sinistral reactivation caused rifting in the central Pangea and ultimate development of a series of rift basins. Mild deformation represented by the gently dipping beds and angular unconformable relationship with the underlying

Carboniferous rocks indicate that the intense deformation observed in the Horton and Windsor groups is pre-Mesozoic.

Overall the study area exhibits a complex array of deformation and has preserved the past history of movement along the Cobequid – Chedabucto Fault (CCF) that has played a major role in the development of many basins formed closer to this boundary.

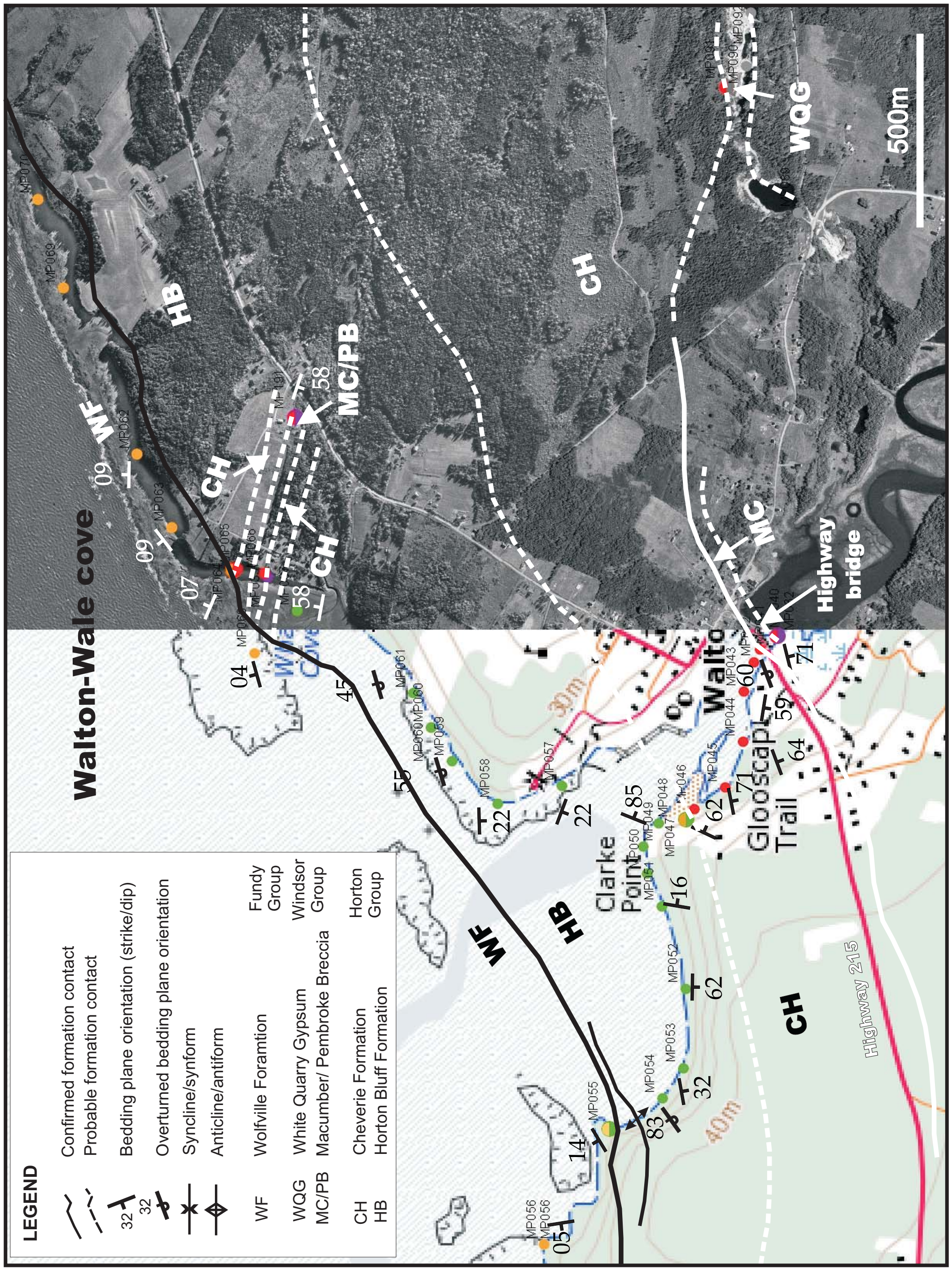


Figure 2.1: Geological map of the Walton – Wale Cove area. Topographic map (western half) was spliced with the orthophoto image (eastern half) due to unavailability of the orthophoto image in the western part.

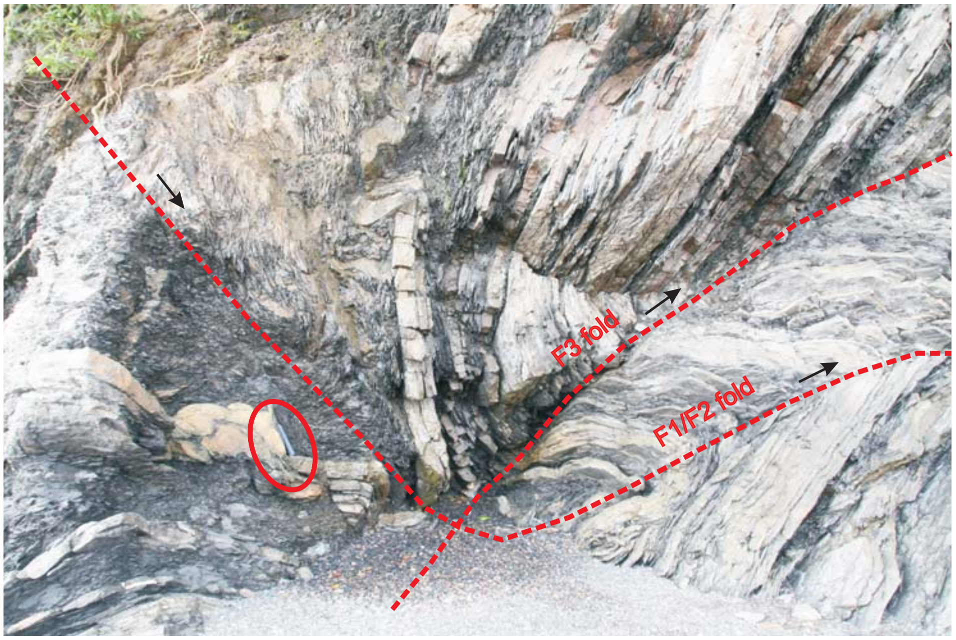


Figure 2.2: Downward facing pair of F1/F2 folds (synformal anticline and antiformal syncline) with curved axial trace developed with the medium to dark grey shale-siltstone beds of the Horton Bluff Formation at the Walton River mouth. The F3 fold shows the latest folding resulted from F1/F2 folds that plunge SW.

Figure 2.3: Upward facing antiforms (large fold and lower fold to the right) and synform (upper tight fold in the right) developed within the thick sandstone beds of the Horton Bluff Formation are exposed in the Rainy Cove. These F1/F2 Folds are plunging moderately towards WNW.

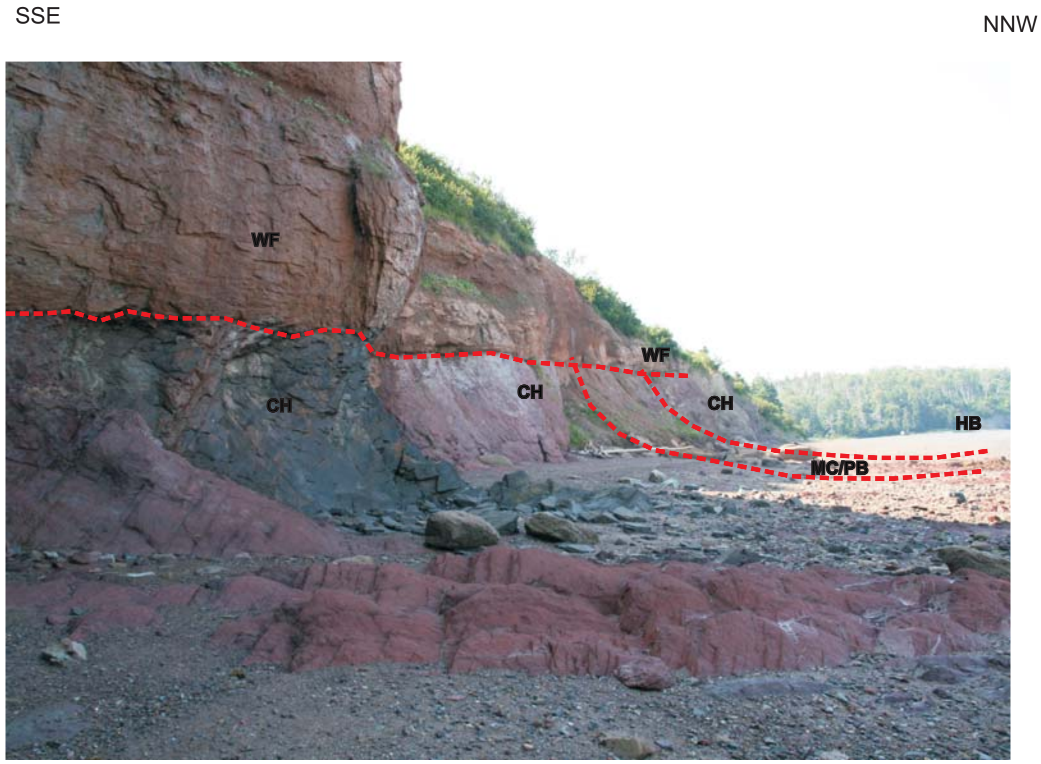


Figure 2.4: West facing photograph showing the angular contact of Wolfville Formation (WF) with the Cheverie (CH), Macumber (MC)/Pembroke (PB) along the Whale Cove shore.

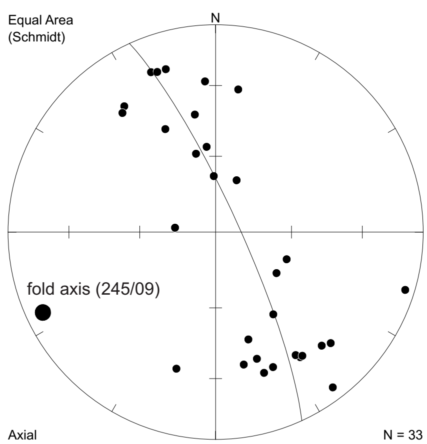


Figure 2.5: Pi-diagram showing the distribution of poles to the bedding planes and the best-fit great circle the pole of which shows the orientation of the fold axes in the Walton-Wale cove area.

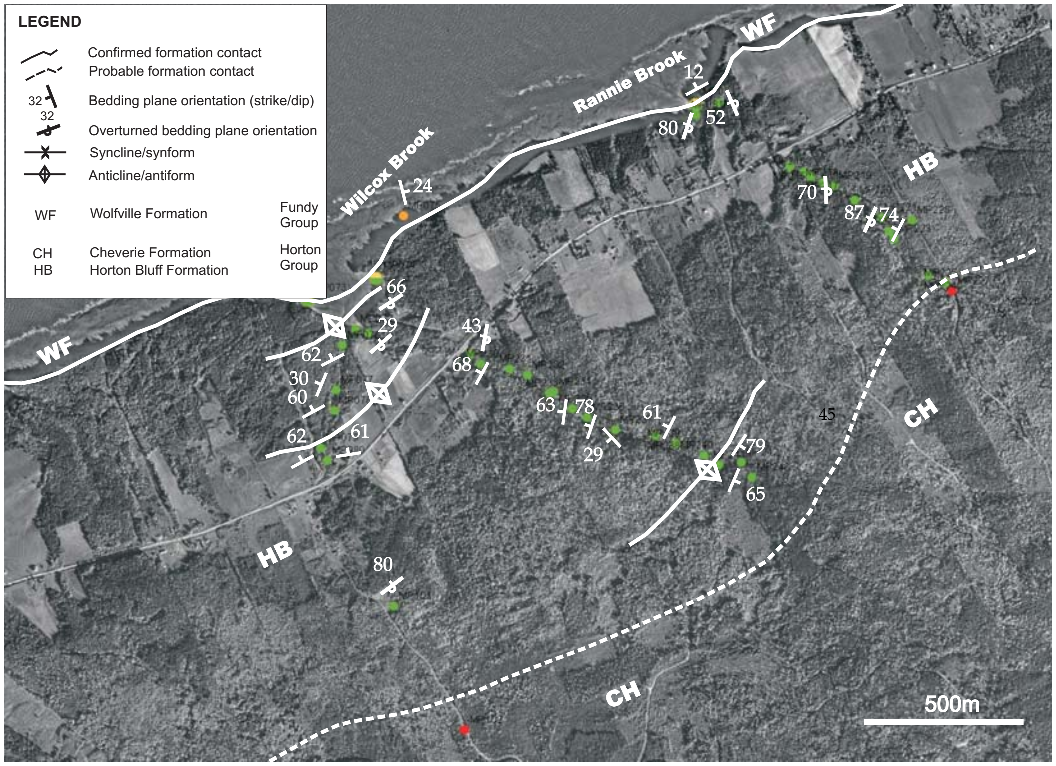


Figure 2.6: Geological map of the Wilcox – Rannie brooks area.

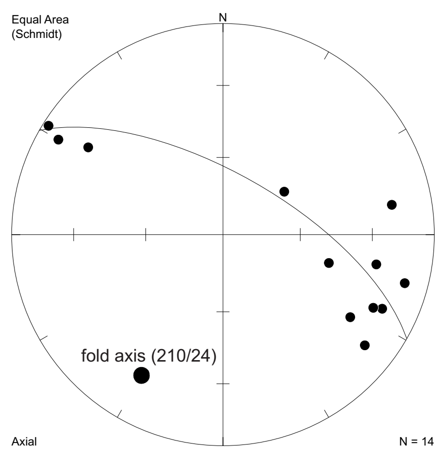


Figure 2.7: Pi-diagram showing the distribution of poles to the bedding planes and the best-fit great circle; pole to this great circle shows the orientation of the fold axes in the Wilcox-Rannie brooks.

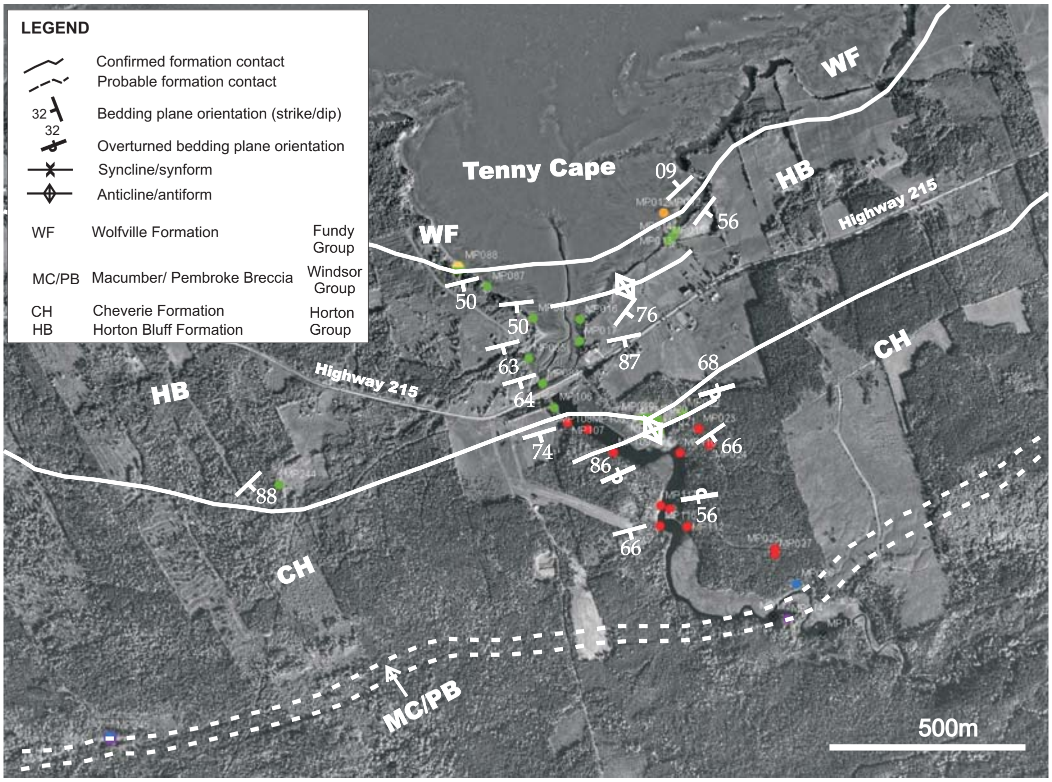


Figure 2.8: Geological map of Tennycape.

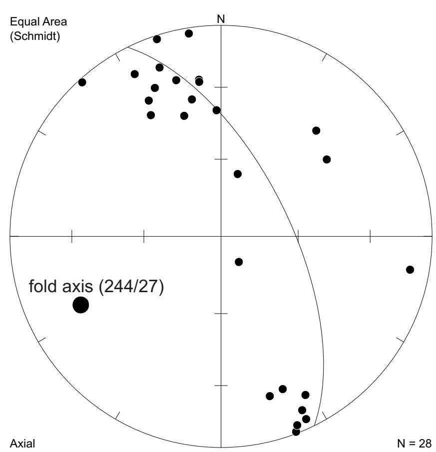


Figure 2.9: A stereoplot (pi-diagram) showing the distribution of poles to the bedding planes and the best-fit great circle; pole to this great circle shows the orientation of the fold axes in the Tennycape area.

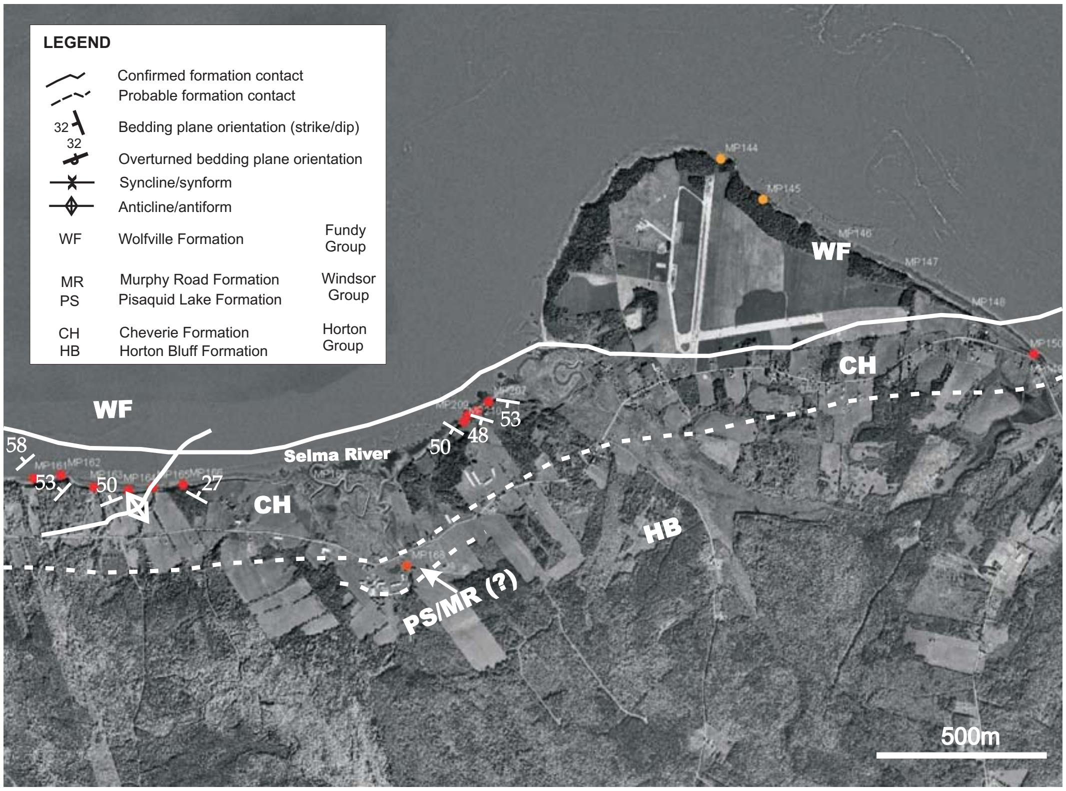


Figure 2.10: Geological map of the Selma – Maitland area exposing Wolfville (WF), Cheverie (CH) and Pesaquid Lake (PS)/Murphy Road (MR) formations.

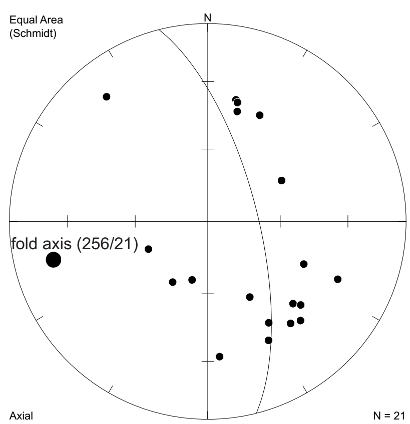


Figure 2.11: A stereoplot (pi-diagram) showing the distribution of poles to the bedding planes and the best-fit great circle; pole to this great circle shows the orientation of the fold axes in the Selma-Maitland area.

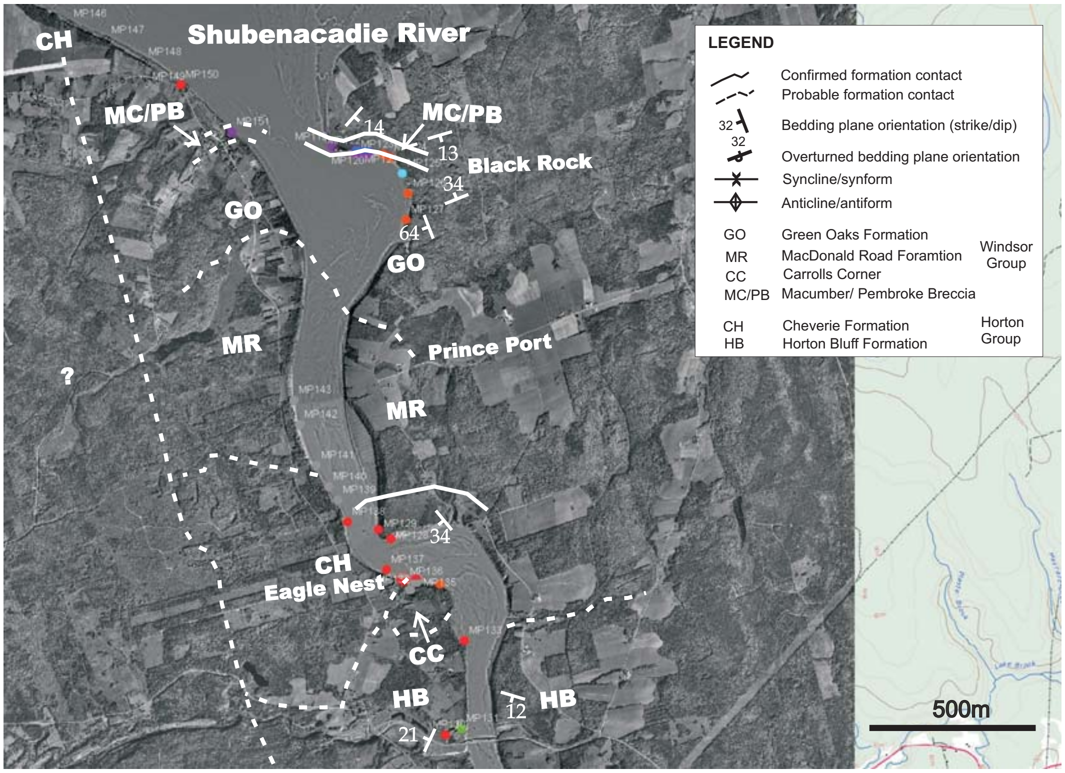


Figure 2.12: Geological map of the Shubenacadie River section. Formations exposed include: HB, Horton Bluff; CH, Cheverie; MC/PB, Macumber/Pembroke; MR, MacDonald Road; GO, Green Oaks formations.

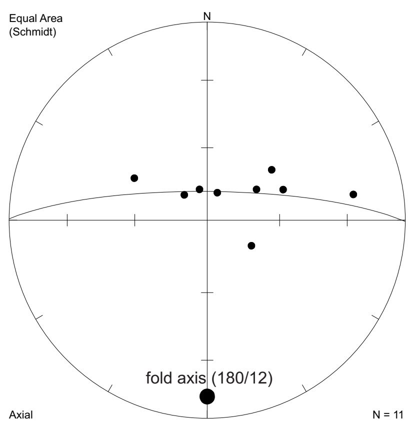


Figure 2.13: A stereoplot (pi-diagram) showing the distribution of poles to the bedding planes and the best-fit great circle; pole to this great circle shows the orientation of the fold axis in the Shubenacadie River section.

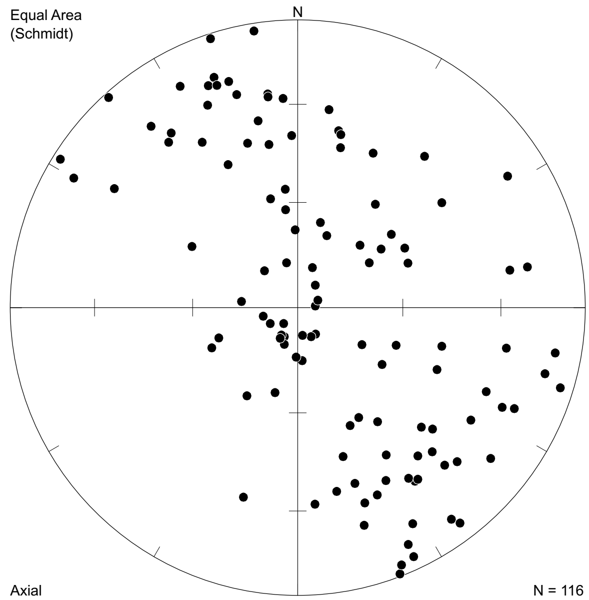


Figure 2.14: A stereoplot showing the distribution of poles to the bedding planes measured in the study area.

3. Subsurface Stratigraphy

This chapter summarizes the subsurface lithologic descriptions of the Maritimes Basin sediments extracted from the mudlogs and their seismic characteristics. Mudlogs of Avondale#1, Avondale#2, Coolbrook-1, Kennetcook-1, Kennetcook-2 and Creelman-1 wells (Figure 1.5) were used for subsurface stratigraphic analysis. Subdivision of drilled sections in different intervals is established for this project on the basis of lithologic variations picked from the ditch-cutting descriptions and net-to-gross ratios estimated for sandstone in each of these intervals. Porosity values are the visual estimates made by using the sand analyzer installed at the well site. Intervals were made in the Horton Bluff and Cheverie formations, the Windsor and the Cumberland Groups. Intervals identified in the Horton Bluff Formation were then correlated with the member subdivisions of Martel and Gibling (1996) to establish the regional correlations across the drilled wells in the basin.

3.1. Well log stratigraphy

3.1.1. Basement

Only three wells, Kennetcook-1, Kennetcook-2 and Noel-1 (Fig 3.1), penetrated basement rocks which have been included in the Meguma Supergroup (White, 2008). Kennetcook-1 penetrated 29 m of basement described as light to moderate gray and black quartzite. On the mudlog both the rate of penetration (ROP, min/m) and the gas chromatograph data show relatively constant trends indicating that the lithology was uniform (Fig 3.2). Kennetcook-2 drilled 23.5 m of basement comprising light greenish cream quartzite described as having schistose texture with minor pyrite crystals (Fig 3.3). Gas chromatograph data do not show any formation gas (FG) detection through this interval. The ROP plot shows a slight decrease in penetration rate which indicates the massive and hard nature of the quartzite present in the upper part of the basement. The Noel-1 well which was drilled just north of Kennetcook-1 penetrated 52 m of similar lithology.

Well logs of Kennetcook-1 & -2 (Fig 3.1) show that the small interval of basement rocks did not allow the wireline tool to record the response of quartzite in the subsurface. However, in Noel-1 (Figure 3.1), Gamma Ray (GR) shows a slight increase relative to the basal Horton Bluff Formation; sonic (DT) velocity and bulk density (RHOB) curve also show an increase with depth at the basement top which corresponds to an increase in the acoustic impedance and therefore is predicted to result in a positive reflection coefficient. A well-to-seismic tie shows that this corresponds to a positive amplitude or peak event as shown on both 2D and 3D reflection profiles (Fig 3.4 & 3.5).

3.1.2. Horton Group

The Horton Group in the Minas Basin is divided into a lower Horton Bluff Formation and an upper Cheverie Formation. Brief descriptions of both formations encountered in different wells (Fig 1.5) and their seismic signature are given in the following text.

3.1.2.1. Horton Bluff Formation

The Horton Bluff Formation in the study area is divisible into four members (Martel and Gibling, 1996) as discussed in chapter 2. On the basis of described ditch cutting samples and net-to-gross ratios, the drilled section of Horton Bluff Formation has been divided into four intervals: lower; lower middle; upper middle; and top interval. These intervals were then correlated with the four members of Martel and Gibling (1996) on the basis of lithological descriptions. However, variations in net-to-gross ratios and thickness are present, due to lateral facies change and intense deformation in the basin.

The Kennetcook-1 well penetrated about 620 m of the Horton Bluff Formation and also drilled about 29 m of the basement rocks. The Kennetcook-2 well encountered 751.5 m of Horton Bluff Formation and drilled down to upper part of the basement rocks (23.5 m). The Coolbrook #1 well penetrated 312.89 m of Horton Bluff Formation and did not penetrate its base. The Creelman well penetrated 1149.4 m of Horton Bluff sediments and also did not drill the base.

3.1.2.1.1. Harding Brook member

In outcrops, this basal member comprises fluvial sandstone and varying amounts of conglomerate, siltstone and mudstone (Martel and Gibling, 1996). Only three wells, Kennetcook-1, Kennetcook-2 and Noel-1, drilled through the basal part of the Horton Bluff Formation. In the Kennetcook-1 well, this basal member is absent as the well was drilled on the downthrown side of a northwest-dipping normal fault which truncated the Harding Brook member. The Kennetcook-2 penetrated the Harding Brook member from 1911.5 – 1495 m MD (measured depth). This basal member of the Horton Bluff Formation is composed of white, fine to medium grained, well sorted, kaolinitic sandstones having 3% visible porosity, with thin intercalations of dark gray to black, carbonaceous shale which is silty in places. Net-to-gross ratio is 0.92.

3.1.2.1.2. Curry Brook member

In outcrops, the Curry Brook member comprises mudstone in the lower part, interbedded siltstone and sandstone in the middle part, and very fine to medium-grained sandstone in the top section (Martel and Gibling, 1996). The Coolbrook-1 well penetrated 211 m, Kennetcook-2 141.5 m, Kennetcook-1 267.5 m and Creekman-1 131.5 m of the Curry Brook member. Lithological descriptions and net-to-gross ratios estimated from the mudlogs are given in table 3. In general, well correlations of the Curry Brook member show that the sand proportion decreases northeast.

3.1.2.1.3. Blue Beach member

In outcrops, the Blue Beach member is composed of gray clay shale, siltstone, and sandstone (Martel and Gibling, 1996). The member was encountered in Coolbrook-1(150.5 m), Kennetcook-2 (129 m), Kennetcook-1 (222.5 m), and Creelman-1 (1021.7 m). Lithological descriptions and net-to-gross ratios estimated from the mudlogs are given in table 4. Well correlations show that the Blue Beach member thickens and comprises much of the interbedded dark gray shale and siltstone in the northeast of the study area. However, the Creekman-1 well drilled a large thickness (1021.7 m) of the Blue Beach member which includes repeated section.

3.1.2.1.4. Hurd Creek member

In outcrops, the Hurd Creek member is composed of sandstone, siltstone, and clay shale organized in coarsening-upward cycles (Martel and Gibling, 1996). The Hurd Creek member was encountered in Coolbrook-1 (41.39 m), Kennetcook-2 (64.5 m), Kennetcook-1 (130.5), and Creelman-1 (28.8 m). The subsurface lithological characteristics of the Hurd Creek member are described in table 5. Well correlations and a gradual decrease in thickness show that the member suffered uplift and erosion in the northeast and west of the study area. The thickness penetrated in the Kennetcook-1 well as compared with the type section (~ 70-80 m) indicates some probable repeated section.

3.1.2.2. Cheverie Formation

The Cheverie Formation, in the type section, is composed of sandstone, siltstone, and shale and represents alluvial deposits (Moore, 1985; Martel and Gibling, 1996). On the basis of subsurface lithological characteristics and sand-to-shale ratios derived from the mudlogs, the Cheverie Formation could be divided into the lower, middle, and upper intervals. The Coolbrook#1 drilled 305.5 m, Kennetcook-2 penetrated 357.5 m, and Kennetcook-1 penetrated 368.5 m of the Cheverie Formation, whereas, the Creelman Hill well spudded in the Cheverie Formation and did not penetrate its top; in total this well drilled 222 m of the Cheverie Formation.

3.1.2.2.1. Lower interval

This lower interval penetrated in the subsurface of the study area shows a thickness decrease in northeast. The wells in the southwest (Figure 1.5), Kennetcook-1, Kennetcook-2 and Coolbrook-1, drilled a large thickness that may indicate some repeated sections. The total exposed thickness of the Cheverie Formation measured during our fieldwork in the Cheverie Point (1.5) is about 180 m. Lithological descriptions and get-to-gross ratios estimated for this lower interval are given in table 6. Well correlations of this lower interval show lateral continuity of the interbedded siltstone and shale in the basal part of the Cheverie Formation in the study area.

3.1.2.2.2. Middle interval

The middle interval of the Cheverie Formation drilled in the subsurface shows a gradual increase in thickness towards northeast around the Creelman Hill well. Lithological descriptions and net-to-gross ratios estimated for this middle interval are shown in table 7. The net-to-gross (N/G) ratios (table 7) show that this middle member laterally grades to a higher proportion of interbedded siltstone and shale in the northeast towards the Creelman Hill well. Depth correlation of the top of the interval shows a gradual rise in the northeast.

3.1.2.2.3. Upper interval

The upper interval of the Cheverie Formation shows a gradual decrease in thickness towards northeast. Lithological characteristics and net-to-gross ratios (N/G) estimated for this upper interval are listed in table 8. The N/G ratios indicate that the interval is grading to a higher proportion of fine-grained sandstone in northeast. The depths to the top of the interval penetrated in different wells indicate a gradual rise in the top of the interval, and ultimately exposure of the unit in the northeast.

Lithological descriptions and correlations of each interval identified in the Cheverie Formation show thickness variations and lateral facies change that are the consequences of intense deformation in the basin. Varying net-to-gross ratios in the

Cheverie Formation encountered in different wells indicate that sandstone bodies form wedges that have short lateral continuity.

3.1.3. Windsor and Mabou groups

Most of the wells (Figure 1.5) available for this project have penetrated Windsor Group rocks which include the Macumber Formation, the basal anhydrite unit and undifferentiated middle to upper Windsor Group, as described by the well-site geologists. For consistency and correlation purpose, the undifferentiated middle to upper Windsor Group rocks were classified into formations on the basis of lithologic characteristics picked from the mudlogs, and correlation with the Avondale#1 and Avondale#2 wells (Figure 1.5).

Mudlogs and well data indicate that Mabou Group represented by the Watering Brook Formation has not been encountered in the central and eastern part of the Kennetcook-Windsor basin. Typical green-gray and red mudrocks present in the upper part of the Watering Brook Formation were not reported by the well-site geologists. There is possibility that intense deformation has mixed the Watering Brook lithologies within the Windsor Group. On mudlogs, it is difficult to differentiate the Watering Brook Formation from the Windsor Group rocks in the subsurface. For this reason, the Mabou Group, here, is included with the Windsor Group.

3.1.3.1. Lower Windsor Group

The Lower Windsor Group in the Kennetcook-Windsor basin includes the following formations is an ascending order: The Macumber and Pembroke; The White Quarry; and the Stewiacke formations.

3.1.3.1.1. Macumber Formation

The Kennetcook – 1 well drilled 3.5 m of moderate to dark gray limestone which is primarily lime-mudstone with grainy lenses. Kennetcook – 2 penetrated 2.5 m of moderate to dark gray, microcrystalline, dense and very hard limestone. Coolbrook#1 drilled only one metre of light brownish gray, planar laminated dolostone that has silica-filled microfractures.

3.1.3.1.2. White Quarry Formation

In the study area, Kennetcook – 1 (126.5 m), Kennetcook – 2 (122 m), and

Coolbrook#1 (55.3 m) wells encountered a succession of gypsum and anhydrite which is the part of the White Quarry Formation (Bell, 1960; Gibling, 1995). Lithological descriptions of the basal anhydrite unit drilled in the subsurface are given in table 9.

Avondale#1 well encountered a thick succession of gray anhydrite from 149.35 – 300 m MD. The well-site geologist has marked this interval as the part of the Carrolls Corner Formation. However, the same succession of thick anhydrite (104 – 199.3 m MD) encountered at the top of about 9 m thick salt in the Avondale#2 was described as the part of the MacDonald Road Formation (lateral equivalent of the Wentworth Station/ Pesaquid Lake formations) by the well-site geologist. Our correlation of Avondale#1 and Avondale#2 indicates that the anhydrite unit drilled in the Avondale#1 is part of the Wentworth Station Formation.

The basal anhydrite unit penetrated in Kennetcook-1, Kennetcook-2 and Coolbrrok#1 is correlatable with the White Quarry Formation (lateral equivalent of the Carrolls Corner Formation) (Gibling 1995; Moore et al. 2002; Naylor et al. 2005). It is entirely composed of anhydrite with some local bands of mudstone and fine-grained sandstone.

3.1.3.1.3. Stewiacke Formation

Surprisingly, no single halite bed was encountered in Kennetcook – 1, -2, and Coolbrook-1 wells throughout the drilling of Windsor Group sediments. Only Avondale#2 well drilled 9.2 m of white to clear halite at the base of a thick succession of anhydrite (table 9).

3.1.3.2. Middle Windsor Group

The Middle Windsor Group in the study area includes the Miller Creek and the Wentworth Station formations. The Middle Windsor Group is correlatable with the McDonald Road Formation in the neighboring Shubenacadie and the Musquodoboit basins.

The Avondale#1 well (226.2 m), the Avondale#2 well (169.9 m) and the Kennetcook-1 well (66 m) drilled the Middle Windsor Group rocks which are dominantly gypsum and anhydrite and correlatable with the Wentworth Station Formation. Lithological descriptions of the drilled section are given in table 10. Thickness penetrated in the subsurface indicates that the middle Windsor Group thickens in the west and southwest of the study area. Apparent dip angles are quite high (60^{O} – 80^{O}) estimated at different depths (table 10) from the cores.

3.1.3.3. Upper Windsor Group

The upper Windsor Group in the Kennetcook-Windsor basin is represented by the Pesaquid Lake and the Murphy Road formations. The Upper Windsor Group is correlatable with the Green Oaks Formation in the neighboring Shubenacadie and Musquodoboit basins.

Avondale#1 (47.95 m), Avondale#2 (3.5 m), Coolbrook-1 (376.8 m), Kennetcook-2 (357 m), and Kennetcook-1 (42.1 m) wells in the study area drilled the Upper Windsor Group that comprises dominantly siltstone and correlates with the Murphy Road Formation. Lithological descriptions of the Murphy Road Formation are listed in table 11. Subsurface thickness data indicate that the formation thickens in the central part of the study area around the Coolbrook-1 well. However, subsurface thickness variations could be attributed to intense deformation that has caused repeated sections within the formation and hence abnormal thickness.

3.1.4. Cumberland Group

The Cumberland Group in the Kennetcook-Windsor basin is represented by the Scotch Village Formation which has disconformable to angular contact with the underlying Windsor Group rocks. Only a few wells penetrated the Scotch Village Formation in the Kennetcook-Windsor area. The thickness of the formation is quite variable due to significant amounts of Pennsylvanian or post-Pennsylvanian erosion.

3.1.4.1. Scotch Village Formation

The Coolbrook#1 well penetrated 281 m of the Scotch Village Formation, dominantly composed of interbedded siltstone and shale alternating with sandstone. The Kennetcook – 1 well penetrated the top of the Scotch Village Formation at 22.00 m MD. The total thickness of the Scotch Village Formation drilled in the Kennetcook – 1 well is about 80 m and composed entirely of sandstone. The Kennetcook – 2 well encountered the base of the Scotch Village Formation at 328 m MD. The top is not known as the geological sampling and ditch cutting descriptions started at 280 m MD. The total thickness of the Scotch Village Formation is probably around 250 – 300 m comprising siltstone that passes down to very fine grained sandstone.

On the basis of lithological descriptions and net-to-gross (N/G) ratios, the Scotch

Village Formation has been divided into lower, middle, and upper intervals.

3.1.4.1.1. Lower interval

The Coolbrook#1 well (91m), the Kennetcook – 2 well (46 m), and the Kennetcook – 1 well (79.6 m) penetrated the lower interval of the Scotch Village Formation. Lithological descriptions and the N/G ratios estimated in the lower interval are given in table 12. The subsurface thickness of the lower interval penetrated in the central part of the study area shows an increasing trend towards west.

3.1.4.1.2. Middle interval

Lithological correlations indicate that the Kennetcook-2 and the Kennetcook-1 wells did not penetrate this middle interval. The Coolbrook-1 well drilled through the middle interval. The middle interval (203 – 84.5 m MD) in the Coolbrook-1 well is mainly interbedded siltstone and shale at the base overlain by mottled green and red, pyritic shale that contains plant fragments. Siltstone is red to mottled red and green and contains calcareous intervals locally.

3.1.4.1.3. Upper interval

The upper interval of the Scotch Village Formation was also not penetrated in the Kennetcook – 1 and -2 wells. Only the Coolbrook-1 well drilled this upper interval (84.5 – 12.5 m MD). It comprises red siltstone with some mottled gray and green patches, interbedded with brownish gray, moderate gray, very fine to fine grained, cross-bedded, locally bioturbated pyritic sandstone and red shale that is present at the top of this interval. N/G for this interval is 0.38.

3.2. Seismic Stratigraphy

3.2.1. Basement

The top of basement shows both discontinuous and weak seismic response (Figure 3.6) which could be attributed to lateral lithological variations and the fractured nature of the basement rocks; coupled with acquisition and/or processing factors. Below the top section of basement, seismic quality does not allow interpretation of any stratigraphic feature. However, some time slices cut through the seismic volume within the upper part of the basement rocks indicate some curved seismic geometries that could be described as wedges dipping to the northwest (Figure 3.6). The top of basement has significant seismic dip (~ 10^{o}-30^{o}) and is tilted towards the north (Figure 3.7). Most of the faults offsetting the basement have resulted in tilted fault-block geometry deepening it towards Cobequid Bay. This subsurface structural style supports the interpretation of Martel and Gibling (1996) that the basement provided half-graben settings for the deposition of Late Devonian to early Visean sediments in the Maritimes Basin.

3.2.2. Horton Group

The top of the Horton Group is marked by a high Gamma Ray (GR) signal relative to the basal part of the Windsor Group and lows in both sonic (DT) velocity and bulk density (RHOB) log data. This corresponds to a downward decrease in acoustic impedance and hence, a predicted negative reflection coefficient. This matches with a trough event on both 2D and 3D seismic data. However, the sonic and density curves predict a very low acoustic impedance contrast (Figure 3.8) between the Horton Bluff and the overlying Cheverie formation. The seismic-to-well tie matches with a trough event on seismic for the top of the Horton Bluff Formation.

3.2.2.1. Horton Bluff Formation

The basal part of the Horton Bluff Formation is represented by moderately continuous bright reflections quite obvious on both 2D and 3D seismic data (Figure 3.9). Most of the seismic lines (Figure 3.10) show inclined and discontinuous seismic reflections dipping down on the basement rocks. These reflection geometries indicate downlapping clinoforms. Bright reflections in the basal part of the Horton Bluff Formation (probable alluvial fan wedges) dipping on the basement rocks are also present on some 2D dip lines (Figure 3.11).

Thickness variations along the nearly north-south 2D lines follow the inclination and tilted fault-blocks of the basement. The thickness of the Horton Bluff sediments increases generally northwards (Figure 3.12) where the basement becomes deeper and is tilted towards Cobequid Bay. Dipping seismic reflections show moderately continuous and high angle dips (~ 30^{o}-50^{o}) of the sediments which are present in the northern part as imaged by many dip lines (Figure 3.13). These seismic reflections indicate probable deformed wedges tilted at a high angle and may indicate southward transportation of the sediments. Time slices cut through Horton Bluff Formation show similar geometries (Figure 3.14). The thickness of the Horton Bluff Formation also varies along east-west strike lines where the thickest parts are preserved towards the eastern part within tilted fault-bocks of the basement (Figure 3.15). Seismic reflections are moderately to fairly continuous and are high angle (~ 20^{O}-30^{O}) due to intense deformation along the basement-cutting faults. Seismic reflections across the faults have variable dip angles and represent tilted fault-blocks. Seismic imaging is not good in the shallower section and does not allow precise interpretation of any shallow stratigraphic and/or structural features.

3.2.2.2. Cheverie Formation

The Cheverie Formation shows much less thickness variation as evident from the seismic data (Figure 3.15). This evidence confirms that the half-graben geometry had already been occupied by the Horton Bluff sediments at the time of Cheverie Formation deposition. However, similar dipping seismic reflection geometries are also present within the Cheverie Formation. Due to high angle of the sediment wedges and shallower depths in the northern part of the Minas Basin, seismic imaging is not of good quality. Nonetheless, curved seismic signatures showing some clinoform geometries could be interpreted on some time slices cut through the Cheverie Formation in the 3D data (Figure 3.16).

3.2.3. Windsor Group

Well logs show that the top of the Windsor Group is represented by a low and uniform GR response as compared with the underlying top of the Cheverie Formation (Figure 3.17). The sonic velocity of Windsor Group is slightly higher than the overlying Cumberland Group and produces positive acoustic impedance at the boundary and correlates with a positive reflection coefficient and therefore a peak event on the seismic.

The Windsor and Mabou group rocks show discontinuous, chaotic and high angle seismic reflection geometries (~30^{O}-50^{O}) in the subsurface where the thickest parts are preserved (Figure 3.18). It is difficult to pick tops of individual formations within the Windsor Group. However, discontinuous and weak seismic reflections indicate evaporites and the basal halite (Figure 3.18). The base of the Windsor Group shows bright and moderately continuous reflections which represent the hard and massive limestone of the Macumber Formation. Some dipping reflections geometries present on many seismic profiles (Figure 3.18 & 3.19) look like primary depositional geometries. Actually high angle reflection geometries indicate structural collapse features that were the result of evaporite withdrawal. Mostly the depositional features have been imprinted by these structural collapses due to evaporite mobility. At shallower depth, intermixed lithologies encased within high velocity evaporites give rise to poor imaging of Windsor sediments on seismic (Figure 3.20).

3.2.4. Cumberland Group

The Cumberland Group that is represented by the Scotch Village Formation shows excellent, moderately continuous and uniform seismic reflections which are laterally traceable where the Scotch Village sediments are very moderately deformed. Inclined reflection geometries in the basal part dip down on the top of the Windsor Group (Figures 3.19 & 3.21) which provided an uneven erosional surface for deposition. Where the Scotch Village Formation has suffered significant erosion and is present only in the near subsurface, seismic imaging of the underlying Windsor Group sediments is poor and reflections are weak, discontinuous and chaotic.

Seismic data show that the thickness of the Scotch Village Formation is variable and depends on the underlying topography provided by highly deformed Windsor sediments (Figures 3.15, 3.18, 3.19, 3.22). Inclined reflectors within the Scotch Village Formation indicate that the accommodation space was being created during evaporite movement. Thus, this seismic expression and thickness variations in the Scotch Village Formation indicate that it was deposited in minibasins created by evaporite withdrawal (Waldron 2005, Figure 3.22).

3.3. Interpretation: basin history

Seismic and well data from the Kennetcook-Windsor basin confirm the fractured and highly deformed nature of the Meguma Supergroup rocks which acted as basement to the Late Devonian-Carboniferous rocks in the southern part of the Maritimes Basin. The geometry of tilted subsurface fault-blocks at the top of basement and thickness variations within the Horton Bluff Formation confirm that the deposition of the Horton Bluff sediments took place in graben or half-graben settings during an extensional episode (Gibling, 1995; Martel and Gibling 1996). Movement on the basin-bounding normal faults helped accommodate the Late Devonian to Mississippian sediments. Less pronounced thickness variations within the Cheverie Formation as indicated by seismic data (Figure 3.15, 3.18) are consistent with a change of depositional setting to a meandering fluvial system as indicated by minor proportion of deep water facies (i.e. dark gray and black clay shale) present both in the outcrop and subsurface penetrated by various wells.

The tops of the Horton Bluff and the Cheverie formations encountered in the wells (tables 3 – 8) show a rising trend in the north and northeast towards Creelman-1 well. This rising of the surfaces indicates that the faults in the northeast were inverted more than those that suffered inversion in the southwest.

Macumber limestone deposited at the onset of Visean marine incursion in the Maritimes Basin (Gibling, 1995) marks the base of the Windsor Group. A thick succession of gypsum and anhydrite was deposited in restricted marine conditions under relatively higher temperatures and variable salinities (Bell, 1921). Mixed lithologies (sandstone, siltstone, shale, limestone) within the middle to upper Windsor Group show collapse structures due to evaporite mobility which caused thickness variations and high dip angles recorded by the seismic and well data. Repeated sections drilled in the wells within the Windsor Group also show intense deformation. Tops of different Windsor Group formations encountered in the wells indicate a rising trend towards the west and southwest where Avondale#1 and #2 wells drilled the upper Windsor sediments.

In contrast, the overlying Pennsylvanian Scotch Village Formation is much less deformed, which indicates that its deposition postdates the deformation of the Windsor sediments. The Scotch Village Formation is thickest where the underlying Windsor evaporites have been withdrawn (Waldron, 2005) creating minibasins which are quite evident on seismic profiles (Figure 3.22).

Net-to-gross ratios estimated from the mudlogs for individual members and intervals made for the Horton, Windsor and Cumberland groups, and their correlations indicate lateral facies variations which are attributed to the architecture (i.e. high/low slope gradient) of the depositional sites and their distance from the source area. Abnormal thicknesses encountered in the subsurface in different wells as compared with the outcrop thicknesses indicate repeated sections caused by the local thrusts that don’t have much lateral continuity and terminate within the sediments of the Horton Group.

Thickness variations and disconformable relationships within the Maritimes Basin sediments confirm that the basin developed as a result of episodic subsidence and uplift (Gibling et al., 2008). Interpreted progradational geometries on the time slices within the Horton Group probably indicate that the South Mountain Batholith could have shed sediments in the tilted fault-blocks of the Meguma basement.

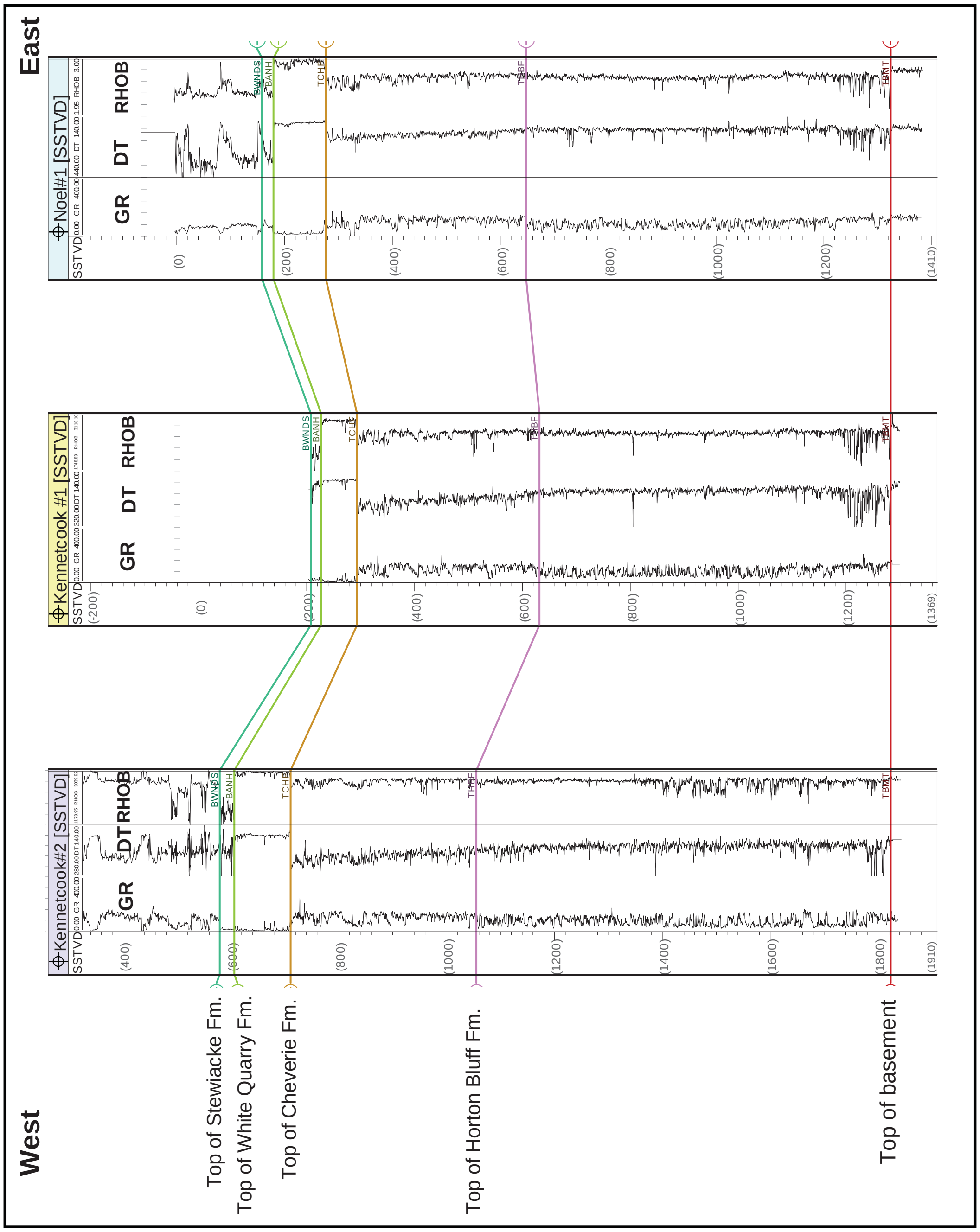


Figure 3.1: East – west correlation panel flattened at the top of basement showing Kennetcook-2, Kennetcook-1 and Noel-1 wells.

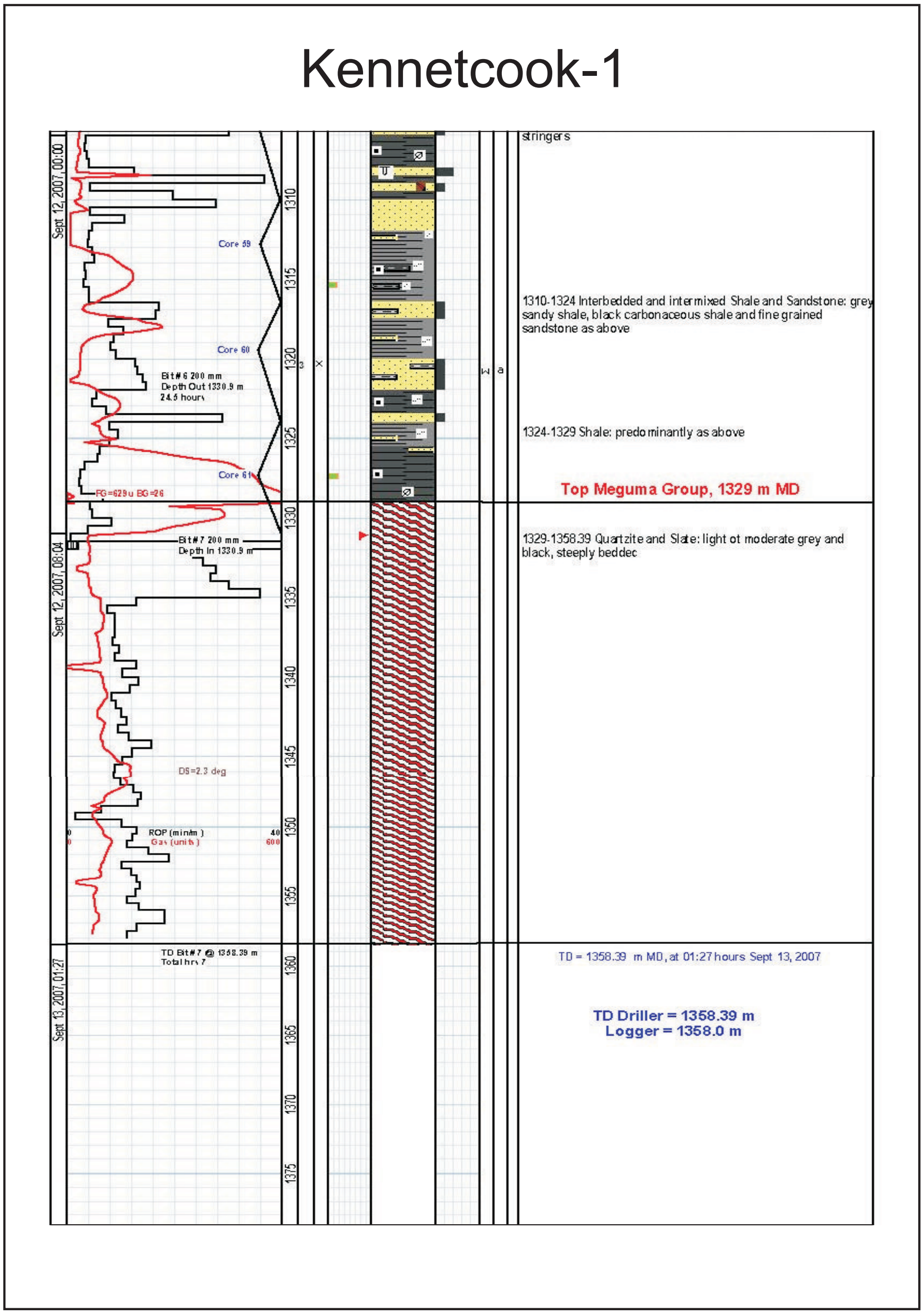


Figure 3.2: Kennetcook-1 mudlog showing the penetrated basement rocks.

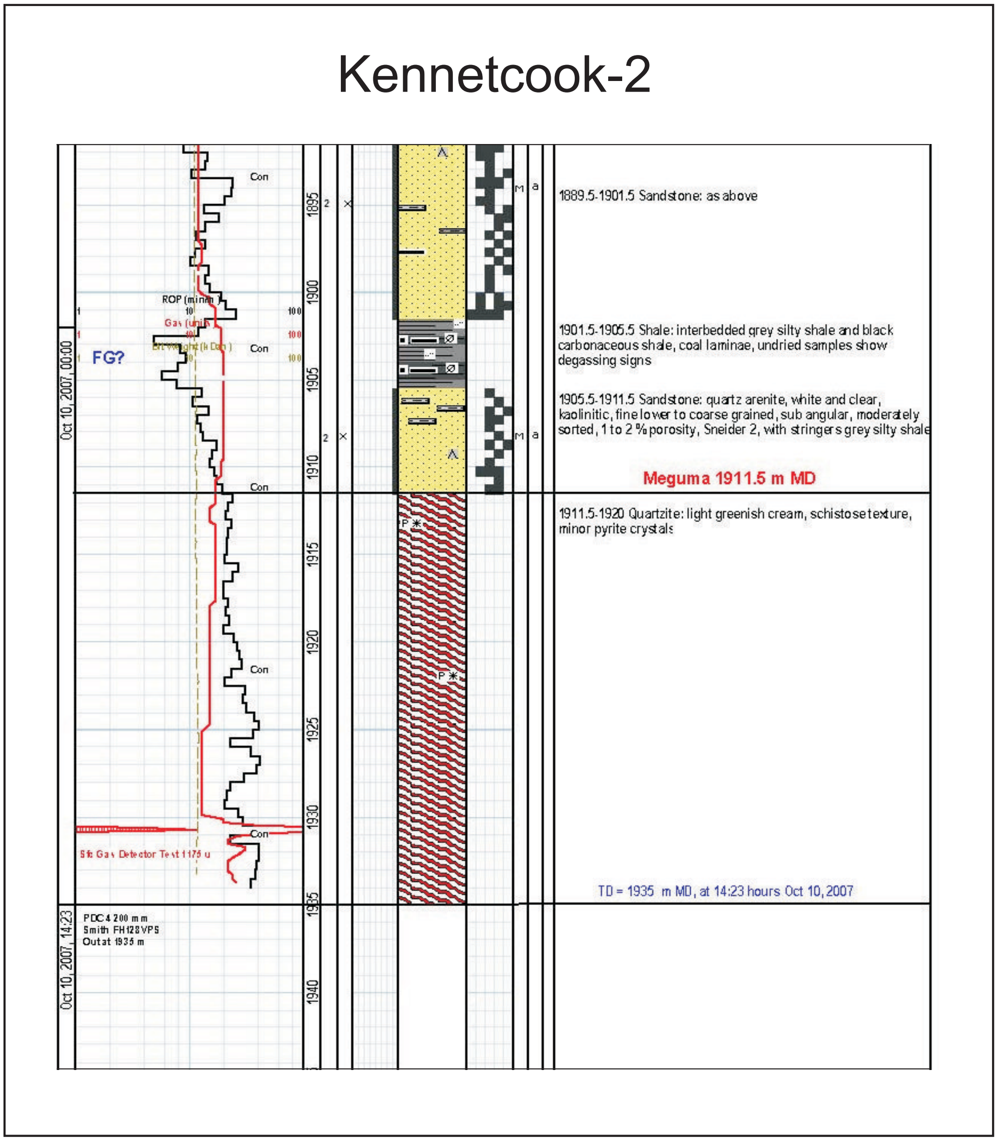


Figure 3.3: Kennetcook-2 mudlog showing the penetrated basement rocks.

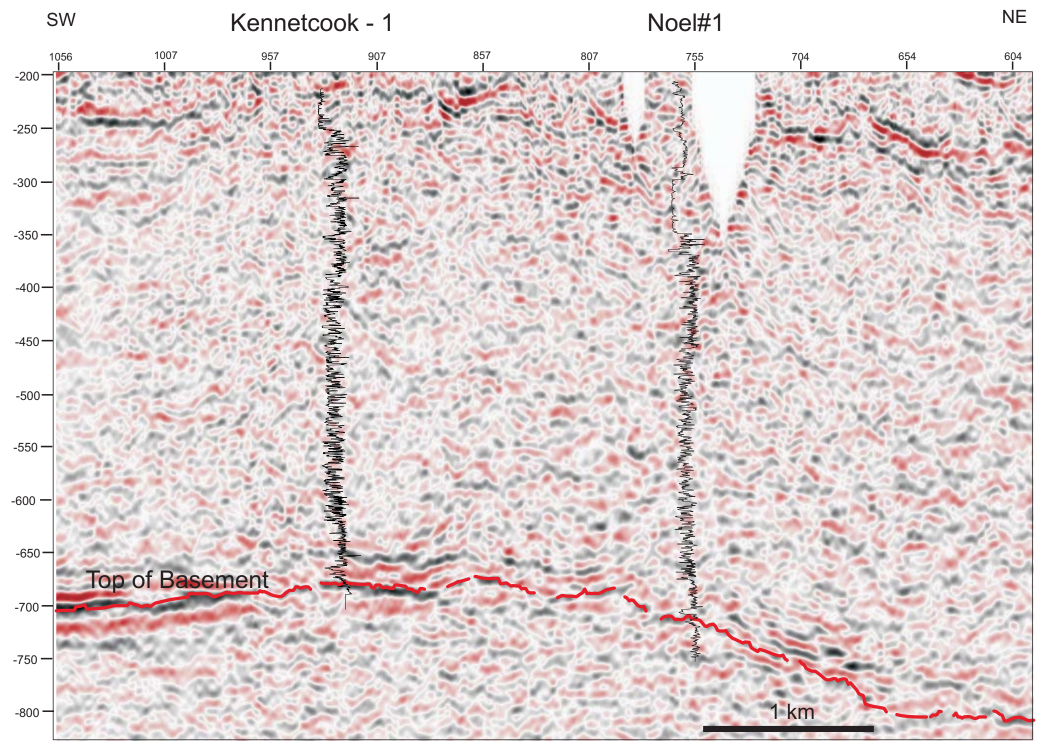


Figure 3.4: 2D seismic line NOL-01-002 with Gamma Ray (GR) log display of Kennetcook-1 and Noel-1 wells showing well-to-seismic tie at the top of the basement.

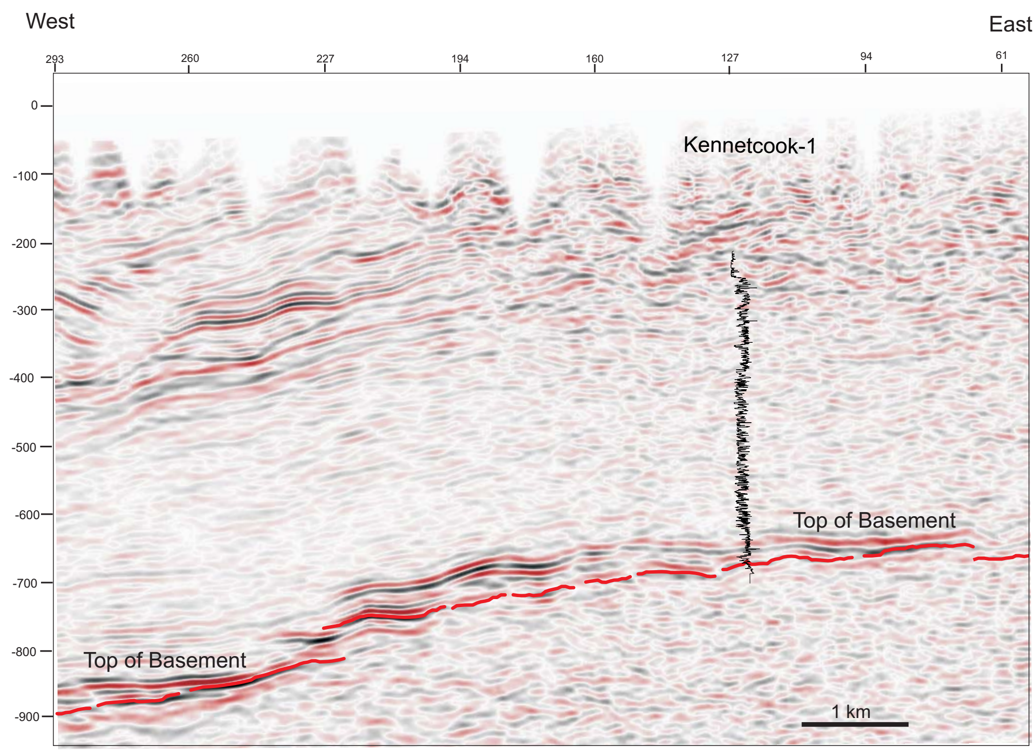


Figure 3.5: 3D seismic inline 185 with GR log display of Kennetcook-1 showing well-to-seismic tie at the top of the basement.

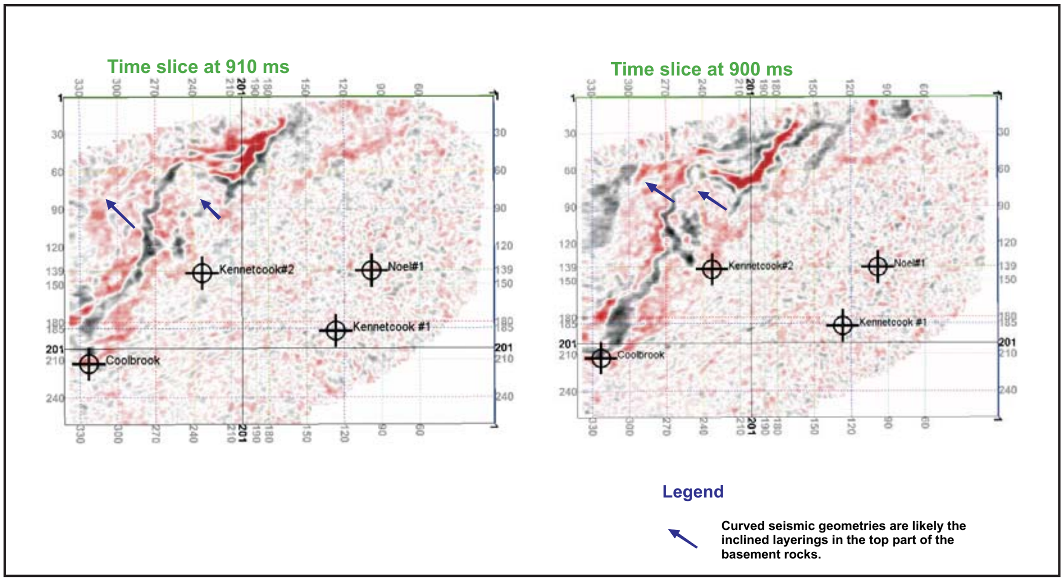


Figure 3.6: Time slices at 910 and 900 ms showing curved seismic geometries possibly representing inclined layering within the basement rocks.

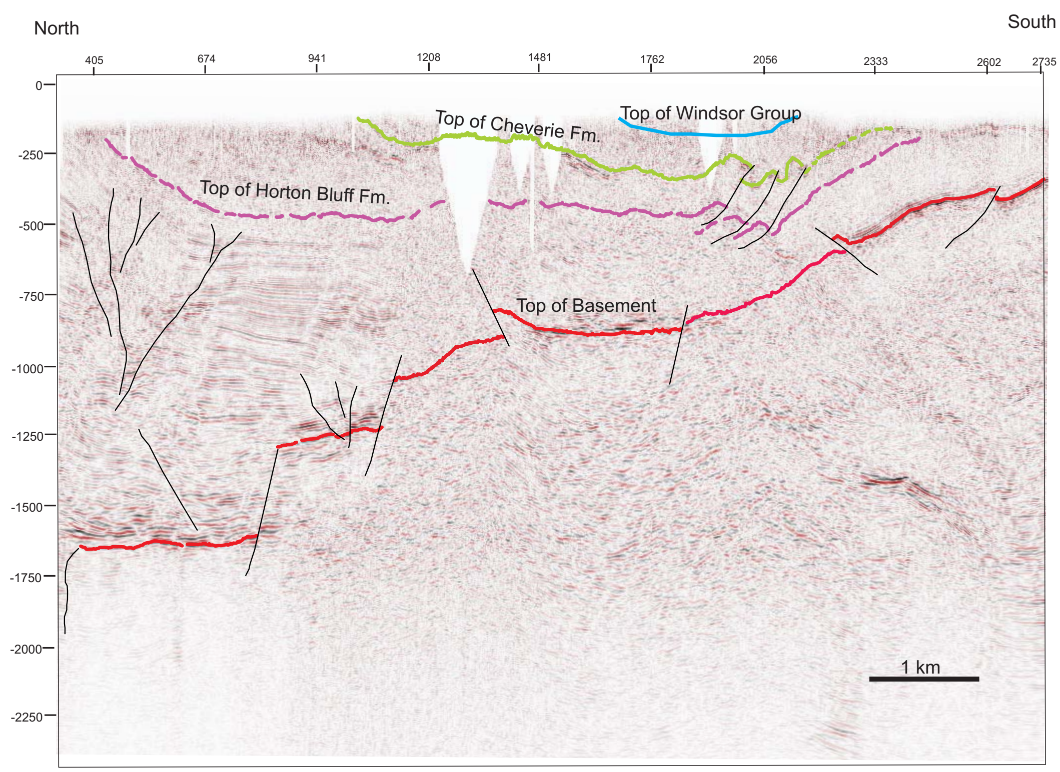


Figure 3.7: Interpreted 2D seismic line WND00-007 showing basement tilt and deepening in the north.

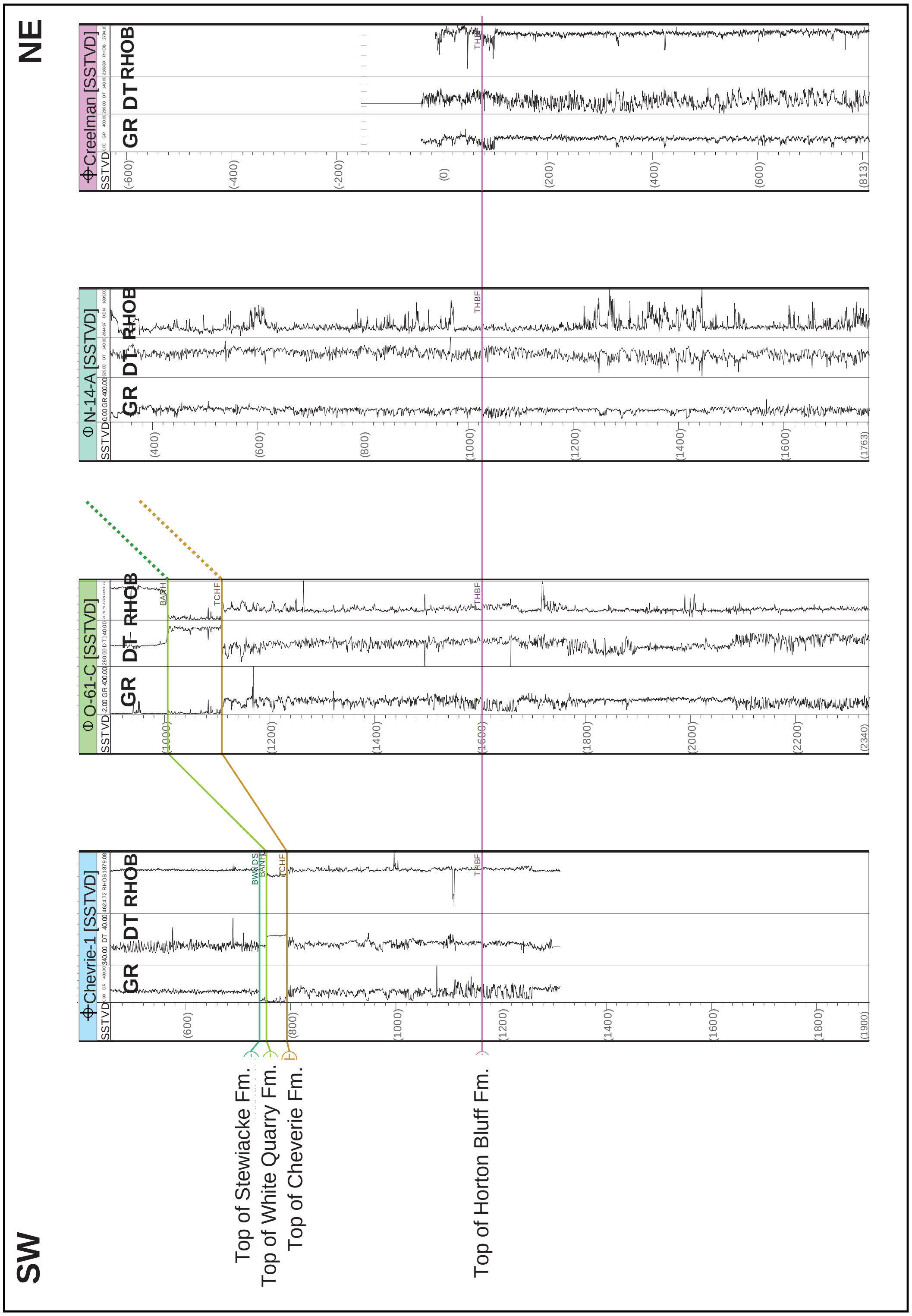


Figure 3.8: NE-SW well correlation panel flattened at the top of the Horton Bluff Formation showing very small contrast in density and sonic logs at the top of the Horton Bluff Formation. Gamma Ray (GR) is displayed in the left, Sonic (DT) in the middle and density (RHOB) in the right tracks of each well.

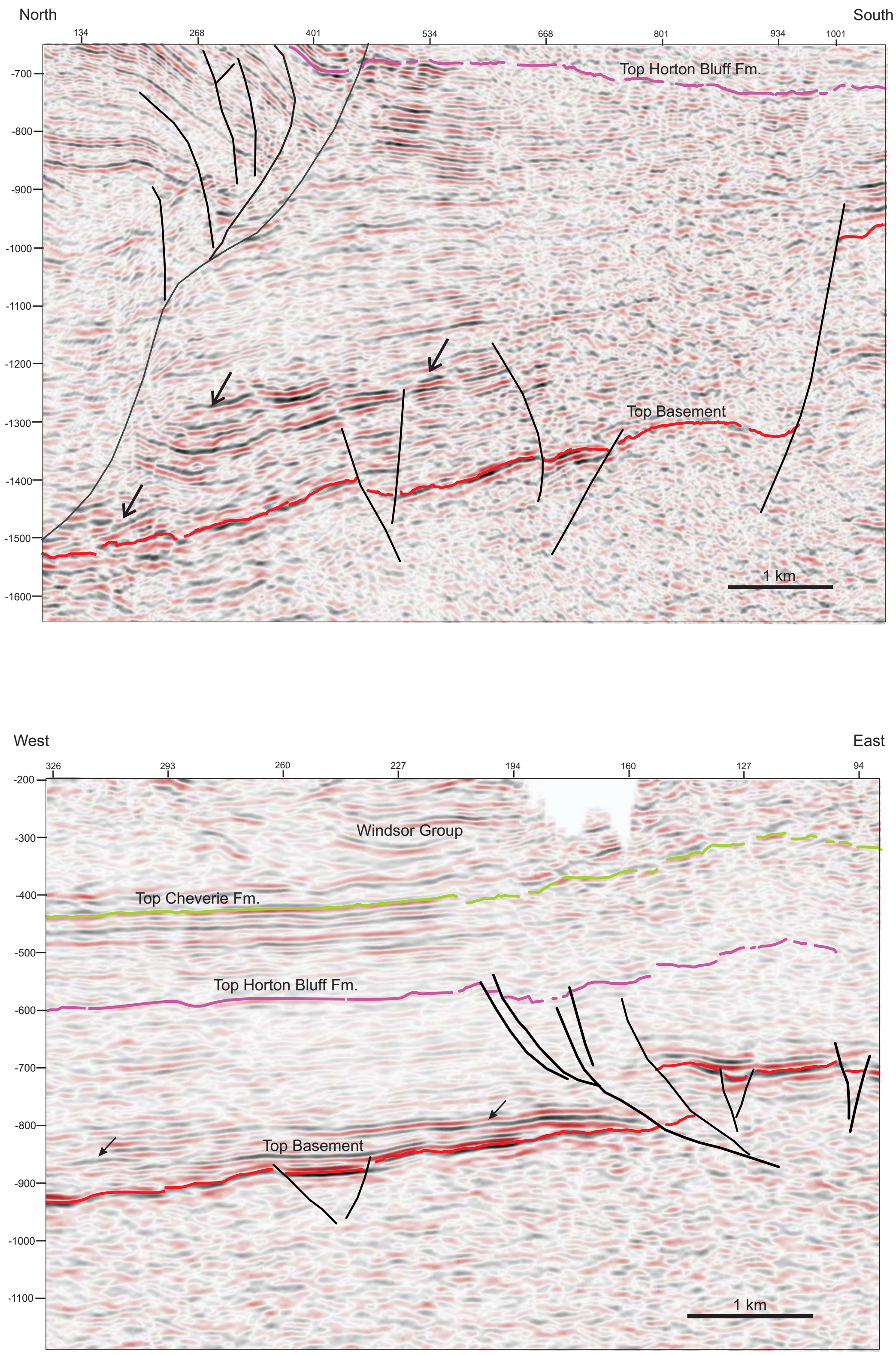


Figure 3.9: 2D seismic line kenn-07-04 (top) and 3D inline 150 (bottom) show bright reflections (black arrows) in the basal part of the Horton Bluff Formation.

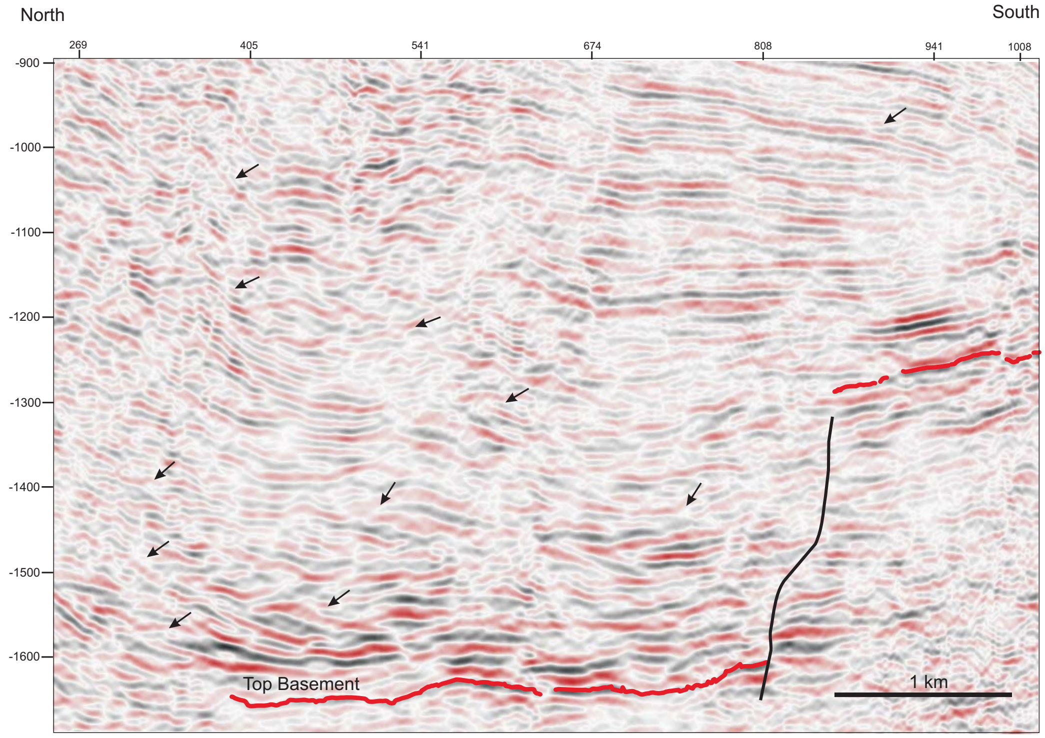


Figure 3.10: 2D seismic line WND00-007 showing inclined reflection geometries (arrows show downlap) present in the Horton Bluff Formation.

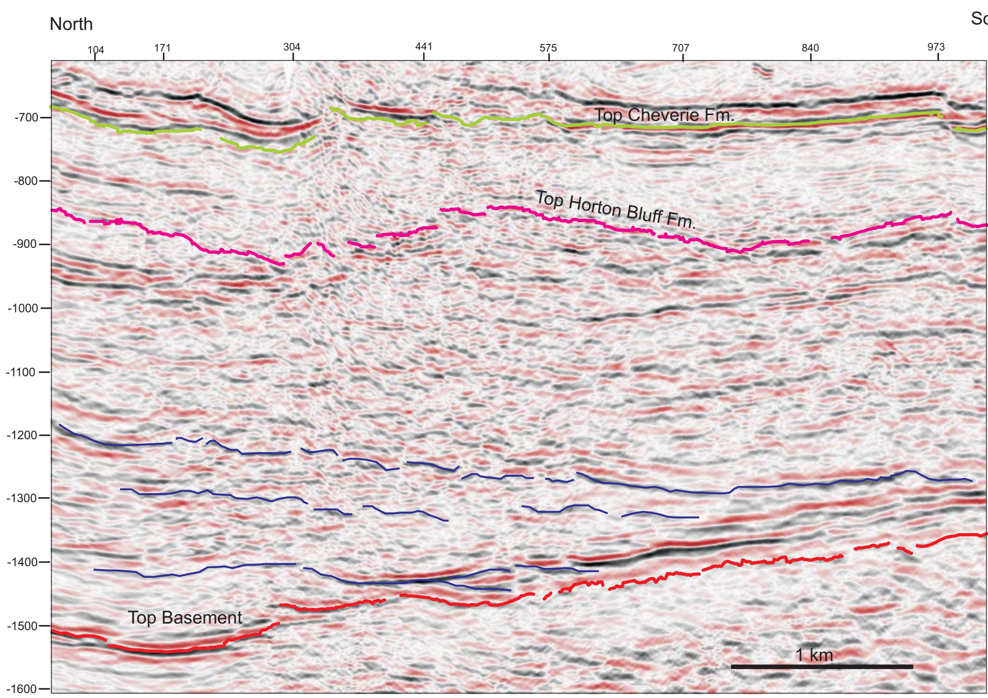


Figure 3.11: 2D seismic line WND00-003 showing inclined reflection geometries dipping towards the basement rocks; these outline a wedge of sediments that is possibly the part of an alluvial fan preserved in the basal part of the Horton Bluff Formation.

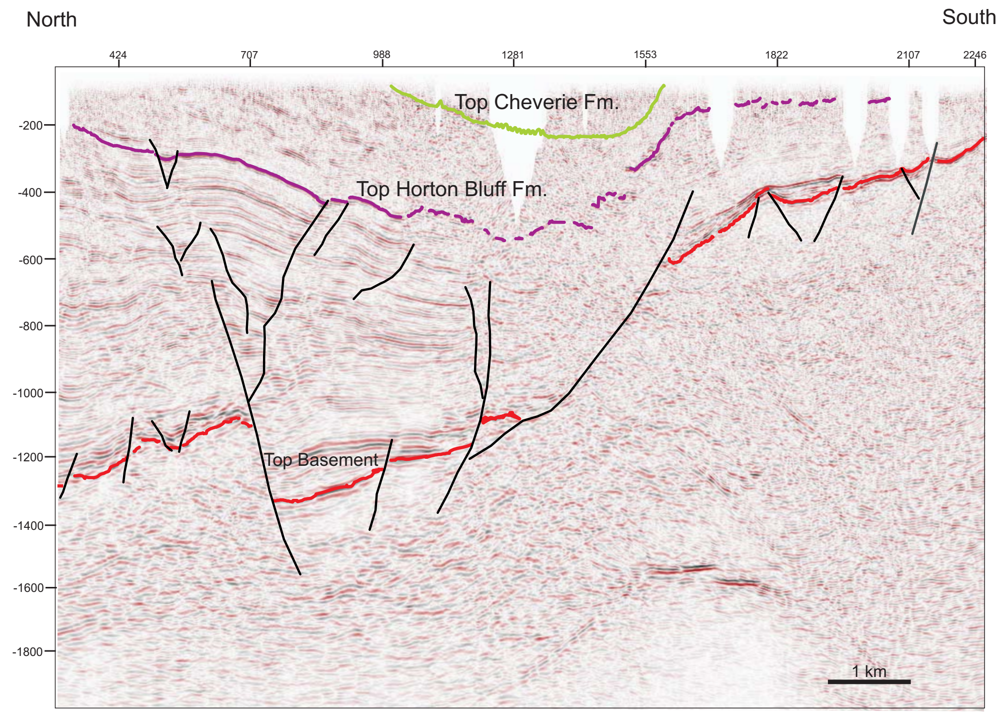


Figure 3.12: Interpreted 2D seismic line WND00-008 showing thickness increase within the Horton Bluff Formation to the north where the basement is deepening. This confirms the deposition of the Horton Bluff Formation in a graben to half-graben setting.

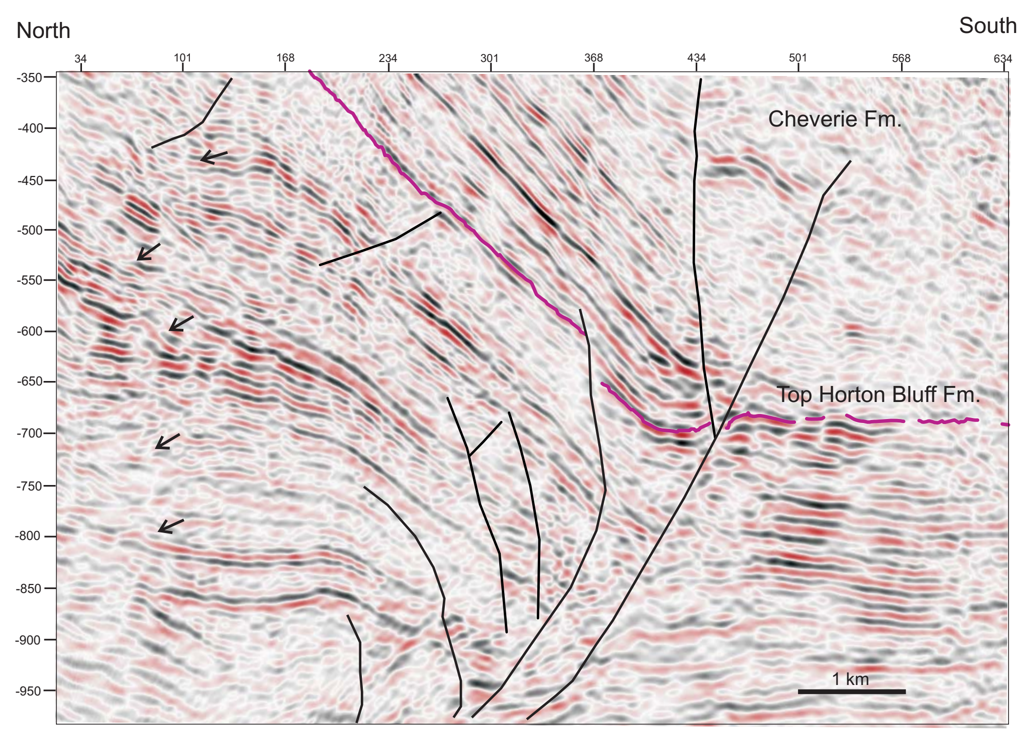


Figure 3.13: Interpreted 2D seismic line kenn-07-04 showing high-angle reflection geometries (black arrows) preserved within the Horton Bluff Formation.

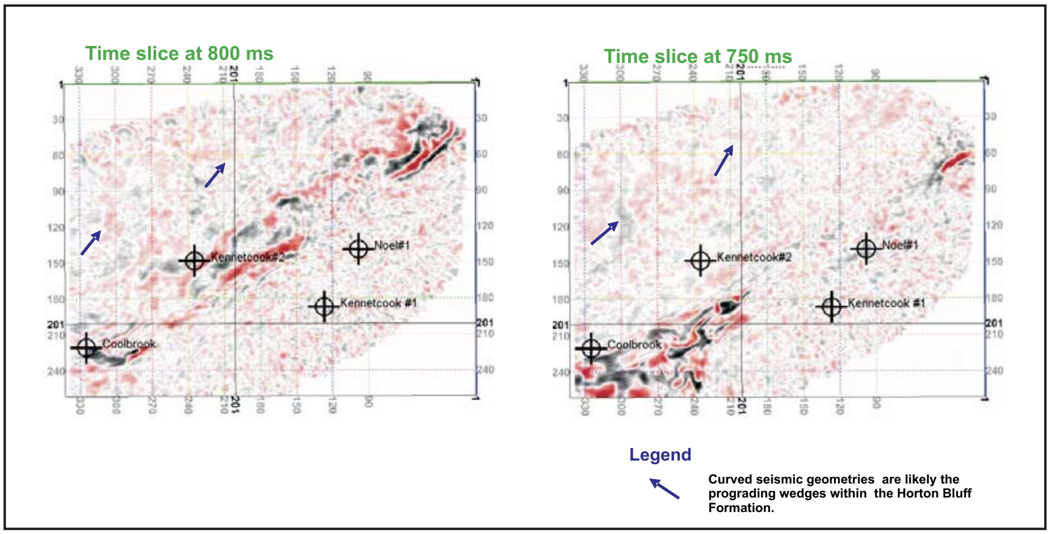


Figure 3.14: Time slices at 800 and 750 ms showing curved seismic geometries that resemble prograding wedges within the Horton Bluff Formation.

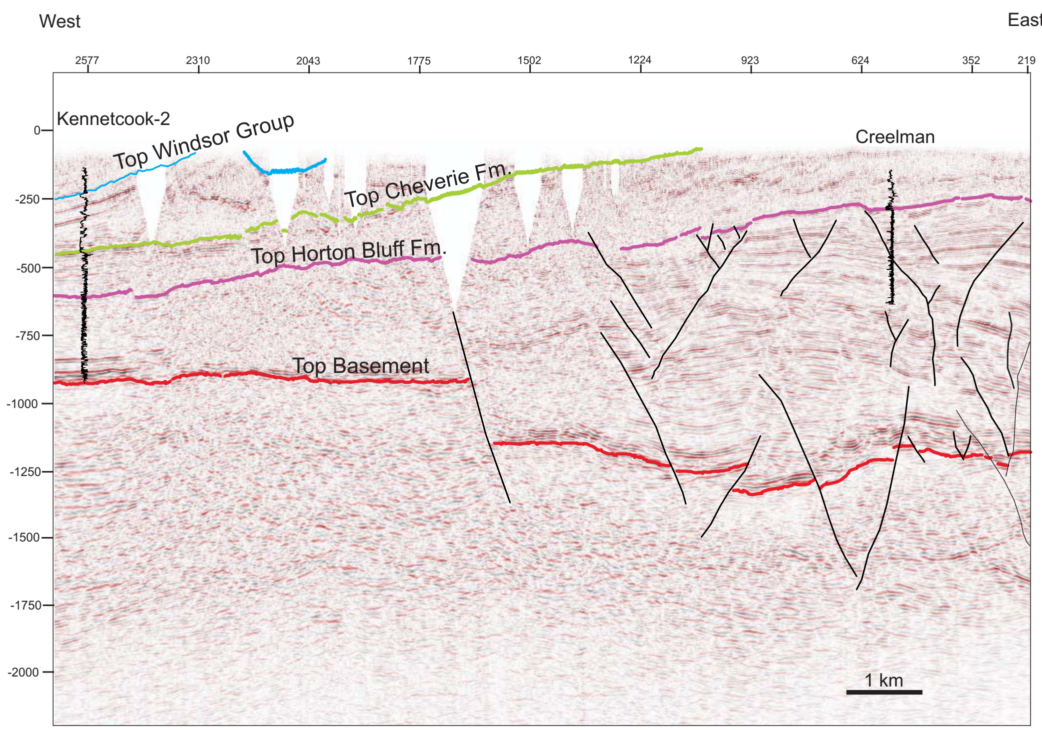


Figure 3.15: Interpreted 2D seismic line WND00-001 showing E-W thickness variation within the Horton Bluff Formation. The thickest part is preserved in the tilted fault blocks. This confirms the deposition of the Horton Bluff Formation in graben to half-graben settings.

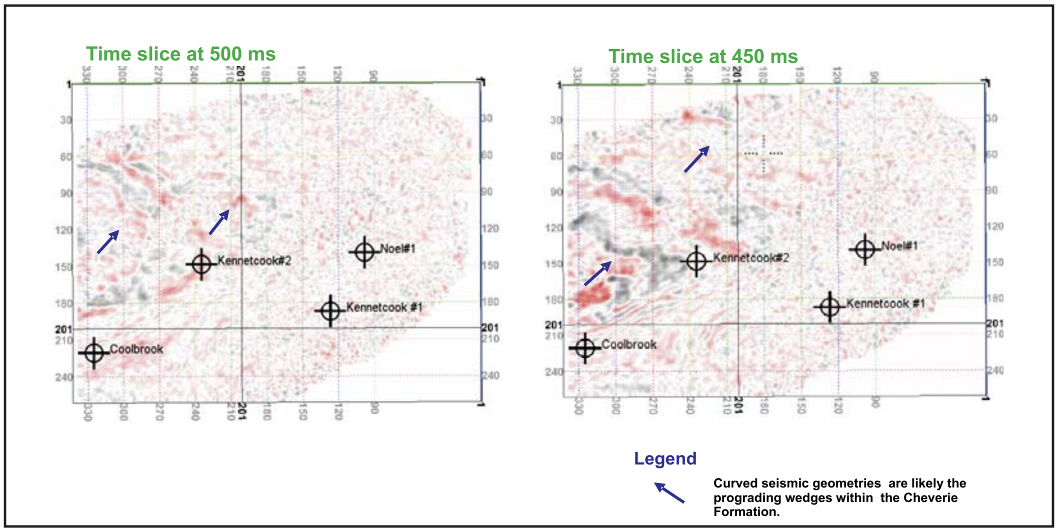


Figure 3.16: Time slices at 500 and 450 ms showing curved seismic geometries that resemble prograding wedges within the Cheverie Bluff Formation.

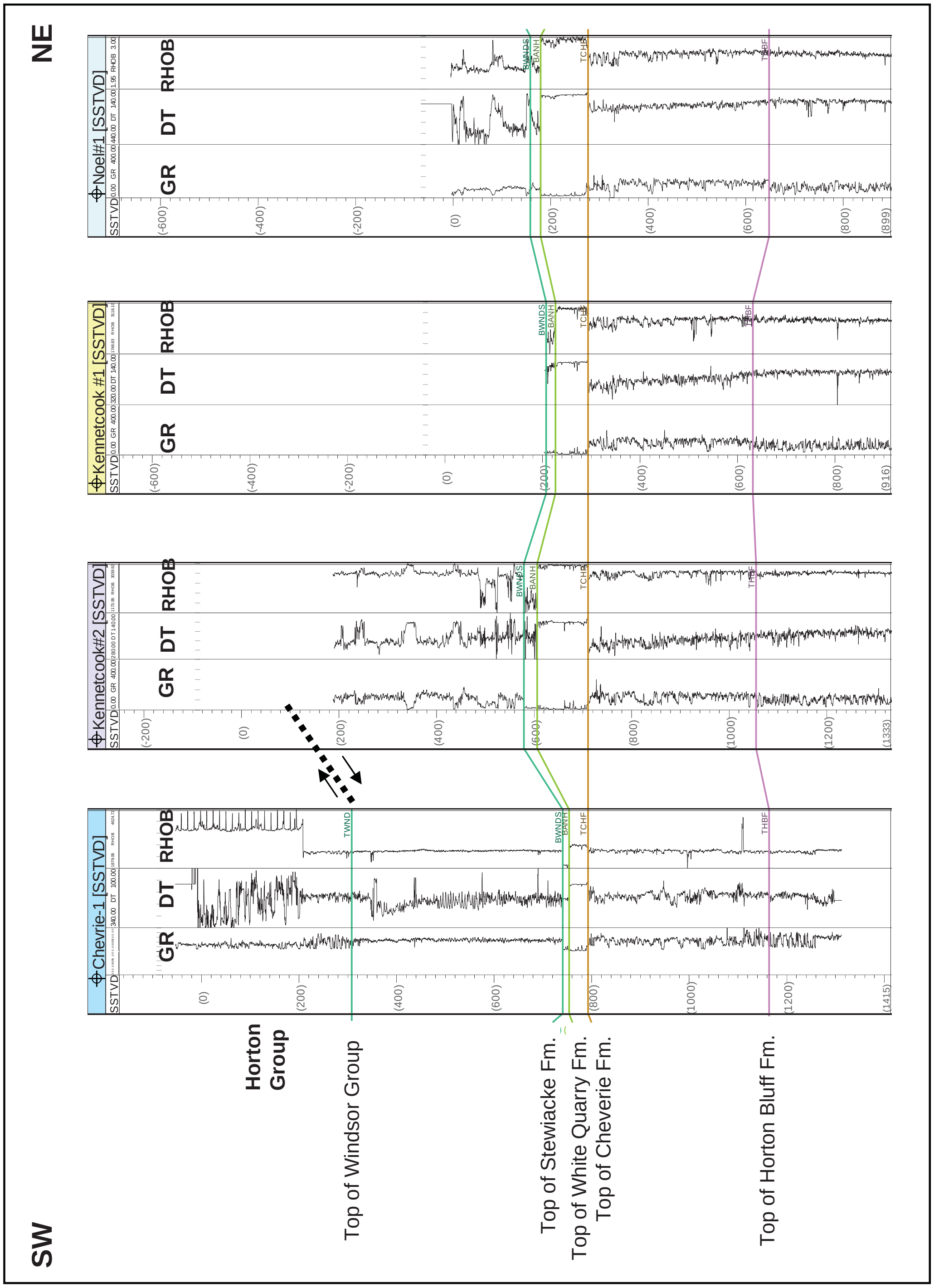


Figure 3.17: NW-SE well correlation panel flattened at the top of the Cheverie Formation showing gamma ray, density and sonic logs response through the Windsor Group and the top of the Cheverie Formation. Gamma Ray (GR) is displayed in the left, Sonic (DT) in the middle and density (RHOB) in the right tracks of each well.

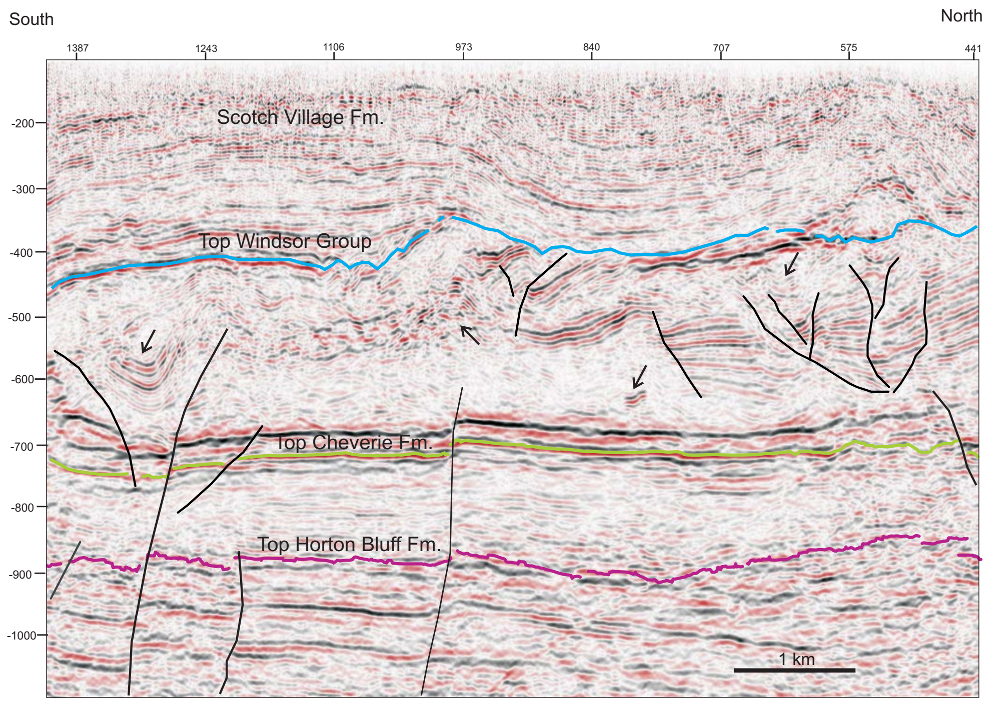


Figure 3.18: Interpreted 2D seismic line WND00-003 showing high-angle and chaotic reflections geometries (black arrows) representing structural collapses within the Windsor Group rocks.

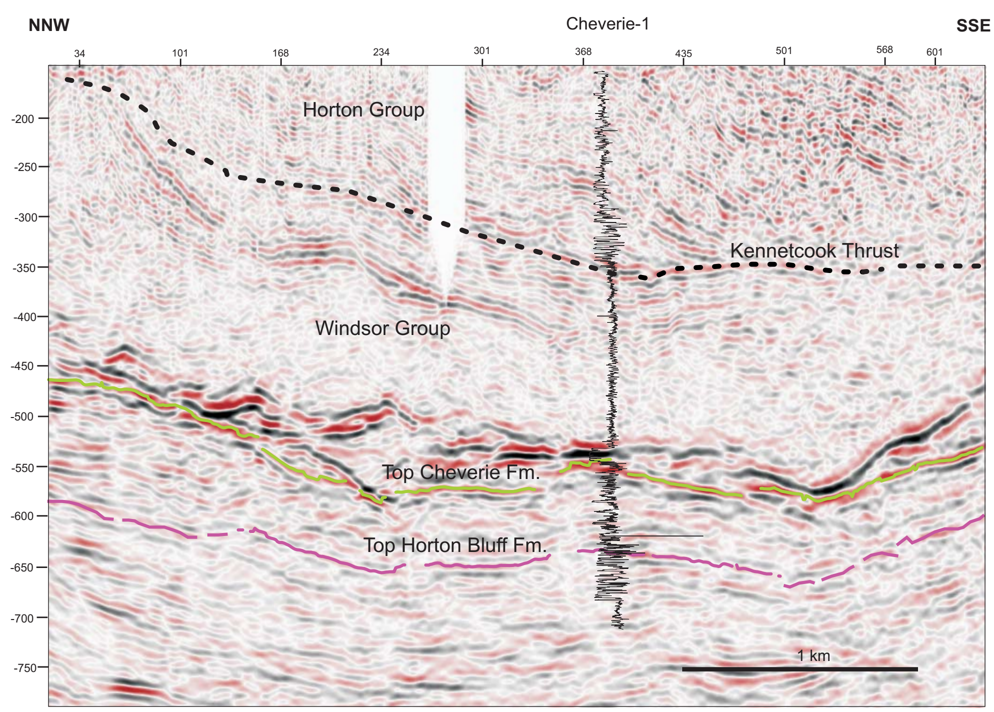


Figure 3.19: Interpreted 2D seismic line WND00-002 showing dipping reflection geometries within the Macumber Formation which is composed entirely of dense, massive limestone.

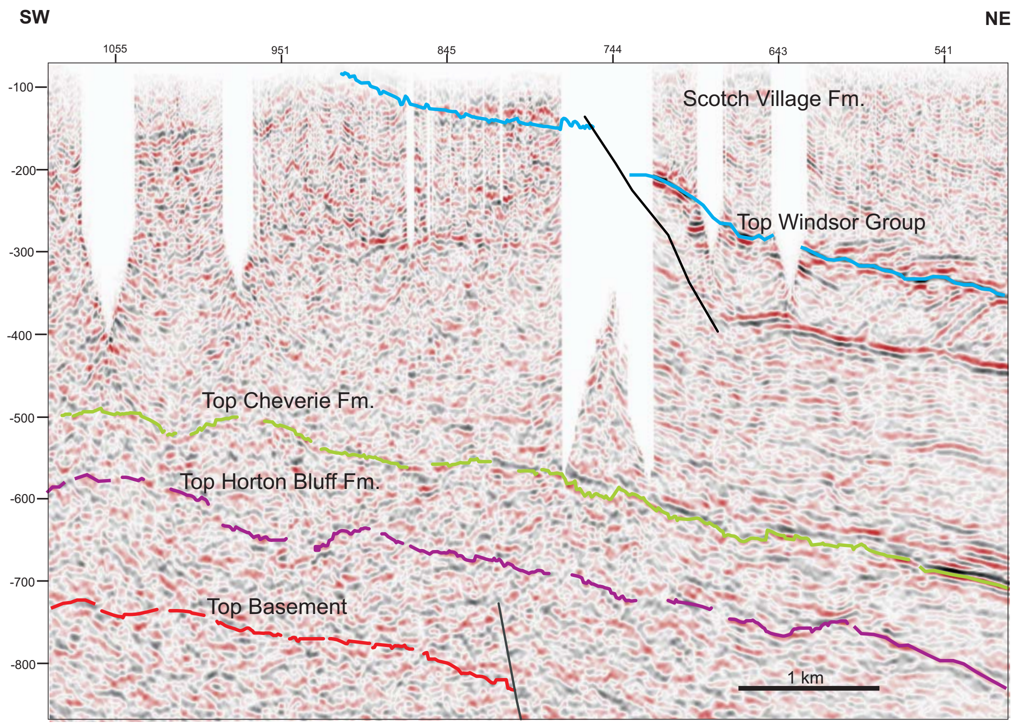


Figure 3.20: Interpreted 2D seismic line WIND-02-004 showing poorly imaged Windsor Group rocks present in the shallower depth.

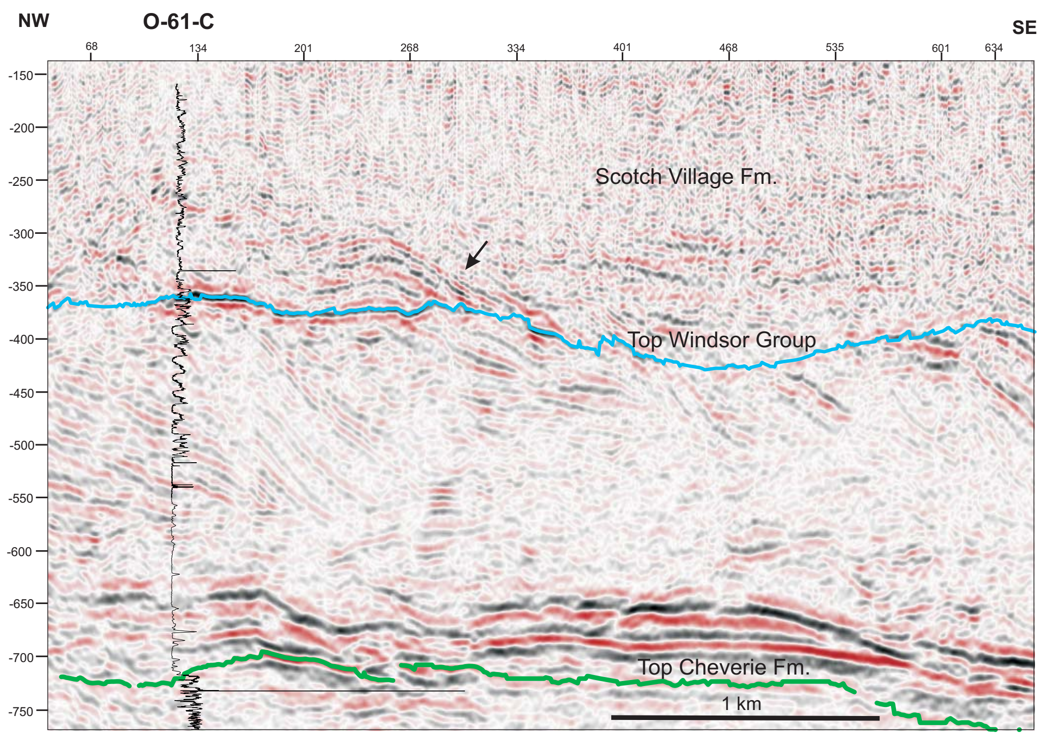


Figure 3.21: Interpreted 2D seismic line WND00-004 showing dipping reflection geometries in the basal part of the Scotch Village Formation (Cumberland Group) downlapping on the top of the underlying Windsor Group.

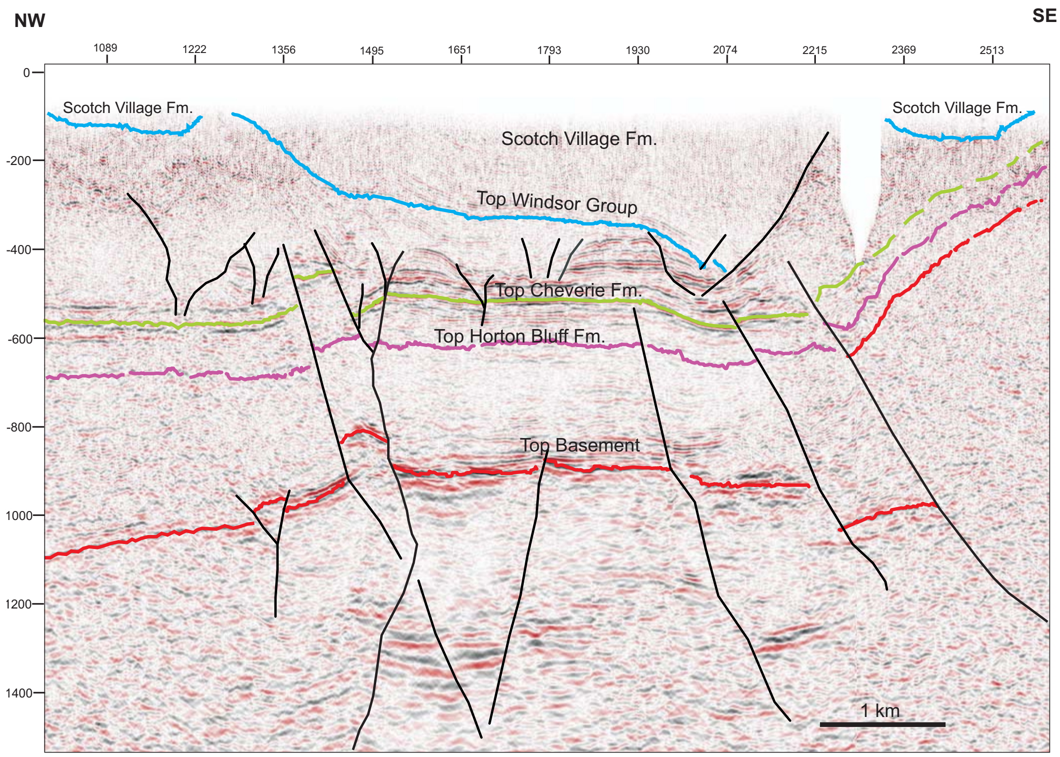


Figure 3.22: Interpreted 2D seismic line WND00-006 showing minibasins created by evaporite mobility within the Windsor Group. These minibasins were filled by Pennsylvanian Scotch Village Formation.

Curry Brook member

Well	Interval (m, MD)	Thickness (m)	N/G	Lithological description
Coolbrook-1	1345 – 1224	121	0.52	Comprises gray, moderate to dark gray, fine to medium and occasionally coarse grained, micro-fractured sandstone having carbonaceous plant fragments, interbedded with gray siltstone and dark gray, black, silty, bioturbated, laminated shale. Siltstone is laminated and also has carbonaceous plant fragments.
Kennetcook-2	1495 – 1353.5	141.5	0.51	Comprises white, fine grained, moderately well sorted, kaolinitic sandstones with 6% visible porosity, interbedded with gray to black, fissile, carbonaceous shale.
Kennetcook-1	(a)1218.5–1061.5 (b)1329.0–1218.5	(a) 157.0 (b) 110.5	(a) 0.67 (b) 0.25	(a) Moderate gray to white-gray, white-gray, fine grained, well sorted, kaolinitic sandstones with thin beds of black, dark gray, carbonaceous, silty shale. (b) gray black, black, carbonaceous and lustrous shale alternating with moderately thick (0.5 – 4m) beds of medium gray, very fine to fine grained, bioturbated, cross-bedded and well-sorted sandstones.
Creelman-1	1407 – 1275.5	131.5	0.21	Predominantly dark gray to black, carbonaceous, bioturbated shale with minor siltstone interbeds and 2 – 10 m thick sandstone beds which are light gray, fine to medium grained, and have minor carbonaceous plant fragments. The top of this part is marked by breccia which marks a possible location of a fault zone.

Table 3: Subsurface lithological descriptions of the Curry Brook member in the study area.

Blue Beach member

Well	Interval (m, MD)	Thickness (m)	N/G	Lithological description
Coolbrook-1	1224–1073.5	150.5	0.11	Light to dark gray, bioturbated, laminated to cross-bedded siltstone with local soft-sediment deformation features, interbedded with dark gray to black shale. Light gray, fine to very fine grained sandstone beds having carbonaceous plant fragments are also present in the middle part.
Kennetcook-2	1353.5–1224.5	129	0.38	Clear quartz-arenite, moderately well sorted, loosely consolidated sandstones with 6% visible porosity, kaolinitic in places, alternating with thick beds of gray, dark gray to black, fissile, carbonaceous shale.
Kennetcook-1	1061.5–839	222.5	0.35	Comprises white to white-gray very fine to fine grained, well sorted, kaolinitic sandstones alternating with moderate gray to dark gray, fissile, silty, carbonaceous shale.
Creelman-1	(a) 948.2–253.8 (b) 1275.5–948.2	(a) 694.4 (b) 327.3	(a) 0.07 (b) 0.06	(a) Dominantly interbedded siltstone and shale. Siltstones are black to dark gray, moderately bioturbated and have wavy laminations. Shales are black to dark gray having carbonaceous plant fragments. Sandstones in this interval are dark gray and gray to white, very fine to fine, locally medium grained, cross-bedded and contain carbonaceous patches of plant fragments. (b) dominantly interbedded siltstone and shale which is thinly laminated and bioturbated. Shales are black and dark gray and have micro-fractures filled with calcite. Sandstones are fine to very fine and coarse grained in the lower part of this interval, laminated, pyritic and micaceous.

Table 4: Subsurface lithological descriptions of the Blue Beach member in the study area.

Hurd Creek member

Well	Interval (m, MD)	Thickness (m)	N/G	Lithological description
Coolbrook-1	1073.5–1032.11	41.39	0.77	Composed of sandstones that are light gray to dark gray, medium to coarse grained to conglomeratic towards the top, carbonaceous, pyritic, and interbedded with thin beds of siltstone and shale.
Kennetcook-2	1224.5 – 1160	64.5	0.81	Composed of white to clear, quartz arenite, very loosely consolidated, fine grained, moderately well-sorted with 6% porosity, sandstones interbedded with gray, dark gray to black fissile, carbonaceous shale.
Kennetcook-1	839 – 708.5	130.5	0.48	Composed of white, clear, very fine to fine grained, poorly consolidated, well-sorted sandstones alternating with moderate gray, fissile, carbonaceous shale and brick red, brown siltstone grading to mudstone.
Creelman-1	253.8 – 225	28.8	0.95	Composed of clean, fine to coarse grained, locally medium to coarse grained, pyritic sandstone with thin intercalations of dark gray siltstone. Very thin dark green, silty, and bioturbated shale is also present in this interval. Coarse grained sandstone in this interval is marked as the glass sand of the Horton Bluff Formation.

Table 5: Subsurface lithological descriptions of the Hurd Creek member in the study area.

Lower interval

Well	Interval (m, MD)	Thickness (m)	N/G	Lithological description
Coolbrook-1	1032.11–855.5	176.61	0.08	Dominantly red and dark gray siltstone interbedded with dark gray to black shale, and thinly bedded light gray, dark green and dark gray, laminated, very fine to fine and fine to medium-grained, moderately bioturbated sandstone. Microfractures are filled with silica and locally mottled red-green patches are present within fine grained sandstones.
Kennetcook-2	(a)1042–959.6 (b)1160–1042	(a)82.4 (b)118	(a)0.07 (b)0.05	(a) Predominantly brick-red to brown-red, micaceous, slightly waxy siltstone with interbeds and stringers of gray shale and fine grained sandstone. Some occasional beds of white to light gray and clear, loosely consolidated, kaolinitic fine grained sandstone are present. This lower middle interval also has more siltstone as compared with Kennetcook-1. (b) composed of gray to white gray, silty, blocky to sub-fissile shale grading to very fine grained sandstone in places. Thin beds of brick-red to brown-red, micaceous siltstone are also present in this part. This basal part has more siltstone as compared with the Kennetcook-1 well.
Kennetcook-1	(a)582–521.7 (b)708.8–582	(a)60.3 (b)126.8	0.07	(a) Comprises red to brown siltstone interbedded with greenish gray, blocky to sub-fissile and fissile shale. Siltstone in this interval grades upwards to red mudstone. (b) predominantly moderate to dark gray, firm to hard, fissile shale with occasional stringers of fine grained, white to clear sandstone and red siltstone/mudstone. Some thin beds of white to clear, loosely consolidated, kaolinitic sandstone with 6% visible porosity are also present.
Creelman-1	225 – 152.7	72.3	0.05	Dominantly interbedded siltstone and shale. Siltstone is red and green, cross-bedded, bioturbated and has carbonaceous plant fragments. Very fine to fine locally medium grained sandstone lenses are also present.

Table 6: Subsurface lithological descriptions of the lower interval of the Cheverie Formation in the study area.

Middle interval

Well	Interval (m, MD)	Thickness (m)	N/G	Lithological description
Coolbrook-1	885.5–813.8	71.7	0.71	Mainly composed of brownish gray, gray, grayish red, fine to medium grained, locally conglomeratic, cross-bedded sandstone interbedded with red, grayish red, laminated, cross-bedded siltstone.
Kennetcook-2	959.6–910	49.6	0.88	The upper middle part (m MD) is mainly composed of white to light gray, clear, loosely consolidated, kaolinitic, fine grained, moderately sorted , slightly calcareous, sandstones having an estimated 6% visible porosity with thin beds of light greenish and reddish brown, sub-fissile, waxy shale that has stringers of sandstone. N/G ratio is 0.88. This member has more sandstone as compared with the Kennetcook-1 well.
Kennetcook-1	521.7–410	111.7	0.28	Composed of greenish gray and light greenish gray to light gray, sub-fissile, waxy, silty shale interbedded with white to clear, fine grained, loosely consolidated, kaolinitic sandstone which is moderately sorted with 6% visible porosity.
Creelman-1	(a)130.8–30.6 (b)152.7–130.8	(a) 100.2 (b) 21.9	0	(a) Composed of interbedded siltstone and shale. Siltstone is light gray to dark gray, red and green, cross-bedded, bioturbated and contains carbonaceous plant fragments. One meter thick red, laminated shale is also present in the basal part of this interval. (b) comprises entirely siltstone which is brownish gray and contains sandy lenses.

Table 7: Subsurface lithological descriptions of the middle interval of the Cheverie Formation in the study area.

Upper interval

Well	Interval (m, MD)	Thickness (m)	N/G	Lithological description
Coolbrook-1	(a)792.2–726.6 (b)813.8–792.2	(a)65.6 (b)21.6	(a)0.49 (b)0	(a)Predominantly dark gray, gray, red and brownish gray, feldspathic, fine to coarse-grained, laminated to cross-bedded carbonaceous sandstone alternating with red feldspathic, laminated to cross-bedded, burrowed siltstone. (b) The upper middle part (m MD) comprises interbedded siltstone and shale which is dark gray to black, cross-bedded and contains carbonaceous plant fragments.
Kennetcook-2	910 – 809.5	100.5	0.15	Predominantly brick-red, micro-micaceous siltstone that grades to very fine grained sandstone. Sandstone is moderate gray, poorly consolidated, fine grained, moderately well sorted and has an estimated 6-9% visible porosity. Minor conglomeratic sandstones are also present in the middle part of this interval.
Kennetcook-1	410 – 340	70	0.51	Predominantly white to clear, red brown to brick red, fine grained, micaceous, well sorted, kaolinitic sandstone having an estimated 6% visible porosity, interbedded with brick-red, blocky to sub-fissile, micro-micaceous, siltstone grading to red mudstone. In the upper part, these red siltstones grade upwards to very fine-grained sandstones (i.e. coarsening upwards).
Creelman-1	surface – 30.6	>30.6	0.65	Pominantly sandstone interbedded with siltstone. Sandstone is grayish brown, light gray, fine to very fine grained. Siltstone is light to dark gray, red, green and olive green, cross-bedded, bioturbated and has some soft-sediment deformation features.

Table 8: Subsurface lithological descriptions of the upper interval of the Cheverie Formation in the study area.

Lower Windsor

Well	Interval (m, MD)	Thickness (m)	N/G	Lithological description
Avondale#2	208.5 - 199.3	9.2		Comprises white to clear halite encountered at 199.3 m, confirmed the top of the Stewiacke Formation which was drilled only in the Avondale#2 well. The well did not encounter the base of the Stewiacke Formation.
Coolbrook-1	726.6 - 670.8	53.8		Predominantly medium gray that is petroliferous on freshly broken surfaces and contains disseminated organic matter.
Kennetcook-2	807 - 685	122		Dominantly white to light gray, with minor thin limestone and gray shale stringers. One metre white to clear, loosely consolidated, kaolinitic, fine grained, moderately well sorted sandstone having an estimated 6% visible porosity was encountered at the base of a thick succession (~ 17 m) of clear to white gypsum that has selinite crystals and stringers of red siltstone, gray shale and fine grained sandstone.
Kennetcook-1	336.5 - 210	126.5		Composed of white to light gray, massive anhydrite with dark gray limestone stringers, primarily lime-mudstone. Limestone beds (0.5 – 5 m) are present in the upper part of this basal anhydrite interval. Limestone is dark gray to black, microcrystalline to cryptocrystalline, dominantly mudstone with traces of grainy lenses and crinoid fragments. Ten metres of thick clear to white gypsum with selinite crystals mark the top of this basal anhydrite unit in the Kennetcook – 1 well.
Creelman-1				The well was spudded in the Cheverie Formation

Table 9: Subsurface lithological descriptions of the lower Windsor Group in the study area.

Middle Windsor

Well	Interval (m, MD)	Thickness (m)	N/G	Lithological description
Coolbrook-1				Faulted-out
Kennetcook-2				Faulted-out
Kennetcook-1	210 – 144	66	0.13	Comprises white to light gray, massive anhydrite interbedded with sandstone, siltstone and shale. Dark gray to grayish black limestone, primarily mudstone with crinoid stems, locally grading to grainstone, is present in the middle and upper part of this interval. Shale is light to moderate gray, blocky to sub-fissile. Siltstone is reddish brown and grades upwards to very fine grained sandstone. Sandstone is mult colored but dominantly light gray, slightly calcareous and well sorted. Correlatable with the Wentworth Station Formation.
Avondale#1	(a)149.35–73.8 (b)300–149.35	(a)75.55 (b)150.65	0.39	(a)Comprises thick bluish white, grey, light gray to dark gray interbedded gypsum, limestone and sandstone. Limestone is primarily grey-brown lime mudstone, laminated, moderately oil stained but locally heavily oil stained, and grades upwards to wackstone and packstone. Laminations in the limestone make an apparent dip angle of 80^{O}. Minor and major fractures within limestone and sandstone are filled with calcite and gypsum. Sandstone is light red, gray, locally mottled red gray, fine to medium grained, calcareous and fractured. The base of the interval is marked by a sandstone bed at 149.35 m MD. This middle interval (73.55m thick) represents the upper part of the Wentworth Station Formation. (b) Composed entirely of gray, thickly bedded, slightly calcareous anhydrite with some occasional bands of sediments. This thick evaporite succession is the part of the Wentworth Station Formation. The Avondale#1 well did not penetrate the base of the Wentworth Station Formation and drilled 150.65 m of this anhydrite.
Avondale#2	(a)84.4 - 29.35 (b)199.3 – 84.4	(a)55 (b)114.9		(a)Composed entirely of limestone facies which are brownish gray, light brown, moderately bioturbated floatstone to packstone and grainstone, with abundant brachiopods, pelecypods, crinoids and bryozoans. They are locally petroliferous, and have light oil staining and moderate moldic porosity. Apparent dip angle within this limestone is about 60^{O}. The well drilled about 55 m of this limestone. (b) A succession of anhydrite with occasional beds of limestone and dolomite. This anhydrite is probably the lower part of the Wentworth Station Formation. The anhydrite is moderate gray, white with red-green mottling, locally nodular and contains light oil staining and laminated bands of fine grained sandstone and siltstone. Apparent dip angle of the laminations recorded within the anhydrite is 50^{O}. Dolomitized grainstone with sucrosic texture and gypsum-filled fractures are also present in the upper part of the formation. Limestone is black, dark gray, dominantly mudstone to wackstone, laminated and dips at 70^{O}. A limestone unit present in the middle part is brecciated at the base and may mark the location of a local fault zone. A 2.5 m thick unit of wackstone to grainstone with minor anhydrite clasts in a mudstone matrix is present in the lower part.

Table 10: Subsurface lithological descriptions of the middle Windsor Group in the study area.

Upper Windsor

Well	Interval (m, MD)	Thickness (m)	N/G	Lithological description
Coolbrook-1	(a) 335 – 294 (b)529.8 – 335 (c)670.8 – 529.8	(a)41 (b)194.8 (c)141		(a)Comprises moderate gray, dark gray, nodular to bedded, oolitic, strongly petroliferous limestone interbedded with bluish white, grayish white anhydrite that is laminated and intermixed with wackstone. Anhydrite present at the top of this interval is brecciated and contains veinlets of gypsum and bitumen. Very fine to fine-grained mottled reddish green sandstone with gypsum veinlets is present in the upper part of this interval. (b) Composed of interbedded siltstone and shale, mottled light gray shale, anhydrite and dolomite. Anhydrite is bluish white, dark gray to black, light gray and petroliferous, and is intermixed with dolomitized grainstone/packstone. Dolomite is medium gray, primarily oolitic packstone, petroliferous and contains minor pyrite. Siltstone is red with gray mottling, and has wavy bedding and soft sediment deformation features. Both the lower and middle intervals are correlatable with the Murphy Road Formation (c) Predominantly interbedded siltstone and shale with some minor beds of medium gray, dark gray limestone (primarily lime-mudstone), locally oolitic, and occasionally composed of interlaminated grainstone and wackstone. Siltstone is dark gray to black and exhibits soft-sediment deformation features. Red green mottled laminations within this siltstone are 45^{O} to the core axis. Thick beds of red, fine grained sandstone are present at the base of this interval.
Kennetcook-2	(a)427.5 – 328 (b)520 – 427.5 (c)685 – 520	(a)99.5 (b)92.5 (c)165		(a)Dominantly composed of siltstone with some occasional thick beds of light gray, silty, locally calcareous shale in the basal part of this interval and thin beds of light gray locally silty, tight limestone. This limestone that is primarily lime-mudstone in the topmost part marks the top of the Windsor Group in this well. This upper part is correlatable with the Pesaquid Lake Formation (b) Comprises siltstone having stringers of gray shale and limestone. Thickly bedded and dense, snow white anhydrite with limestone stringers is present in the topmost part of this interval. Siltstone is red-brown and grades upwards to very fine grained sandstone. Shale is light to moderate gray and blocky. Correlatable with the Murphy Road Formation (c) Predominantly red to red-brown, slightly calcareous, sandy siltstone that has stringers of shale and anhydrite. Dark grey, well cemented limestone, primarily lime mudstone that grades upwards to grainstone, is present in the upper part of this interval. Fine grained, white to clear, poorly consolidated, slightly calcareous and moderately well sorted sandstones are present in the lower and upper part of this interval as well. Correlatable with the Murphy Road Formation
Kennetcook-1	144 – 101.6	42.4		Dominantly siltstone interbedded with moderately thick beds of anhydrite and minor sandstone and limestone stringers. Siltstone is reddish brown, sandy, moderately calcareous, and grades to very fine grained sandstone. Limestone is dark gray to moderate dark gray, dense and primarily mudstone and grainstone. Correlatable with the Murphy Road Formation.
Avondale#1	73.8 – 25.85	47.95		Top is marked by the limestone that is moderate gray, laminated, oil stained mudstone to wackstone with petroliferous odor, in the top section and grainstone at the base. Laminations in the limestone are 80^{O} to the core axis. Minor gypsum is also present within this limestone that is moderate to light gray, petroliferous near the base. The lower part of this upper interval contains fine grained sandstone which is light brownish gray, gray, red, and mottled gray at the base. It has some gypsum and calcite-filled fractures. This upper interval is correlatable with the Murphy Road Formation. The total thickness of the Murphy Road Formation penetrated in this well is 47 m..
Avondale#2	29.35 – 25.85	3.5		Composed of interbedded fine grained sandstone that grades downward to siltstone. Sandstone/siltstone is light gray, slightly calcareous, and has carbonaceous plant fragments and minor gypsum veinlets. This succession comprises an overall coarsening upward sequence. This, about 4 m thick interval comprising siliciclastics is the part of the Murphy Road Formation.

Table 11: Subsurface lithological descriptions of the upper Windsor Group in the study area.

Lower interval (Scotch Village Formation)

Well	Interval (m, MD)	Thickness (m)	N/G	Lithological description
Coolbrook-1	294 – 203	91	0.43	The lower interval is dominantly gray to dark gray, fine to medium grained, locally feldspathic, laminated to cross-bedded sandstone interbedded with red and mottled green, gray to dark gray, laminated siltstone. Dark gray to black and red shale is also present in the lower and middle part of this interval.
Kennetcook-2	(a)299.5 – 282 (b)328 – 299.5	46	(a)1 (b)0	(a) The Upper interval comprises orange brown to white, fine to medium grained, moderate to well sorted sandstone. (b)composed of red to red-brown, slightly calcareous, sandy siltstone that have stringers of sandstone.
Kennetcook-1	(a)42 – 22 (b)101.6 – 42	79.6	(a)1 (b)0.16	(a) Comprises white to light gray and multi-colored, fine to medium grained, moderate to well sorted, slightly calcareous sandstone having poor to fair porosity (~ 3-6%) have interbeds of light gray shale and red-brown siltstone.N/G for this interval is 1 (b) composed of red to red-brown, very slightly calcareous, sandy siltstone that grades to very fine grained sandstone. Light gray, white to gray, very fine to fine-grained, well-sorted sandstone having slightly calcareous siltstone and gray silty shale stingers is present in the middle.
Creelman-1				The well was spudded in the Cheverie Formation

Table 12: Subsurface lithological descriptions of the lower Scotch Village Formation (Cumberland Group) in the study area.

4. Structural interpretation of seismic data

Subsurface seismic data in the Kennetcook-Windsor basin provide an insight into understanding the basin structure. The subsurface seismic imaging is of good quality where there is cover of the Scotch Village Formation (Figure 1.5), whereas it becomes worse where highly deformed evaporites and carbonates of the Windsor Group are at the surface. Time-depth relationships and seismic-to-well correlations were established for the interpretation of regionally traceable horizons. The top of basement, the top of the Horton Bluff Formation, the top of the Cheverie Formation and top of the Windsor Group were selected on the basis of regional extent to document important stratigraphic and structural geometries. These horizons were picked accurately and tied at the intersection of 2D lines and picked by creating composite seismic profiles. Where there were misties between different vintages of seismic data, visual estimation was applied to correlate the seismic character of horizons on both seismic datasets.

This chapter gives a detailed account of subsurface structural geometries, fault correlations, modelling, and horizon interpretation, integrated with well data and surface geology. Two-way-time (TWT) structure maps were generated on the tops of basement, the Horton Bluff, and the Cheverie formations. The thickness maps for the Horton Bluff and the Cheverie formations were also generated to estimate the regional thickening and thinning trends of the Horton Group rocks in the basin.

4.1. Seismic interpretation

4.1.1. Horizon interpretation

4.1.1.1. Top of basement

Well logs (Noel-1, Figure 3.1) indicate that sonic (DT) velocity and bulk density (RHOB) curve show an increase at the basement top which corresponds to an increase in the acoustic impedance and therefore a positive reflection coefficient. A well-to-seismic tie shows that this corresponds to a positive amplitude or peak event as shown on both 2D and 3D reflection profiles (Figures 3.4 & 3.5). In the subsurface, the top of basement shows discontinuous, weak and dipping seismic reflections across the 2D and 3D lines.

4.1.1.2. Top of the Horton Bluff Formation

The Sonic (DT) and the bulk density (RHOB) curves show a slight change at the top of the Horton Bluff Formation as compared with the basal part of the Cheverie Formation (Figure 3.8). Hence, there is a very low acoustic impedance contrast between the basal part of the Cheverie Formation and the top part of the underlying Horton Bluff Formation. However, the seismic-to-well tie matches with a trough event on seismic for the top of the Horton Bluff Formation.

4.1.1.3. Top of the Cheverie Formation

The top of the Cheverie Formation is marked by high Gamma Ray (GR) signal relative to the basal part of the Windsor Group and lows in both sonic (DT) and bulk density (RHOB) log data (Figure 3.8). This corresponds to a decrease in acoustic impedance and hence, a predicted negative reflection coefficient. This matches with a trough event on both 2D and 3D seismic data.

4.1.1.4. Top of the Windsor Group

The top of the Windsor Group shows a low and uniform GR response as compared with the underlying top of the Cheverie Formation (Figure 3.17). The sonic (DT) shows that the interval velocity of Windsor Group is slightly higher than the overlying Cumberland Group and corresponds to positive acoustic impedance that correlates with positive reflection coefficient and therefore a peak event on the seismic.

Well-to-seismic tie and surface geological information allowed an accurate interpretation and picking of these key horizons in the subsurface. Prior to fault modelling and horizon mapping, the subsurface structural geometries were delineated on the regional 2D seismic lines. A brief description of these structural geometries in outlined in the following section.

4.1.2. Subsurface structural geometries

4.1.2.1. High angle normal faults

High angle normal faults that offset the basement and cut through the Horton Bluff Formation are present at most of the places in the subsurface (Figure 4.1, 4.2, 4.3). Fault correlation at the top of basement, Horton Bluff and Cheverie/Macumber formation levels (Figure 4.4, 4.5, 4.6) shows that normal faults strike WSW- ENE and SW-NE and dip both NNW and SSE. However, high-angle normal faults offsetting the top of the Windsor Group (Figure 4.7) strike SW-NE and dip NW. Their strike in comparison with the basement-cutting normal faults is different and rotated more towards north and indicates a different episode of extensional deformation.

4.1.2.2. Listric normal faults

Listric normal faults trending SW-NE offset the Windsor Group rocks (Figures 4.8, 4.9, 4.10). These faults become very low-angle to almost horizontal and die out within the evaporites of the Windsor Group. One prominent feature associated with these listric normal faults is that there is considerable variation in the thickness of the Windsor Group sediments. These faults promoted the mobility of the evaporites to create accommodation space for the Pennsylvanian sediments.

4.1.2.3. Reverse faults

Reverse faults are also widespread in the subsurface and have affected the basement and the younger sediments. Some faults can be classified as deep-seated reverse faults that have affected the Horton Bluff, Cheverie, and Macumber formations as well as the basement (Figure 4.11), whereas, some faults terminate within the individual formations and do not cut upsection (Figures 4.12 & 4.13). Reverse faults also strike WSW-ENE and SW-NE and played an important role in the uplift and juxtaposition of different lithologic units in the subsurface.

4.1.2.4. Low angle thrust system

The surface geological map in the vicinity of Cheverie (Figure 1.5) shows juxtaposition of highly deformed Horton Bluff Formation and Windsor Group rocks. Two seismic lines WND00-002 and -003 oriented nearly north-south pass through this area (Figure 1.5). The Cheverie#1 well located on seismic line WND00-002 (Figures 1.5 & 4.14) drilled 404 m of highly deformed Horton Group rocks. This upper section down to 404 m was reported as part of the Pennsylvanian Scotch Village Formation by the well-site geologist. However, palynological analysis of the well cuttings (Waldron et al., 2010) confirmed that the sediments down to 404 m are the part of the Horton Group. Surface geological investigations of highly deformed Horton Group rocks exposing in the coastal sections northeast of Cheverie confirmed that these rocks are the allochthonous hanging wall of a low angle decollement that has exposure near Cheverie (Waldron et al., 2010). Seismic line WND00-002 (Figure 4.14) shows these allochthonous Horton Group rocks juxtaposed with the Windsor Group rocks. Seismic reflections in the Horton Bluff Formation are gently dipping towards a nearly horizontal thrust below which chaotic and discontinuous reflections in the Windsor Group are truncated. Another trace of this low angle decollement surface is interpreted on seismic line WND00-003 (Figure 4.15). Such decollement surfaces developed in the Windsor Group played an important role in the transportation and distribution of highly deformed rocks into distinctive structural inliers (Gibling, 1995). Waldron et al. (2010) have interpreted these low angle thrusts as the "Kennetcook Thrust System". Nearly N-S oriented 2D seismic lines located east of Cheverie (Figure 1.5) do not indicate any possible extension of this Kennetcook thrust system suggesting either that the amount of transport decreases to the E, or that the allochthonous hanging wall has been removed by erosion.

4.1.2.5. Tilted fault block geometry

Interpretation of the top of basement rocks in the subsurface shows tilted fault-blocks bounded by high angle normal and reverse faults (Figures 4.10, 4.16, 4.17). The seismic data indicate an array of fault-blocks stepping down to north and northwest towards Cobequid Bay (Figures 4.3 & 4.16). This basement geometry provided graben to half-graben setting for the deposition of the Horton Bluff Formation, as described and interpreted in the previous chapter.

4.1.2.6. Flower structures

Subsurface 2D seismic data in the Kennetcook-Windsor basin show good quality images of structural geometries bounded by high-angle reverse and normal faults in the Horton, Windsor and Cumberland group rocks. Individual faults in such geometries spread laterally upsection, become gentler in dip; down-section, they merge with a steeply dipping to nearly vertical master fault. These are excellent examples of both positive and negative flower structures. Figure 4.1 shows interpreted negative flower structures developed within Horton Bluff and Cheverie formations where high angle faults spread upward but merge at depth into a single fault giving a shovel-like geometry. Figure 4.2 also shows an interpreted negative flower structure developed within the Cheverie and Macumber formations. Individual faults dip at high angles and merge down-dip with a basement-cutting fault that has reverse component at the top of the basement. Figure 4.16 shows another interpreted negative flower structure developed in the Horton Bluff Formation where individual faults terminate in the formation and do not extend either upward or downward. Figure 4.15 shows an interpreted negative flower structure developed in the Windsor Group below the O-61-A well. Figure 4.18 shows an excellent example of an interpreted positive flower structure developed in the Cheverie Formation;

individual faults have a reverse offset and merge with a master fault that terminates in the Horton Bluff Formation.

The seismic line WND00-005 (Figure 4.9) shows a local pop-up structure at the top of basement in the south, whereas farther east, on seismic line WND00-004 (Figure 4.8) the same structure shows graben geometry bounded by high-angle normal faults. Subsurface structural geometry (Figures 4.8, 4.9, 4.18) indicates strike-slip movement along the high-angle conjugate faults which have reverse offset in the west and normal offset in the east. These faults probably show variably oblique movement.

The subsurface orientations of these flower structures are SW-NE and WSW-ENE. The presence of these flower structures in the subsurface indicates a strike-slip setting in which transpression and transtension resulted in such geometries along bends and stepovers.

4.1.2.7. Pop-up structures

There are many structural geometries that show blocks that are bounded by high angle reverse faults and are present at the top of basement and within the Horton and Windsor groups (Figures 4.19, 4.20, 4.21, 4.22). The conjugate faults do not merge at depth with a high angle master fault as described in the flower structures. These geometries are interpreted as pop-up structures. Most of these structures are localized, trend WSW-ENE (Figures 4.4, 4.5, 4.6, 4.7) and show uplift of the strata bounded by the reverse faults. These structures could be potential drilling targets if there is a valid petroleum system and the bounding faults have good sealing capacities.

4.1.2.8. Imbricate structures

Some of the 2D dip lines oriented roughly north-south show a thrust stack geometry within the basal Windsor Group (Figure 4.8), Cheverie/Macumber (Figure 4.23) and Horton Bluff Bluff/Cheverie formations (Figure 4.16). Here, low angle thrust faults are interpreted to have stacked up individual horses. These are interpreted as imbricate structure as the individual faults have listric fault geometry and are not connected to a nearly horizontal fault upsection.

4.1.2.9. Dissolution/structural collapse features

Many 2D seismic lines (Figures 4.8, 4.15, 4.24) show high-angle, chaotic and inclined seismic geometries within the Windsor Group rocks. Tilted fault-blocks, pop-up and roll-over structures are interpreted in the Windsor Group. High-angle chaotic reflections coupled with thickness variations are interpreted as dissolution features or structural collapses triggered by evaporite withdrawal or solution. Prominent dipping reflections (Figures 4.8 & 4.24) in the Windsor Group rocks are probably not primary stratigraphic features but rather show intensely deformed sediments encased within evaporites. Two seismic lines WND00-006 and Kenn-07-01 (Figures 4.2 & 4.24) show an almost flat reflector within the Windsor Group where the underlying and overlying reflections are truncated. Due to evaporite withdrawal the surface that was once inclined became almost flat and caused discordance within the underlying and the overlying reflections. Overall, high-angle seismic reflections in the Windsor Group are truncated up-dip and have an angular relationship with the overlying Scotch Village Formation.

4.1.2.10. Truncations

Truncations of seismic reflections are identifiable at the top of the Windsor Group (Figures 4.8 & 4.24) on some 2D seismic lines. However, one 2D seismic line WND00-001 (Figure 4.19) show low angle truncations of the Cheverie Formation below the Macumber Formation. Here, dipping reflections have an angular relationship above and below this seismic reflection which could represent an angular unconformity. Above this surface seismic reflections are downlaping and below this surface seismic reflections have either toplap or truncation.

4.1.2.11. Salt Diapirs

Where the Windsor evaporites are exposed at the surface, seismic imaging is poor due to karst topography (Figures 4.9 & 4.15) of the beds. The Windsor Group sediments also show drastic variations in thickness clearly visible on some 2D lines (Figures 4.8, 4.15, 4.23). Chaotic and high-angle dipping reflections in the subsurface where the Windsor Group sediments are much thinner indicate the probable areas from which evaporites were withdrawn and flowed towards the surface. The surface exposures of the Windsor Group show chaotic and poor reflections on the seismic profiles. Such thick sections within the Windsor Group are here interpreted as salt diapirs which contain highly deformed beds of anhydrite and/or carbonates similar to those exposed at surface near Cheverie, Johnson’s Cove (Waldron et al., 2007) and along the left bank of the Shubenacadie River (Figure 1.5).

4.1.2.12. Minibasins

As discussed earlier, many 2D seismic lines which show chaotic seismic reflections indicate evaporite mobility (Figures 4.2, 4.15, 4.23, 4.24). The areas in the subsurface from where the evaporites moved up and away created depressions which accommodated deposition of the younger Pennsylvanian sediments.

Seismic data (Figures 4.2, 4.15, 4.23, 4.24) in the Kennetcook-Windsor basin indicate that these depressions developed during the deposition of the Cumberland Group represented by the Scotch Village Formation. Nearly horizontal, uniform and continuous reflections within the Scotch Village Formation indicate that the sediments were deposited horizontally. Gently dipping reflections in the Scotch Village Formation (Figures 4.2, 4.23, 4.24) that have discordance with the underlying reflections in the Windsor Group indicate the withdrawal of the evaporites (Waldron and Rygel, 2005). The Scotch Village Formation shows uniform thickness in the subsurface where the underlying Windsor Group has not indicated any evidence of evaporite mobility (Figure 4.15). Thus evaporite withdrawal played an important role in the development of local minibasins and subsequent preservation of the younger sediments.

4.1.2.13. Décollement surfaces

On seismic line Kenn-07-001 (Figure 4.24), the Cheverie Formation is exposed at the surface in the eastern part of the line. Below this eastern end, some high angle dipping reflections within the Horton Group were picked across an uplifted structure. These high-angle reflections die out below 830 milliseconds in the Horton Bluff Formation. Seismic reflections within this dome-like structure show chaotic, discontinuous and dipping geometries that have discordance with a nearly flat reflector below. The surface where the internal reflections become gentler and almost become horizontal marks the location of a possible décollement surface above which this structure formed during an episode of shortening.

Seismic reflections within the Horton and Windsor groups show discordance elsewhere (Figures 4.2, 4.14, 4.24) as indicated by truncations, downlap, onlap, and changes in angle of dipping reflections. Such reflections of discordance are the potential levels of décollement surfaces. Chaotic and discontinuous seismic reflections within the Windsor Group also mark such decollement surfaces (Figures 4.8 & 4.15).

4.1.3. Subsurface fault interpretation and classification

On the basis of subsurface fault interpretation and correlations, basement-cutting faults can be classified into the following six categories that evolved during the development of the basin.

4.1.3.1. Category I

The first category (Figure 4.25a) includes the basement–cutting faults that terminate in the basal Horton Bluff Formation, do not extend up–dip, and have a normal offset component (Figures 4.3, 4.10, 4.12, 4.19, 4.23, 4.24). These faults are quite high-angle (~ 40-70°) and form an array of tilted fault-blocks. Most of these faults cut the coarse alluvial fan deposits in the basal part of the Horton Bluff Formation (Figure 4.3, 4.10, 4.17). These faults mark the extensional phase that controlled the initial opening of the basin. Correlation and mapping of these faults show that they strike SW – NE and WSW – ENE (Figure 4.4).

4.1.3.2. Category II

The second category (Figure 4.25b) comprises basement-cutting faults that also terminate within the Horton Bluff Formation but extend beyond the basal coarse alluvial deposits and show reverse offset updip (Figures 4.16, 4.20, 4.21). These faults form localized pop-up structures (Figures 4.16 & 4.21) bounded by high-angle reverse faults. Faults in this category also bound an array of tilted fault-blocks paired with high-angle normal faults. Fault correlation, modelling and mapping show that they strike SW-NE and WSW-ENE (Figure 4.4). These faults also played an active role in the beginning of the basin development.

4.1.3.3. Category III

A third category of faults (Figure 4.25c) interpreted in the subsurface of the Kennetcook-Windsor basin includes those basement-cutting normal faults that extend almost to the top of the Cheverie Formation and have a normal offset up-dip (Figure 4.2, 4.8, 4.15). These faults are quite high angle (~50^{o} - 80°) and show large offset (~20-50ms) (Figure 4.2 & 4.8) at the basement level as compared to that at the tops of the Horton Bluff and the Cheverie formations. Although these faults show a normal component, inclined and curved seismic reflectors across these faults show some inversion (Figures 4.2 & 4.15); reverse motion during inversion was not as much as the normal component and so they still display net normal offsets. Fault correlation, modelling and mapping at the top of basement show that these faults strike SW-NE and NW-SE (Figures 4.4 & 4.5).

4.1.3.4. Category IV

The fourth category of faults Figure 4.25d) includes those basement-cutting normal faults that terminate in the basal Windsor Group rocks and have reverse offset up-dip at the top of the Horton Bluff and the Cheverie formation levels (Figures 4.2 & 4.8). A normal offset at the basement level is greater than the reverse component up-dip at the shallower levels. Correlation, modelling and mapping at the top of Horton Bluff and Cheverie formations show that these faults strike SW-NE and WSW-ENE (Figures 4.5 & 4.6).

4.1.3.5. Category V

The fifth category of faults Figure 4.25e) comprises those that have reverse offset both at the basement and the up-dip sections at tops of the Horton Bluff and the Cheverie formations. These faults accommodated shortening and caused uplift of the Carboniferous strata (Figure 4.2, 4.15, 4.13, 4.14, 4.22). Most of these faults form high angle pop-up structures with opposite-dipping reverse faults (Figure 4.14 & 4.22) at shallower level. Correlations, modelling and mapping at the top of basement, top of the Horton Bluff and top of the Cheverie formations show that these faults strike SW-NE and WSW-ENE (Figures 4.4, 4.5, 4.6). These faults were mapped in the western and southern part of the study area. Some reverse faults at the top of the Horton Bluff and the top of the Cheverie formations were also mapped in the northeastern part around Noel (Figure 1.5).

4.1.3.6. Category VI

Category VI faults (Figure 4.25f) include those that have reverse offset at the basement level but have normal component up-dip at the tops of the Horton Bluff and the Cheverie formations (Figure 4.2 & 4.14) and terminate in the basal Windsor Group. Normal offset at the shallower levels indicate that these faults, at least, accommodated the early Visean extension and remained active during the deposition of the basal part of the Windsor Group. Probably due to possible local décollement levels and structural collapses as discussed earlier within the Windsor Group, these faults could not extend up-dip and cut the entire Windsor sediments. Correlation, modelling and mapping of these faults at the top of the Horton Bluff and Cheverie formations show that these faults strike SW-NE (Figures 4.5 & 4.6).

4.1.4. Fault modeling

Interpreted faults on the 2D seismic lines after correlation were converted into faults sticks (4.26) using *Petrel 2010.2* interpretation software. These fault sticks were used to create fault pillars which have the flexibility to control the shape (e.g. vertical, inclined, listric and curved) and extent of the faults. After association of the faults according to their relationships (i.e. truncating, branching and cross-cutting etc.), these fault pillars were converted into final modelled faults by pillar gridding. Faults were also modelled using the fault sticks in structural framework for quality control. These modelled faults from the structural model were used in horizon modelling.

4.1.5. Horizon modeling

Horizon modeling was done in the structural framework on the tops of basement, the Horton Bluff and the Cheverie formations prior to generating the final TWT structure maps for quality control (Figure 4.27). Geological relationships (i.e. conformable, disconformable, truncating etc.) were assigned for each interpreted horizon for modeling in the structural framework. Modelled horizons were cross checked along individual 2D seismic lines and minor changes were made in the final horizon picks. The subsurface horizon modelling matched well with the surface geology of the key horizons (Figure 1.5).

4.1.6. TWT (two-way-time) structure maps

4.1.6.1. Top of basement

The TWT structure map on the top of basement (Figure 4.28) shows tilted fault-blocks stepping down to the north and northwest. Surface trends show that the top of basement shallows south and westward where the high-angle reverse faults have brought the basement to the surface. This subsurface interpretation matches well with the surface exposures of the basement rocks (Figure 1.5). Normal faults that strike SW-NE and WSW-ENE in the north and east have brought down and deepened the top of basement towards the Bay of Fundy. Fault correlations and mapping at the top of basement show that there is a swing (bend) in fault strike between the seismic lines WIND-02-003 and WIND-02-002 where the faults strike SW-NE in contrast to the regional strike direction WSW-ENE (in the west and east). This change in the strike direction WSW-ENE in the western part to SW-NE in the central part and then again to WSW-ENE in the eastern part possibly shows the presence of a local stepover developed in the southwestern part of the study area. The seismic lines WND00-004 and -005 (Figures 4.8 & 4.9) show the western margin of this stepover where the pop-up structure at the top of basement, due to a possible wrench movement, merges eastward with a graben (Figure 4.8).

Faults mapped at the top of basement provided graben and half-graben geometry bounding the tilted fault-blocks in the beginning of the basin history. The basement rocks in the western part were severely deformed along the inverted faults (Figures 4.9, 4.11, 4.13).

4.1.6.2. Top of the Horton Bluff Formation

The TWT structure map on top of the Horton Bluff Formation (Figure 4.29) shows rising trends in the northeast, northwest and to the south of the study area. A regional structural low is present between the seismic lines WND00-002 and WND00-006, across which the top of the Horton Bluff Formation rises in both the NE and SW. Two fault-bounded structural highs at the Horton Bluff level are present in the mapped area between the seismic limes KC-09-12 and WND00-002 (4.29). It is interpreted that the faults mapped in the east, northeast and west underwent a greater component of inversion as compared with the faults mapped within this structural low. Tilted fault-blocks probably indicate oblique motion along these faults which have variable throw along the strike.

4.1.6.3. Top of the Cheverie Formation

The TWT structure map on the top of the Cheverie Formation shows nearly similar surface trends, except the structural low in the central area is narrower and bounded between the seismic lines WND00-003 and WIND-02-003 (Figure 4.30). This interpretation shows that most of the faults that were not inverted at the Horton Bluff Formation level accommodated much inversion at the Cheverie Formation level and caused uplift of the top of the Cheverie Formation in the northeast and southwest. Variable amounts of throw and intermittent reactivation of the subsurface faults probably caused variable uplifts at different levels (e.g. the Horton Bluff and the Cheverie formations) and controlled the aerial extent of the structural lows. The TWT map on the top of the Cheverie Formation shows that two fault-bounded structural highs are present in the study area between the seismic lines KC-09-08 and WND00-002.

4.1.7. Thickness maps

4.1.7.1. Horton Bluff Formation

The thickness map of the Horton Bluff Formation (Figure 4.31) indicates that the formation thickens to the northwest (north of the seismic line KC-09-08) and northeast (north of the Kennetcook-2 well). These thickening trends follow the structural trends of the top of basement which deepens northwards towards the Bay of Fundy. The northern area where the top of basement is gradually deepening accommodated much of the Horton Bluff sediments in the tilted fault-blocks.

4.1.7.2. Cheverie Formation

The Cheverie Formation shows thickening in the southwest and northeast (Figure 4.32). However, the thickest parts of the Cheverie Formation sediments have been preserved in the northeast around the N-14-A well. This thickness trend indicates that the faults mapped in the northeast and southwest of the study area were active during the deposition of the Cheverie Formation. Later inversion along these faults also affected the transportation and preservation of the Cheverie Formation in this regional thickening trend. Both north and south of this area the present thickness of the Cheverie Formation gradually decreases due to its exposure on the ground surface and subsequent erosion.

4.2. Conclusion

A variety of structures are present in the subsurface in the Kennetcook-Windsor basin. They include: an array of high-angle normal faults that mostly form tilted fault-blocks at the top of basement; reverse faults; inverted faults; pop-up, imbricate, and flower structures; dissolution/structural collapse features resulted from evaporite withdrawal; salt diapirs; and minibasins. These structures are the products of both extension and shortening episodes that occurred during the geological history of the basin.

Faults mapped and correlated at various levels can be subdivided into six categories: normal faults; reverse faults; normal inverted faults that have normal offset at the top of basement and a reverse offset component up-dip; and reverse inverted faults that have reverse offset at the top of basement and normal offset up-dip. The basement-cutting normal and inverted faults indicate that thick-skinned tectonics also played a key role in the development and deformation of the basin.

2D and 3D seismic datasets show inversion along basement-cutting normal faults (Figures 4.20 & 4.19). There are at least three categories of inverted faults: basement-cutting high angle reverse faults with reverse offset at shallower level (Figure 4.15); basement-cutting reverse faults with normal offset at shallower level (Figure 4.9) and; basement-cutting normal faults with up-dip reverse offset component (Figure 4.2). Thus the faults with normal offsets at basement level and reverse offset component at shallower level or vice versa clearly indicate that episodes of extension and compression occurred during the entire history of the basin. During the inversion of the category II faults, the category I faults, locally, could also have been inverted as indicated by the dipping and curved seismic reflections (Figures 4.1 & 4.3) present in the basal part of the Horton Bluff Formation. However, due to larger normal offset they do not show a reverse component. Divergent and inclined seismic reflections particularly within the Horton Bluff Formation clearly indicate that some of the basement-cutting normal faults remained active during deposition and accommodated a considerable thickness of the formation (Figures 4.3, 4.8, 4.20).

Fault correlation at the top of basement shows dominant extension in NNW-SSE and NW-SE directions (Figure 4.4). Inversion along some of these faults occurred in the same direction of extension with a few exceptions of NNE-SSW. Fault correlation at the top of the Horton Bluff Formation indicates that the dominant extension was also NW-SE. The orientation of the reverse faults indicates that shortening occurred in a NW-SE direction (Figure 4.5). Fault correlation at the top of Cheverie/Macumber formation shows that extension as well as shortening occurred in a NW-SE direction which is the same as suggested for deeper faults (Figure 4.6). Fault correlation at the top of Windsor Group indicates that both extension and shortening also occurred NW-SE, but, rotated slightly towards west (Figure 4.7). The presence of both normal and reverse faults at different levels can not be justified as a product of a pure extension or a shortening phase. However, in a strike-slip setting, their coeval existence and inversion along some of the faults is possible (Waldron, 2005).

Inclined reflection geometries in the basal part of the Horton Bluff Formation dipping on the top of basement within the titled fault-blocks show that graben and half-graben settings were present in the early stages of sedimentation. Divergent and inclined seismic reflections in the Horton Bluff Formation indicate that some of the basement-cutting faults remained active during deposition in the tilted fault-blocks. Seismic reflections in the Cheverie Formation are nearly continuous and do not show any divergent pattern. Dipping reflection geometries that resemble clinoforms are also present in the Cheverie Formation and downlap gently on the top of the Horton Bluff Formation. Seismic resolution does not allow description of a clear truncation or toplap in the upper part of the Horton Bluff Formation below these clinoform geometries.

Positive and negative flower structures interpreted within the Horton Group and the basal part of the Windsor Group indicate that both transpressional and transtensional episodes not only controlled the deformational styles in the basin but also participated in the uplift and subsidence events in the basin history. Imbricate and pop-up structures mapped in the subsurface are only localized features and are not widespread. These structures indicate shortening events and subsequent uplift in the area.

Listric normal faults that terminate in the basal Windsor mark the latest extension which triggered salt diapirs and created minibasins for the deposition of the Pennsylvanian sediments. Thus the creation of the accommodation space here was mainly controlled by tectonic elements that would have probably overwhelmed any base-level control.

Uniform and nearly continuous seismic reflections within the Scotch Village Formation show a very mild deformation and mark a clear boundary at the top of the Windsor Group. Gently dipping reflections in the basal part of the Scotch Village Formation have a discordant relationship with the underlying high-angle seismic reflections in the Windsor Group. This boundary has a clear seismic signature on many 2D seismic profiles and marks a major angular unconformity. Gently dipping to nearly horizontal reflections in the Scotch Village Formation indicate a different depositional and deformational episode in the history of the Kennetcook basin.

The TWT structure map at the top of basement shows tilted fault-blocks stepping down to north and northeast. Faults in the west and south show intense inversion and caused uplift of the top of basement. Probably oblique movement (SW-NE) on the subsurface faults affected the basement architecture and the opening of the basin. Oblique strike-slip tectonics caused the tilting of the fault-blocks and controlled the syndepositional deformation in the basin. TWT maps at the tops of the Horton Bluff and the Cheverie formations show a structural low in the central area and rising in the northeast, west, and south. However, the structural low on the top of the Cheverie Formation is narrower and indicates that the fault reactivation was episodic and controlled the uplifts differently at the tops of both formations. This interpretation suggests that faults mapped at the top of the Cheverie Formation were inverted more than those on the top of the Horton Bluff Formation.

Comparison of the thickness maps of the Horton Bluff and the Cheverie formations indicate an overall thickening in the north and northeast. However, the Horton Bluff Formation shows gradual thickening in the northeast and follows deepening of the basement. This thickening trend shows that the depocenter is located north in Cobequid Bay. Both thickness maps indicate that activity on the subsurface faults was the controlling factor that influenced the deposition and preservation of the sediments in both formations.

The structural interpretation of the subsurface seismic data indicates a complex history of overprinting of deformational episodes which controlled the reactivation of the faults through time. The oblique motion and strike-slip tectonics compartmentalized the subsurface geology into tilted fault-blocks which affected the deposition and preservation of the overlying younger sediments. This interpretation may also suggest the presence of some local stepovers that developed contemporaneous episodes of transtension and transpression and controlled the behaviour of the faults. The TWT structure maps show that tilted fault-blocks bounded by both normal and reverse faults have variable throw along the strike.

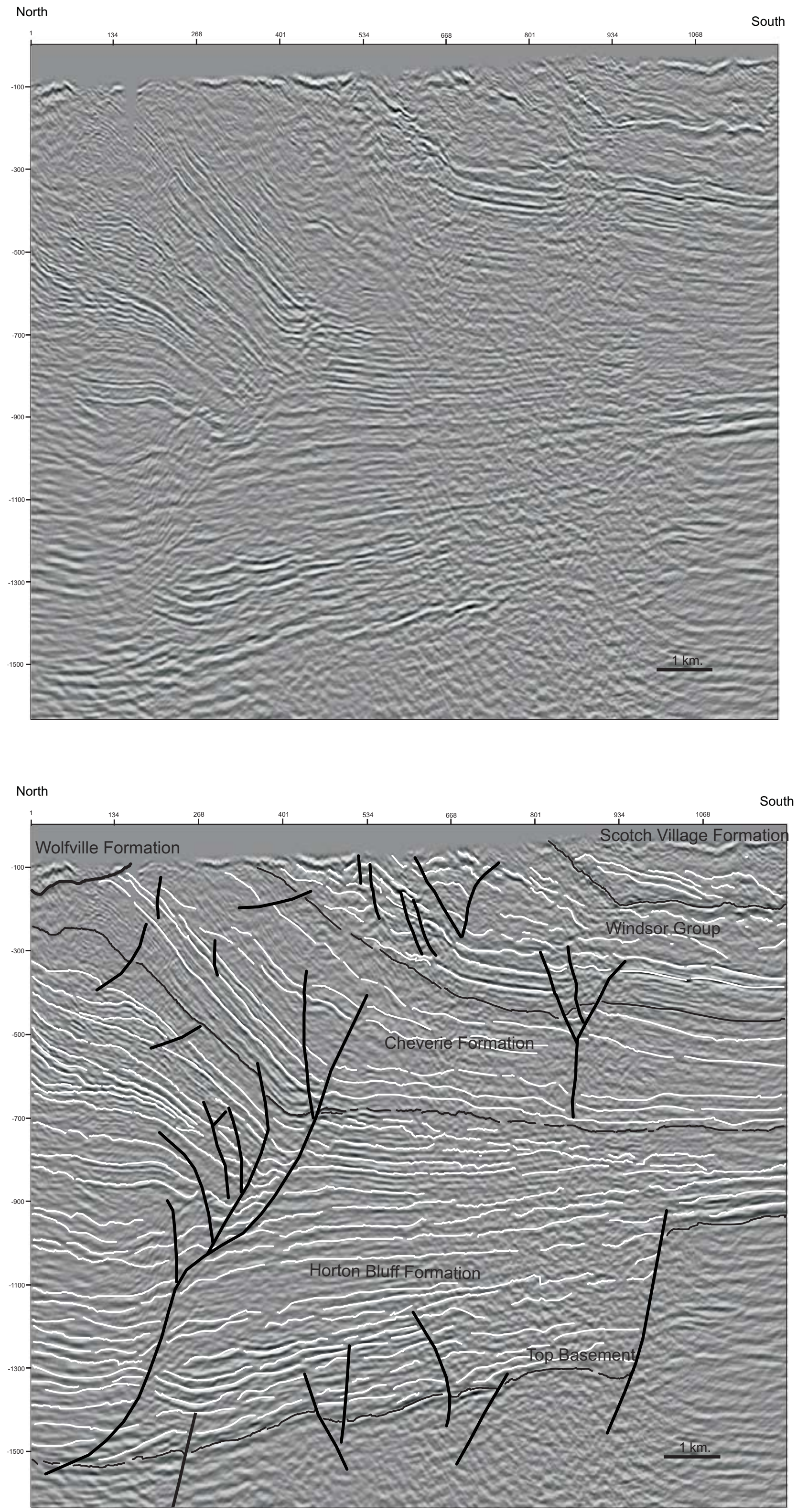
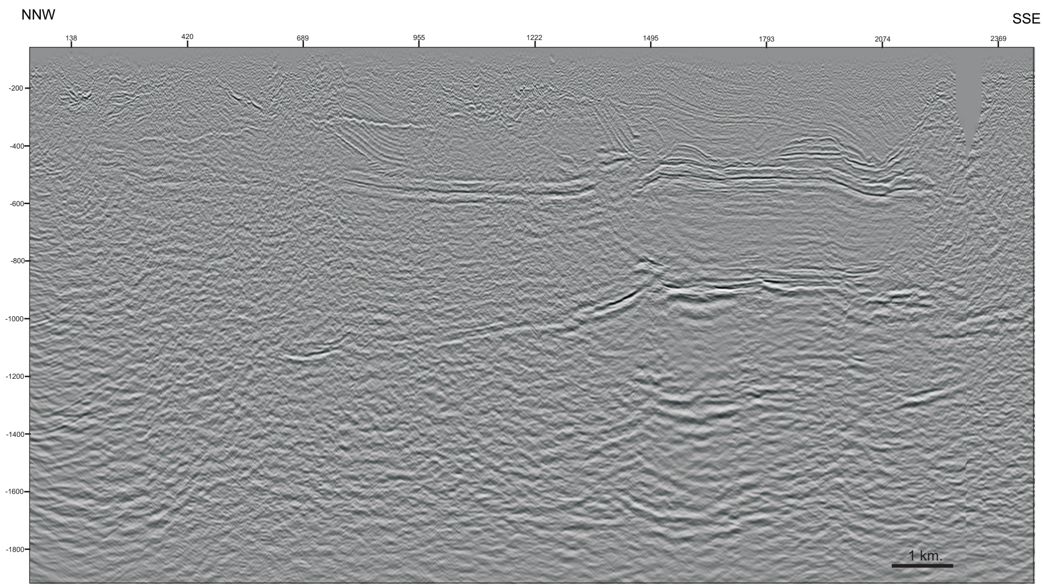


Figure 4.1: Uninterpreted N-S 2D seismic line Kenn-07-04 (top). Interpretation (below) shows high-angle basement-cutting normal faults and flower structures in the Horton Bluff and Cheverie formations.



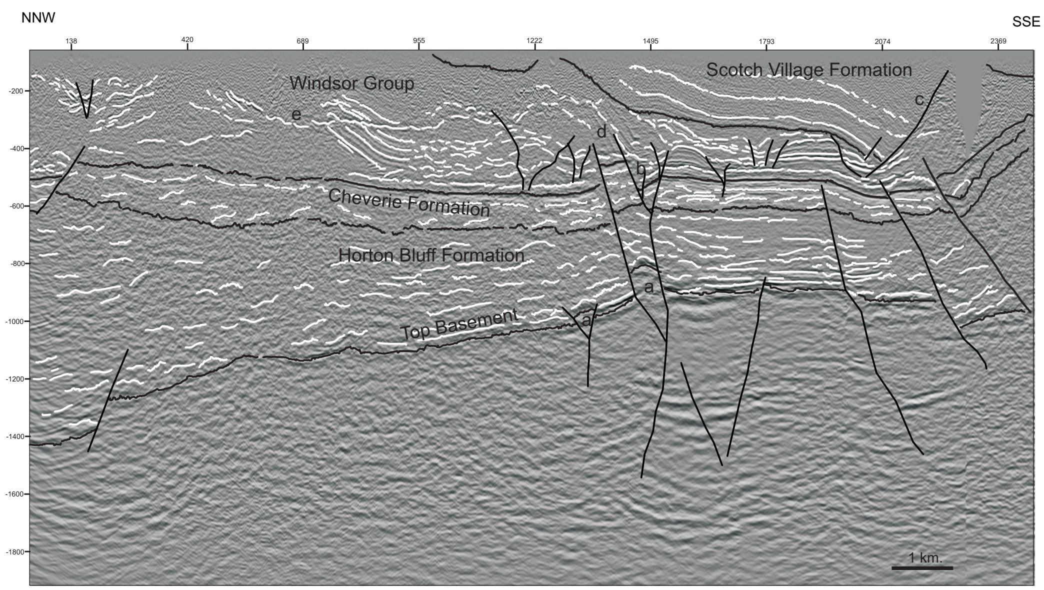


Figure 4.2: Uninterpreted NNW-SSE 2D seismic line WND00-006 (top). Interpretation (below) shows high-angle basement-cutting normal faults, pop-up structures (a), and flower structure (b) in the Cheverie Formation. A listric normal fault (c) in the Windsor Group cutting upsection into the overlying Scotch Village Formation also probably caused the development of a minibasins. Chaotic reflections in the Windsor Group indicate structural collapses (d) and detachment surfaces (e).

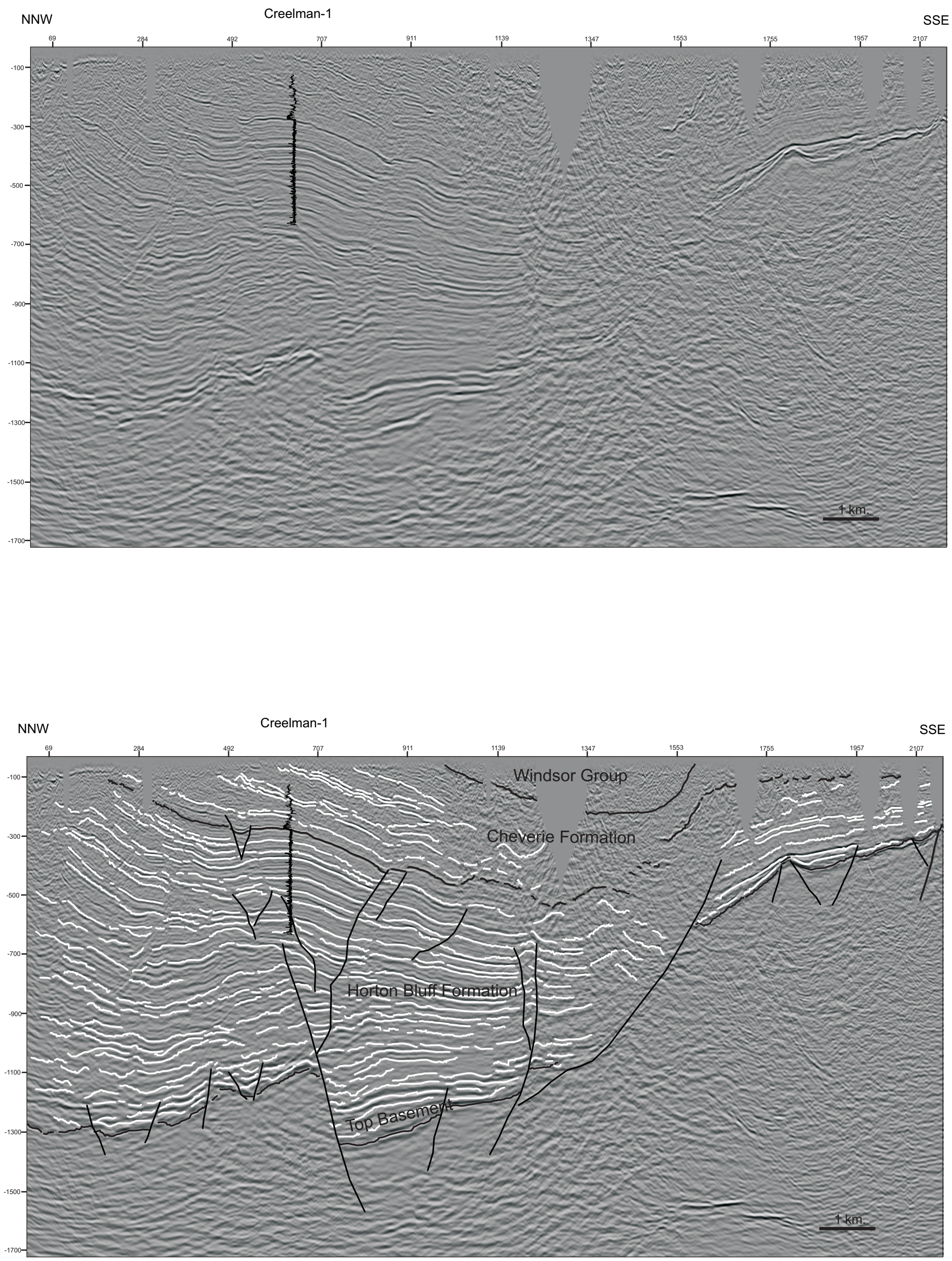


Figure 4.3: Uninterpreted NNW-SSE 2D seismic line WND00-008 (top). Interpretation (below) shows high angle basement cutting normal faults forming tilted fault-blocks and half-graben geometry.

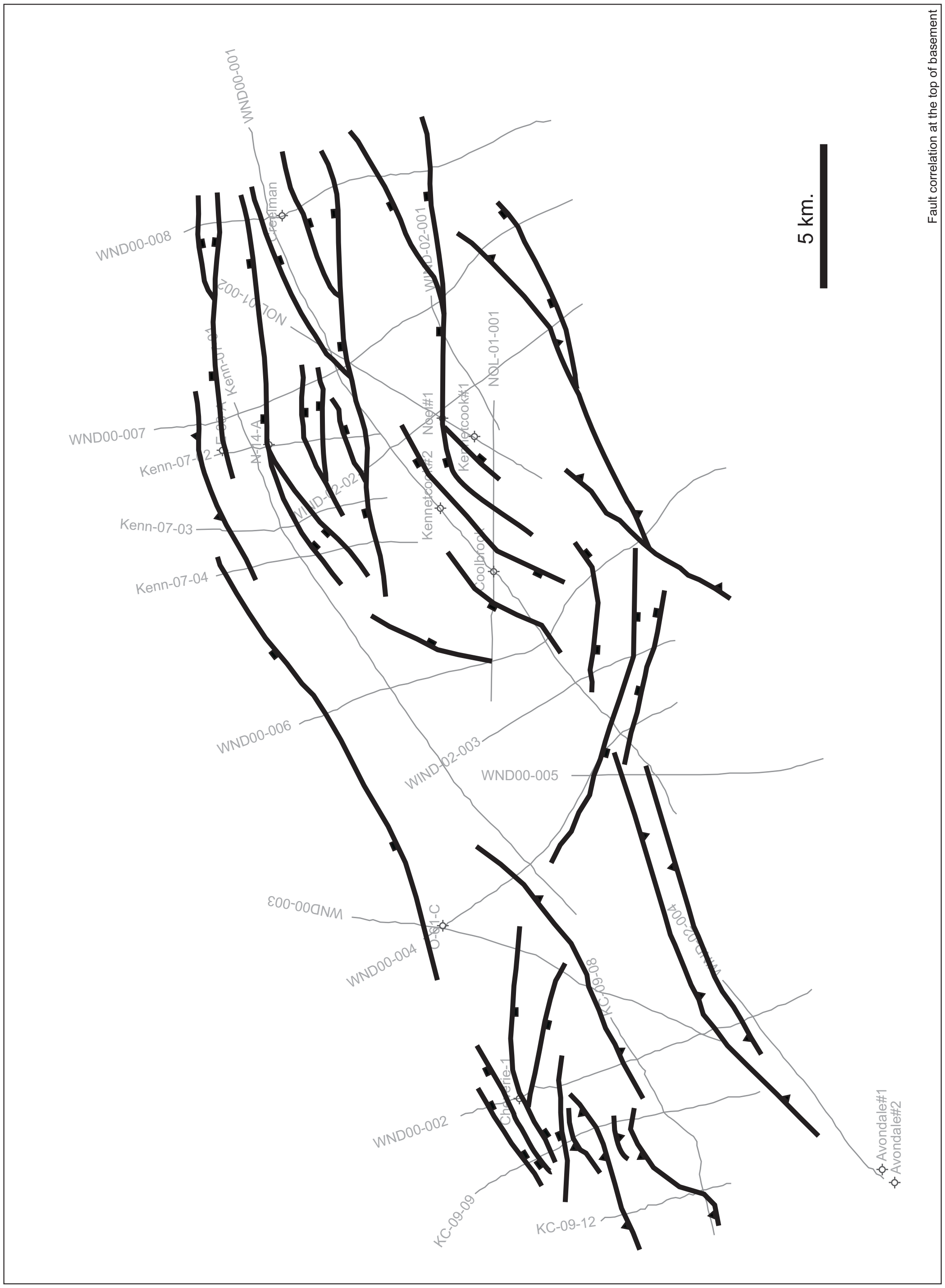


Figure 4.4: Map showing fault correlation at the top of basement.

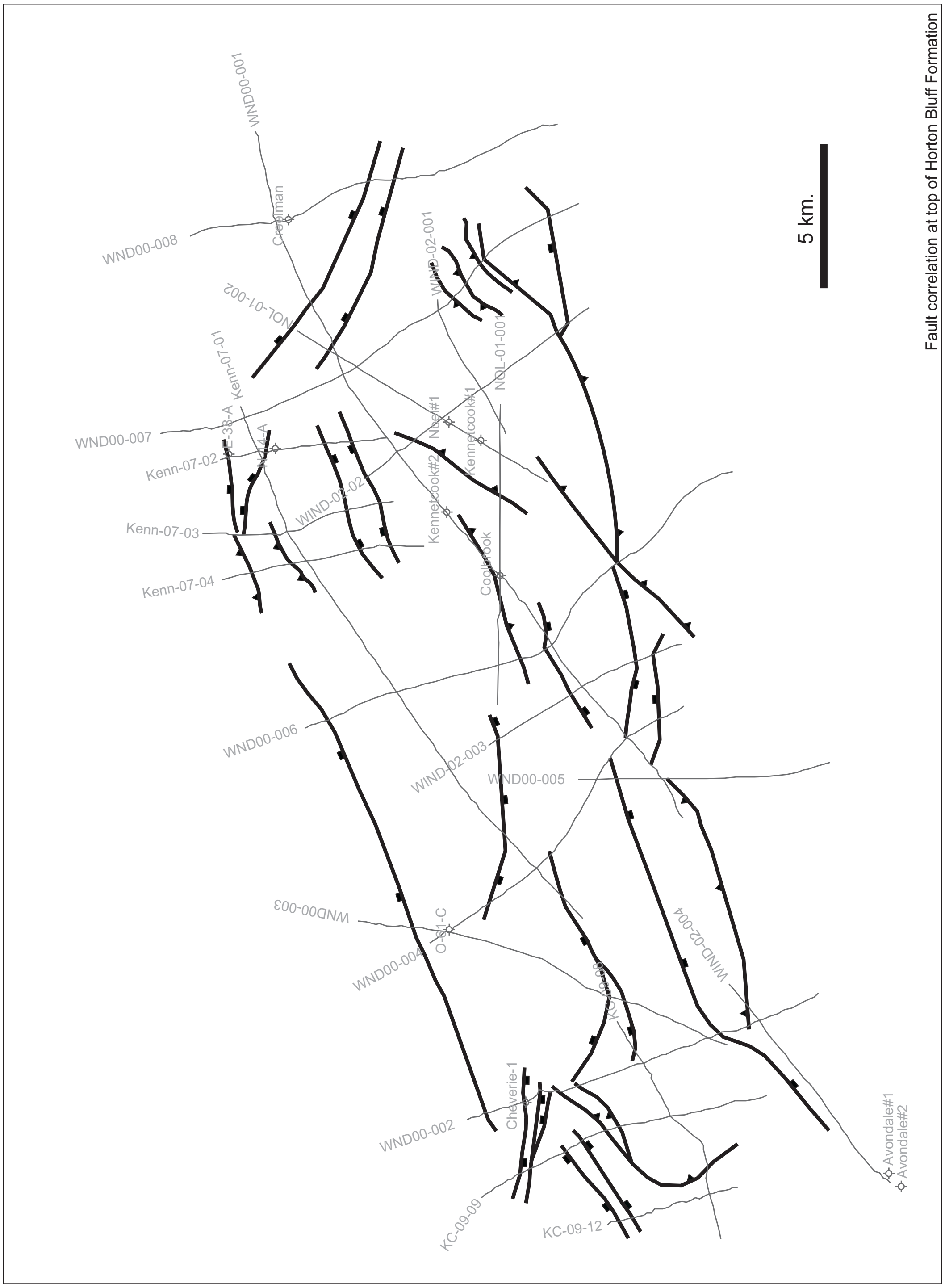


Figure 4.5: Map showing fault correlation at the top of the Horton Bluff Formation.

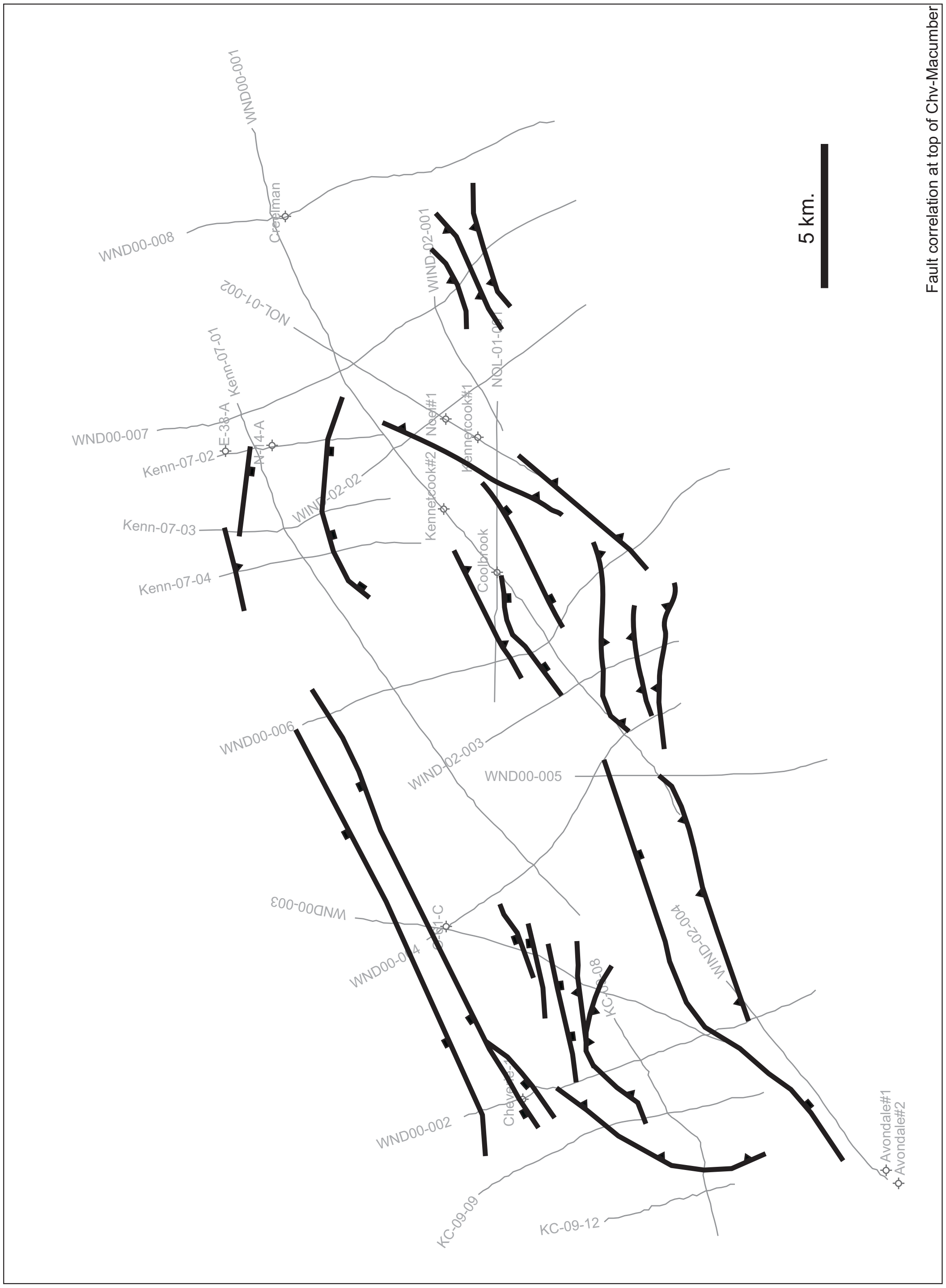


Figure 4.6: Map showing fault correlation at the top of the Cheverie-Macumber Formation.

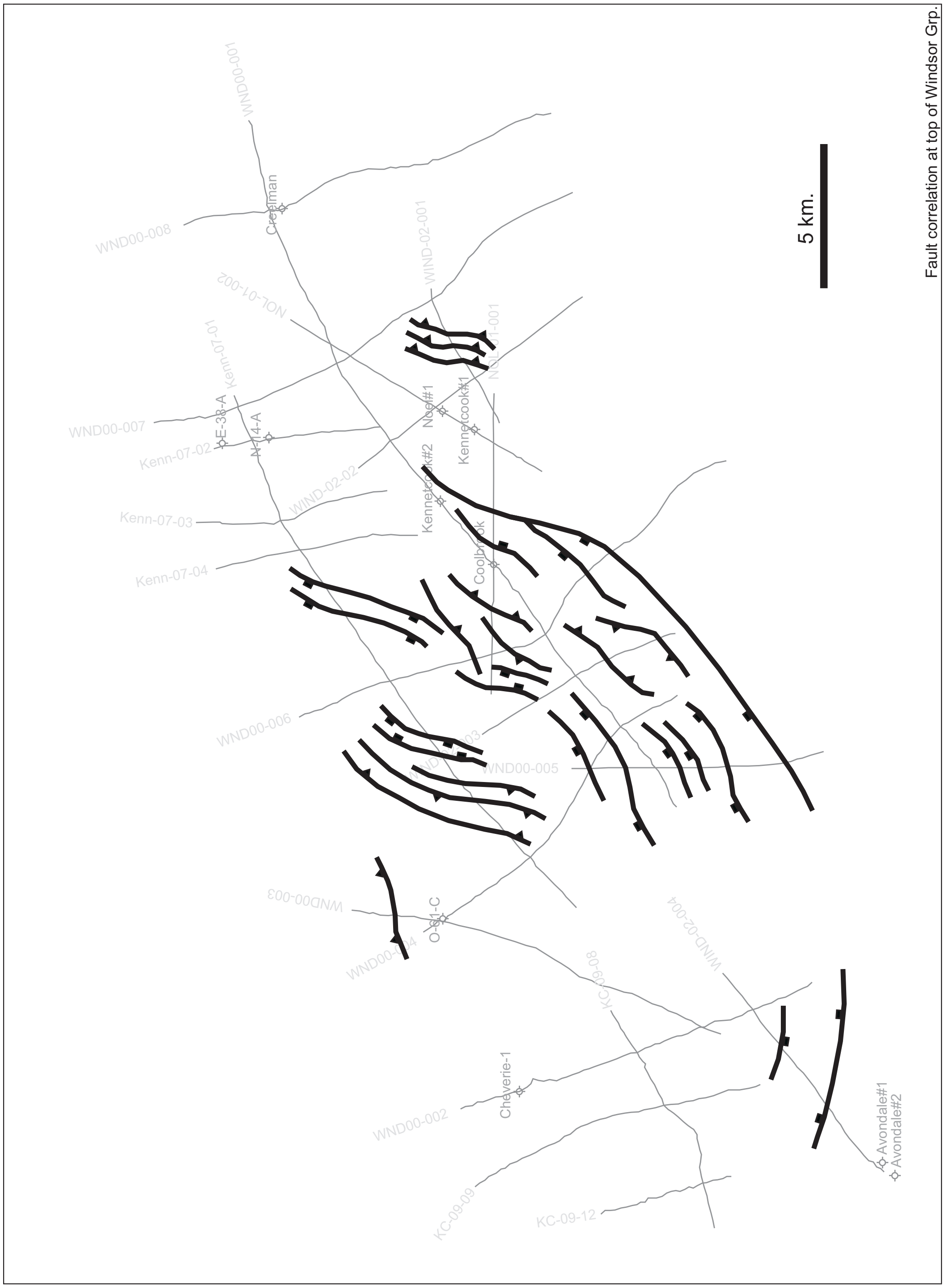


Figure 4.7: Map showing fault correlation at the top of the Windsor Group.

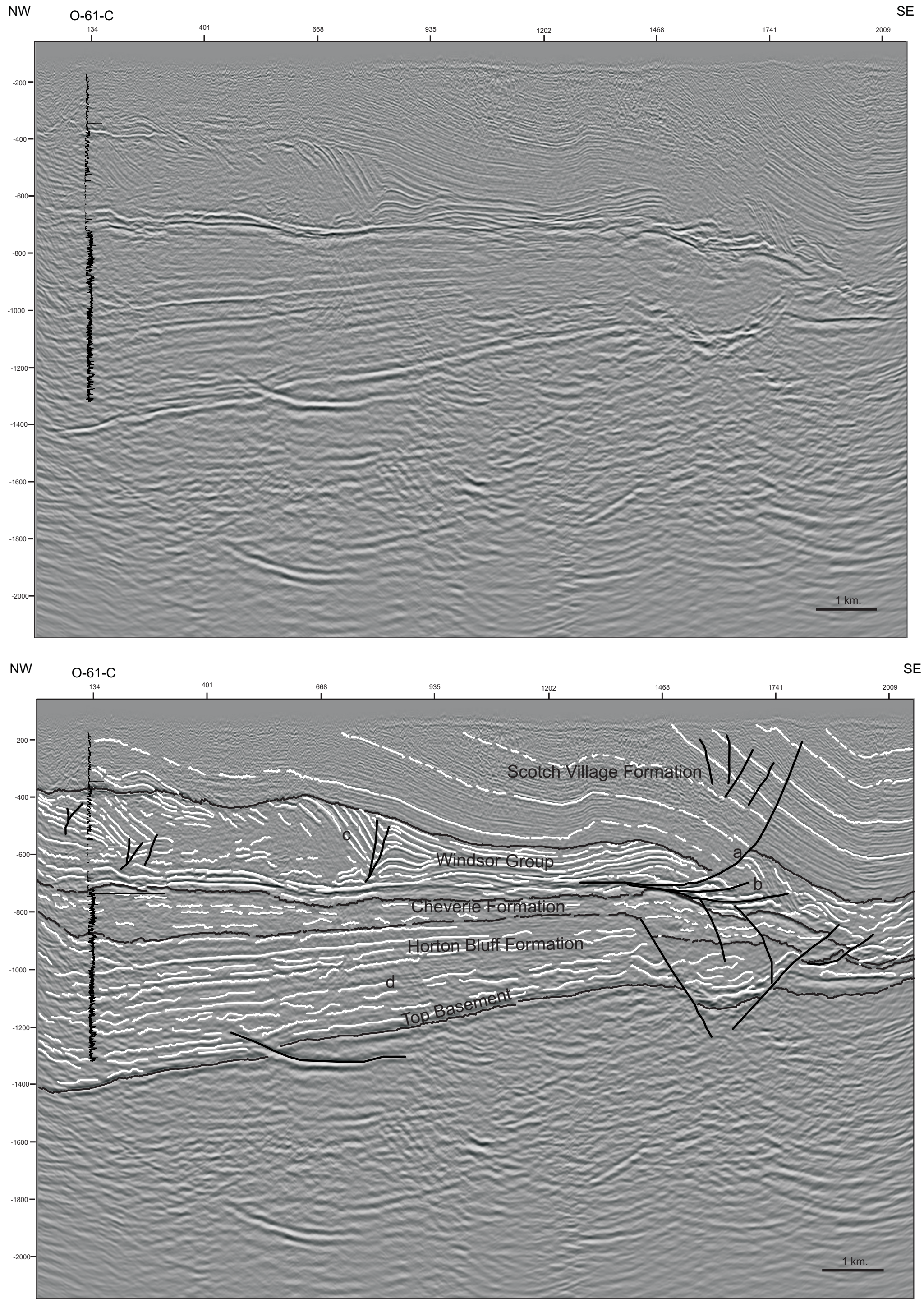


Figure 4.8: Uninterpreted NW-SE 2D seismic line WND00-004 (top). Interpretation (below) shows listric normal fault (a) in the Windsor Group and the Scotch Village Formation, imbricate structure (b) and the structural collapse features (c) in the Windsor Group. Chaotic and high angle reflections in the Windsor Group indicate evaporite withdrawal and the development of minibasins that have preserved huge thickness of the Scotch Village Formation. Divergent and gently inclined reflections (d) in the Horton Bluff Formation indicate fault activation during the deposition.

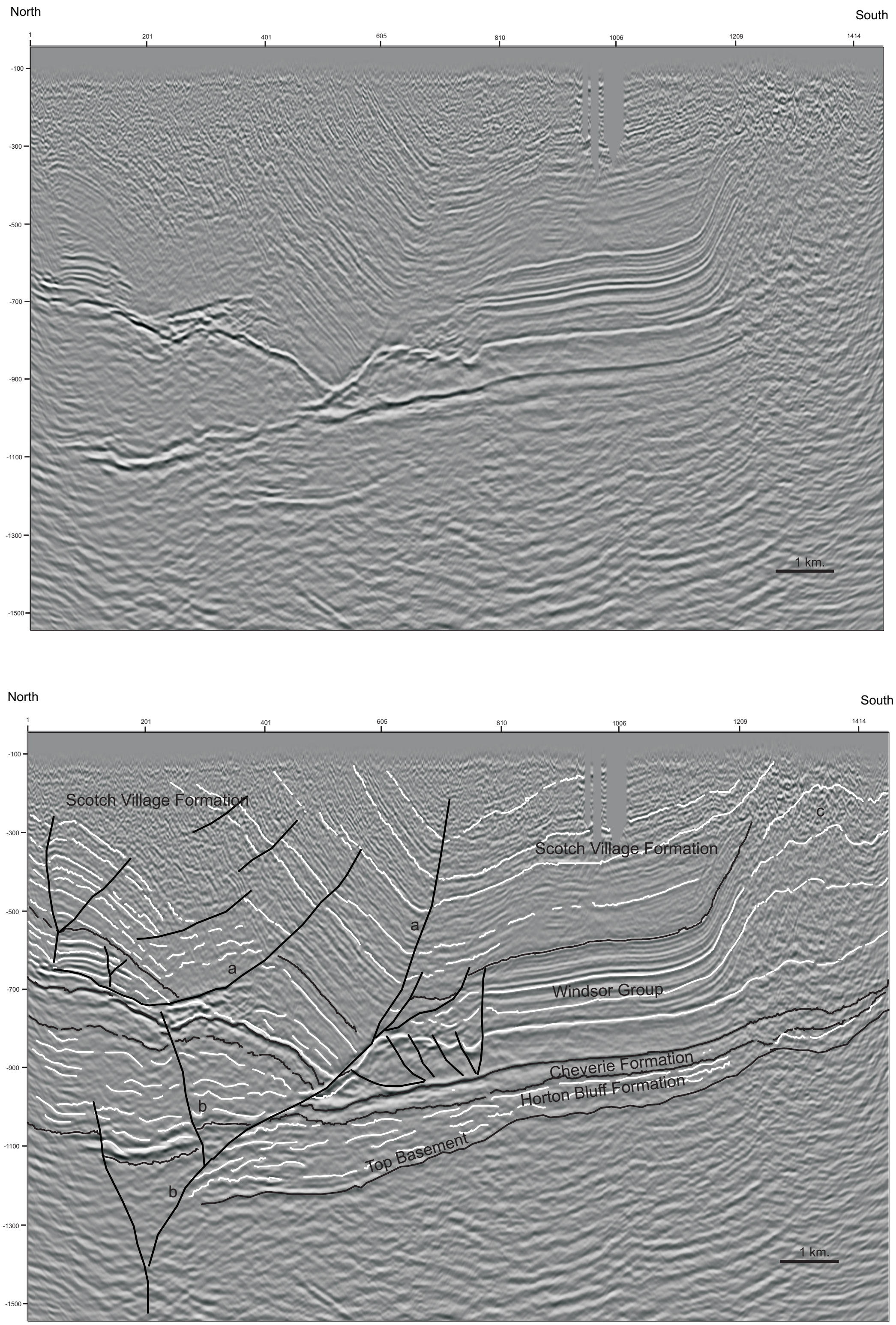


Figure 4.9: Uninterpreted N-S 2D seismic line WND00-005 (top). Interpretation (below) shows listric normal faults (a) in the Windsor Group and the Scotch Village Formation, basement inverted faults (b) and a salt diapir (c) in the right upper corner within the Windsor Group.

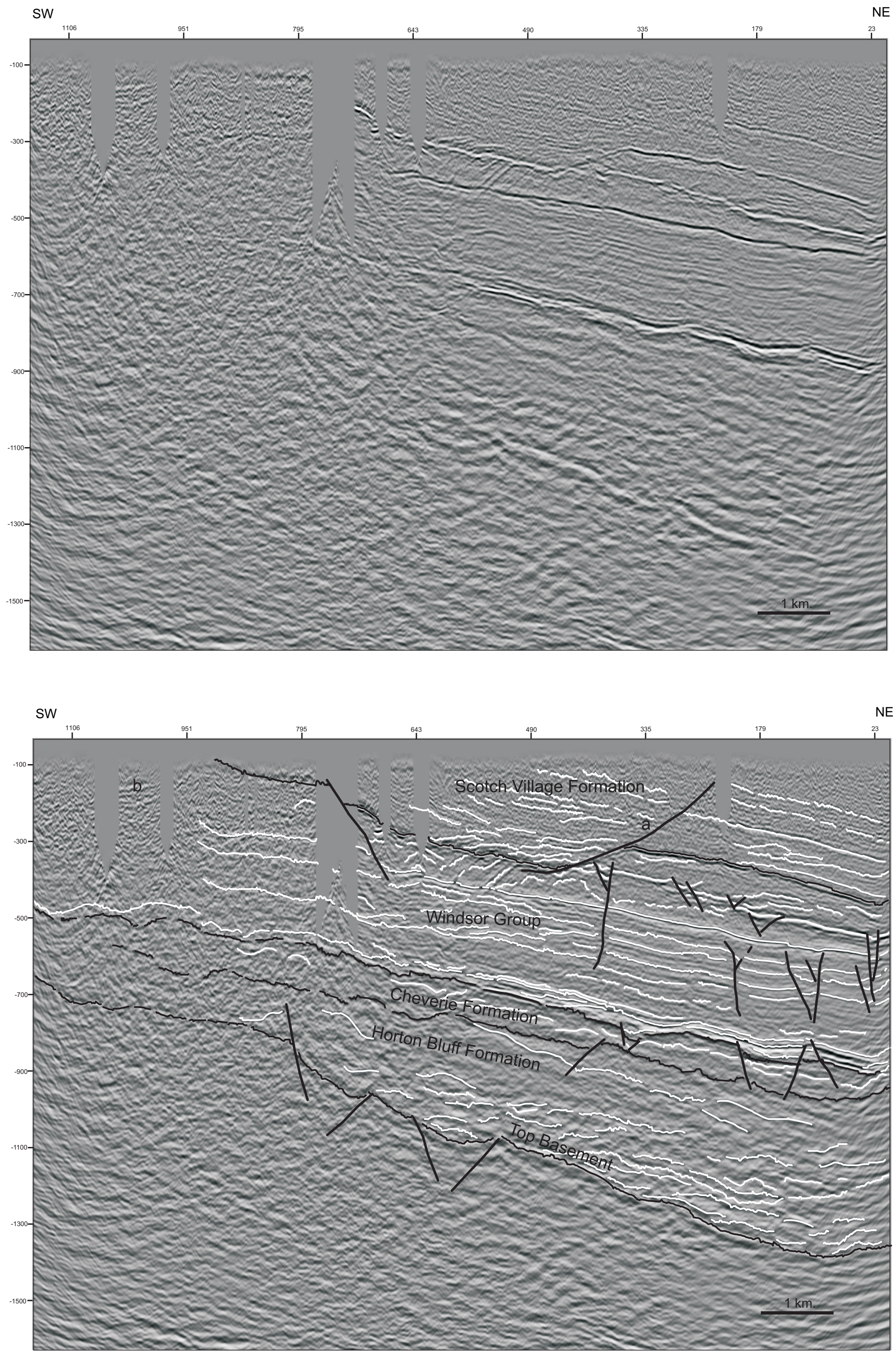


Figure 4.10: Uninterpreted SW-NE 2D seismic line WIND-02-004 (top). Interpretation shows a listric normal fault (a) and a salt diapir located in the left upper corner (s) of the profile.

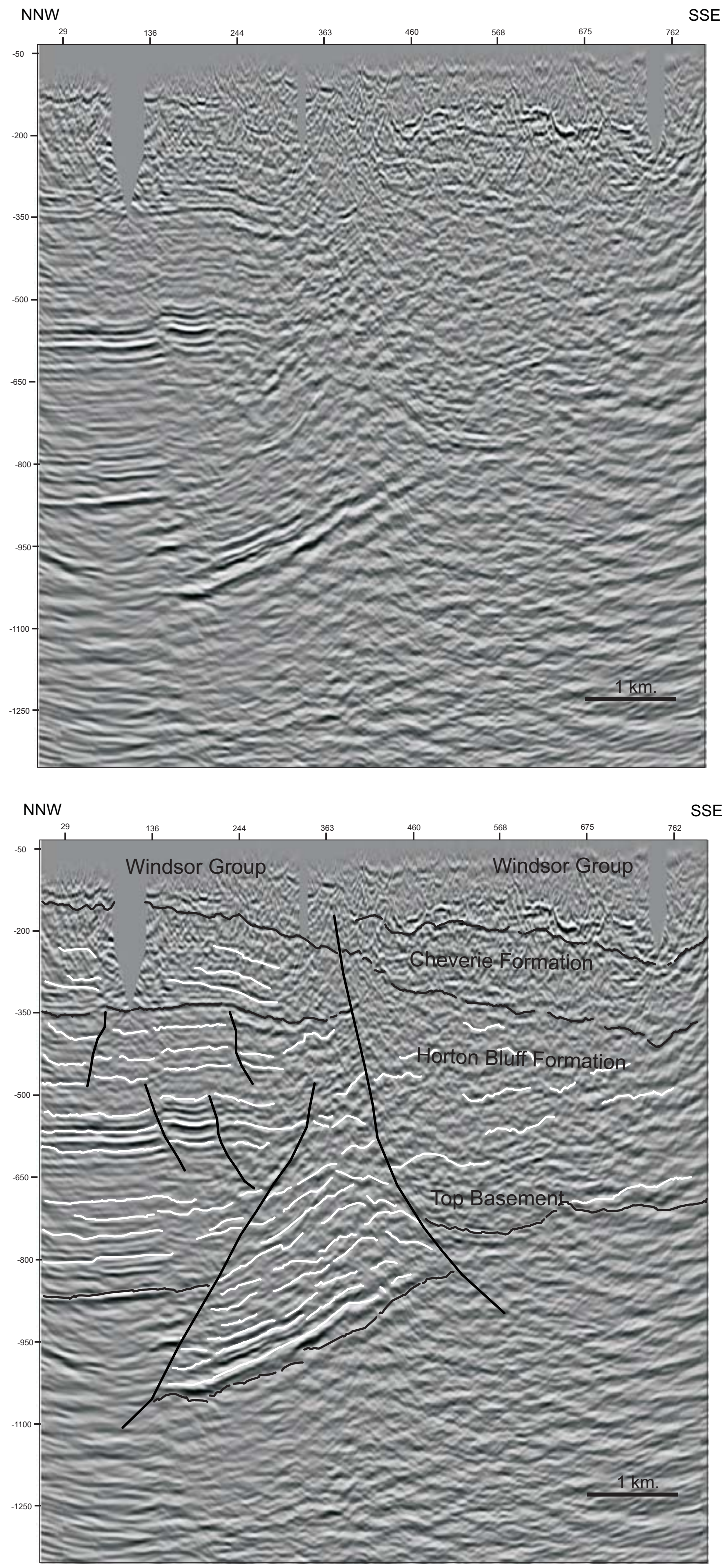


Figure 4.11: Uninterpreted NNW-SSE 2D seismic line KC-09-12 (top). Interpretation (below) shows high angle reverse faults cutting basement and the Horton Group.

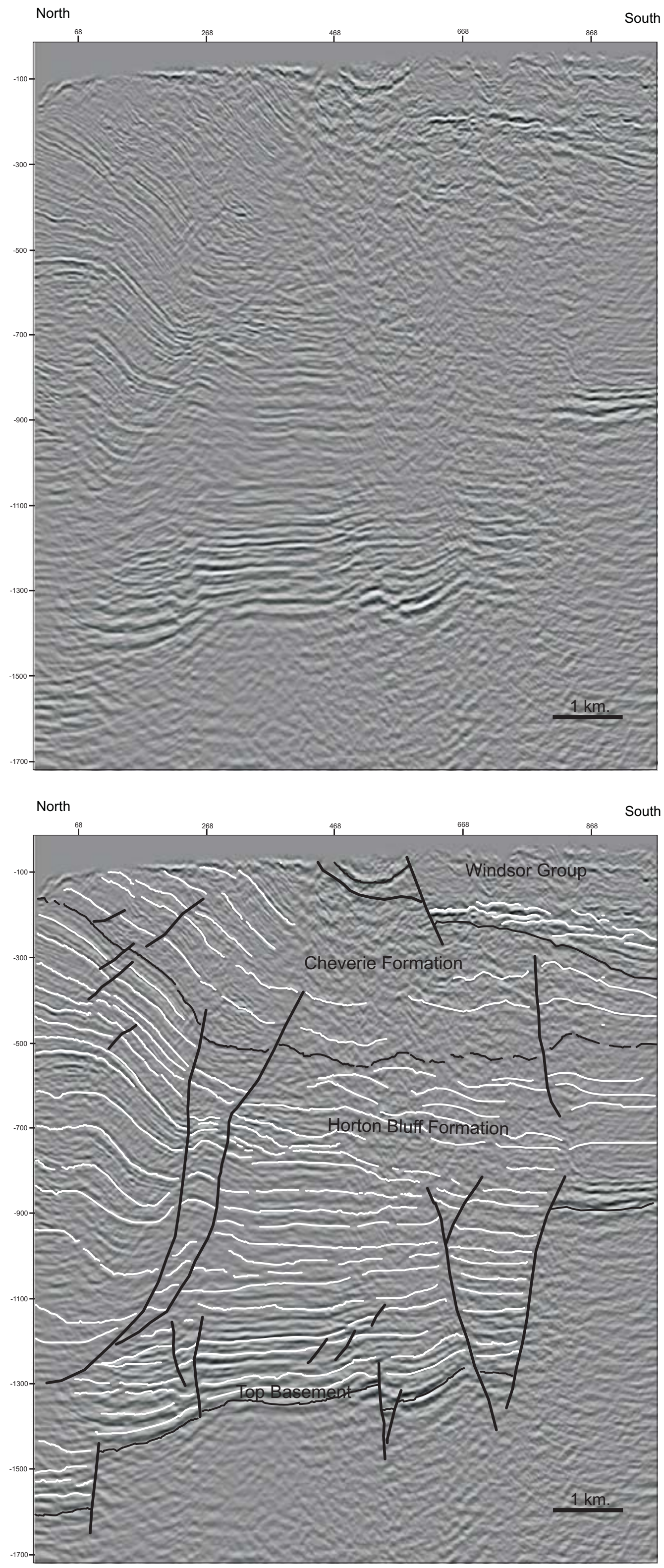


Figure 4.12: Uninterpreted N-S 2D seismic line Kenn-07-02 (top). Interpretation (below) shows high angle reverse faults within the Horton Bluff and the Cheverie formations whereas basement-cutting normal faults form an array of tilted fault-blocks.

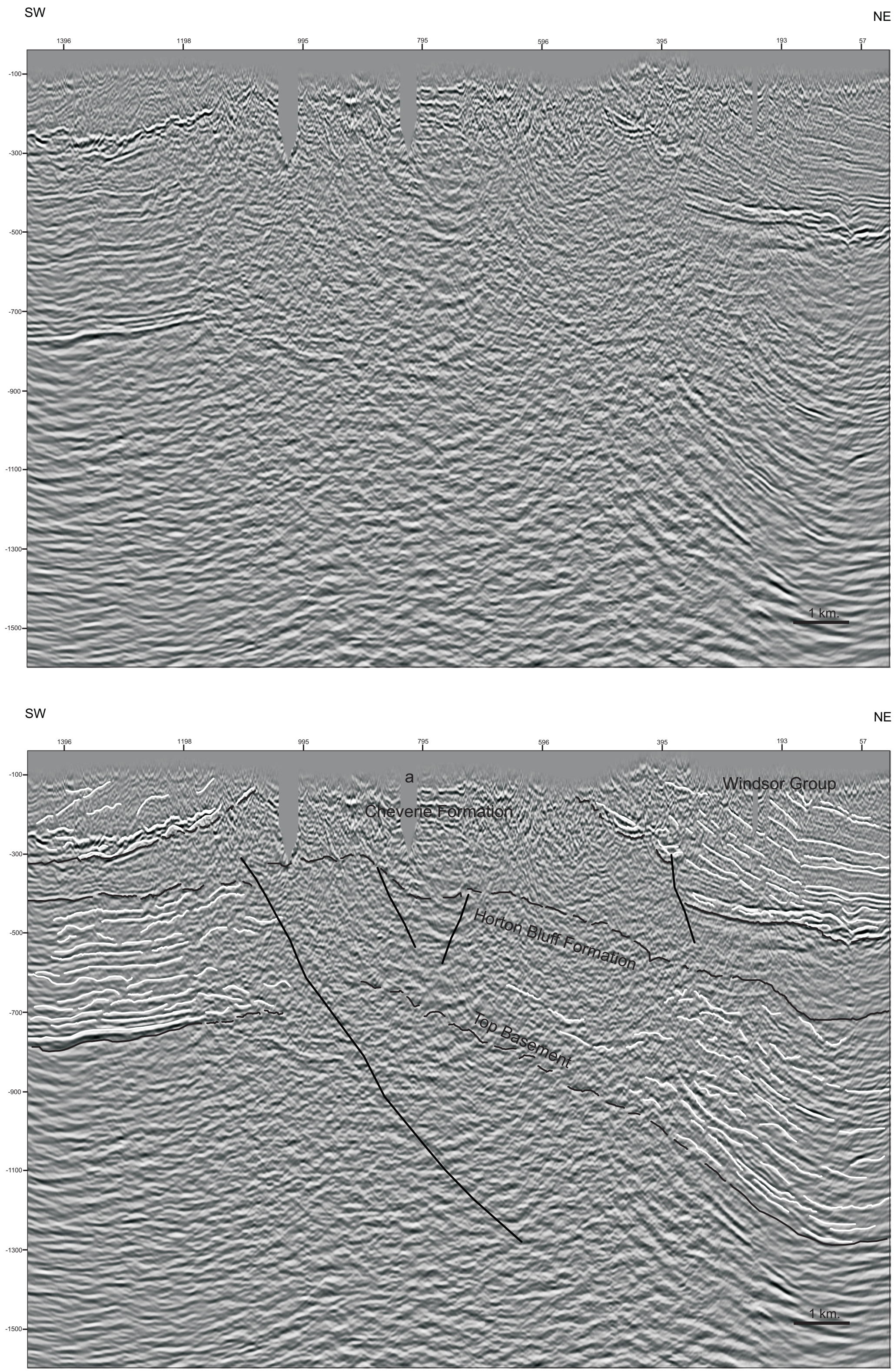


Figure 4.13: Uninterpreted SW-NE 2D seismic line KC-09-08 (top). Interpretation (below) shows high-angle reverse faults cutting through basement and the Horton Bluff Formation. Seismic profile also shows a thrusted anticlinal structure (a) flanked by Windsor rocks and exposes the Cheverie Formation in the core.

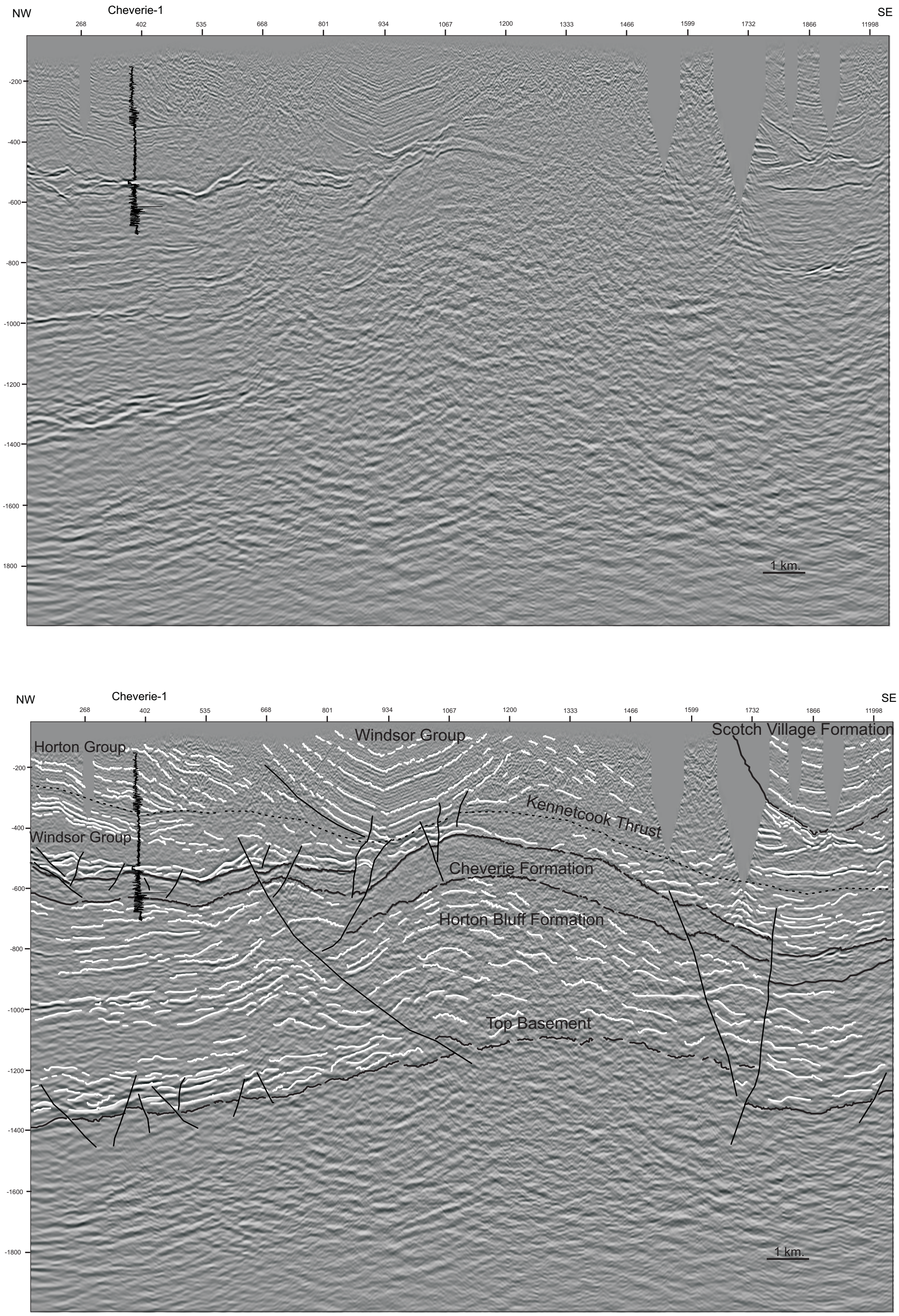


Figure 4.14: Uninterpreted NW-SE 2D seismic line WND00-002 (top). Interpretation (below) shows normal and inverted faults at the top of basement. Trace of a low angle thrust (the Kennetcook thrust) in the Windsor Group is interpreted across the entire seismic profile on the basis of discordance of reflections above and below this surface.

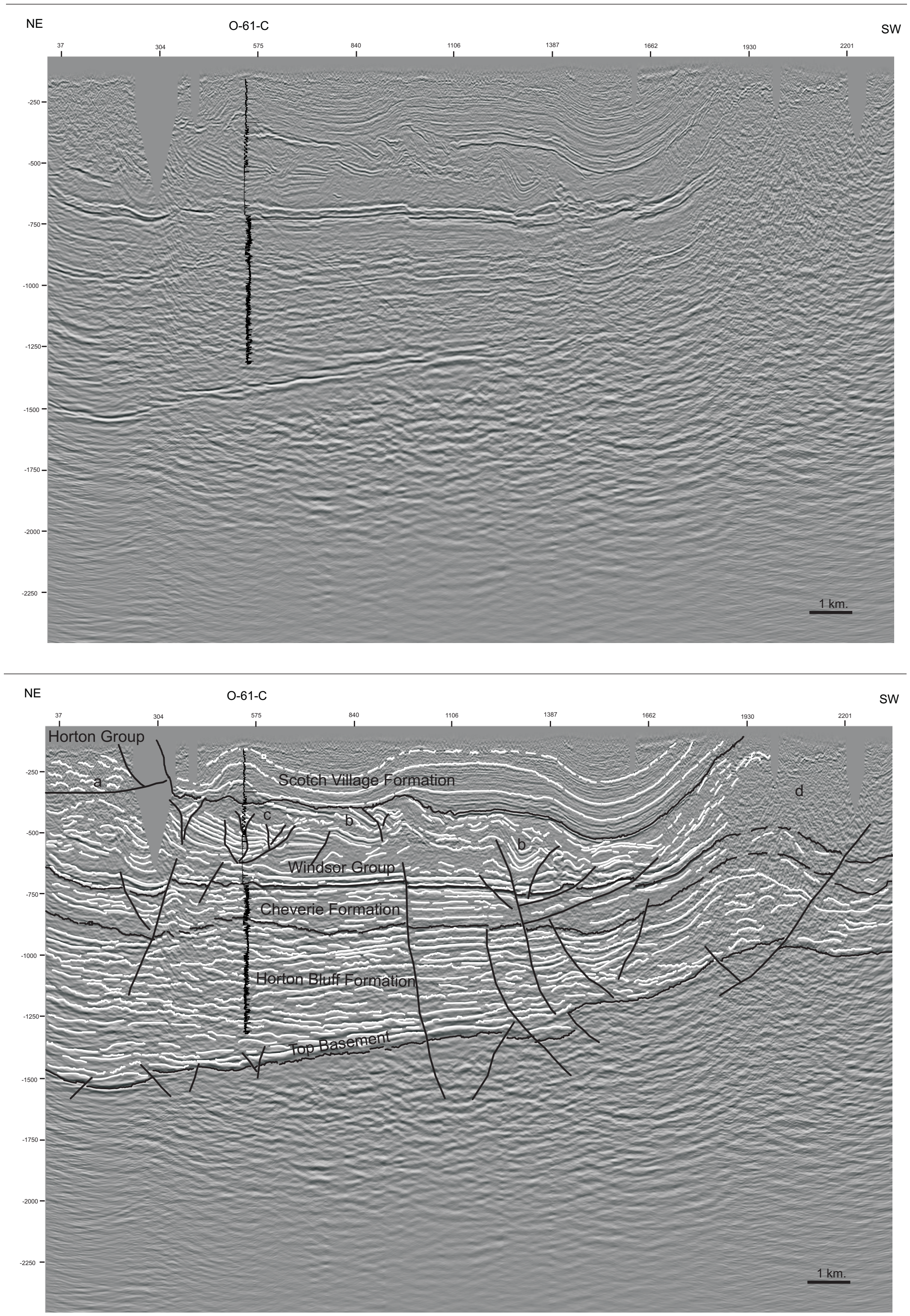


Figure 4.15: Uninterpreted NE-SW 2D seismic line WND00-003 (top). Interpretation (below) shows normal and inverted faults at the top of basement. Trace of the Kennetcook thrust (a) is interpreted in the upper left corner on the basis of surface geology. Structural collapse features (b), negative flower structure (c) and salt diapir (d) in the Windsor Group are also quite obvious.

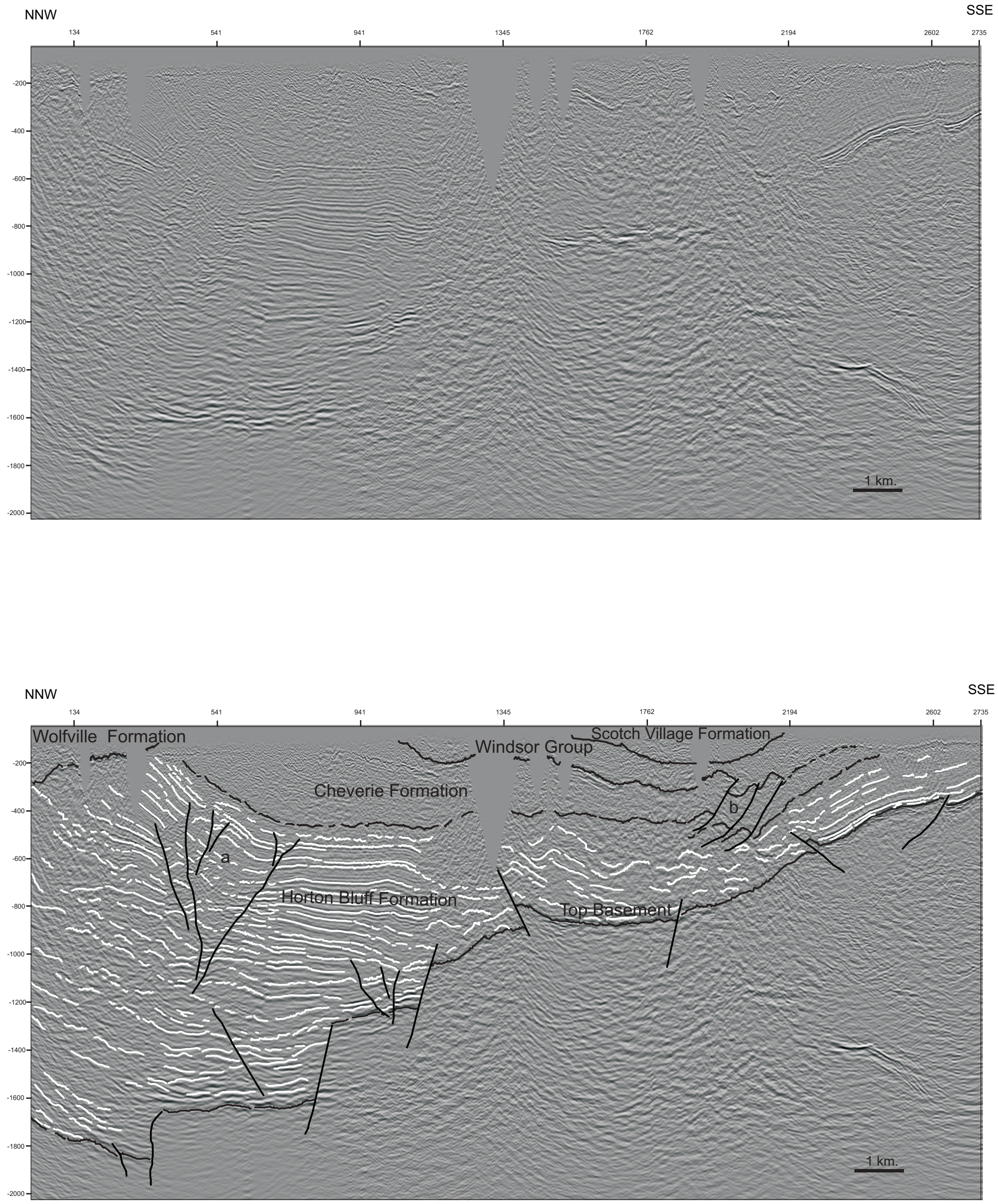
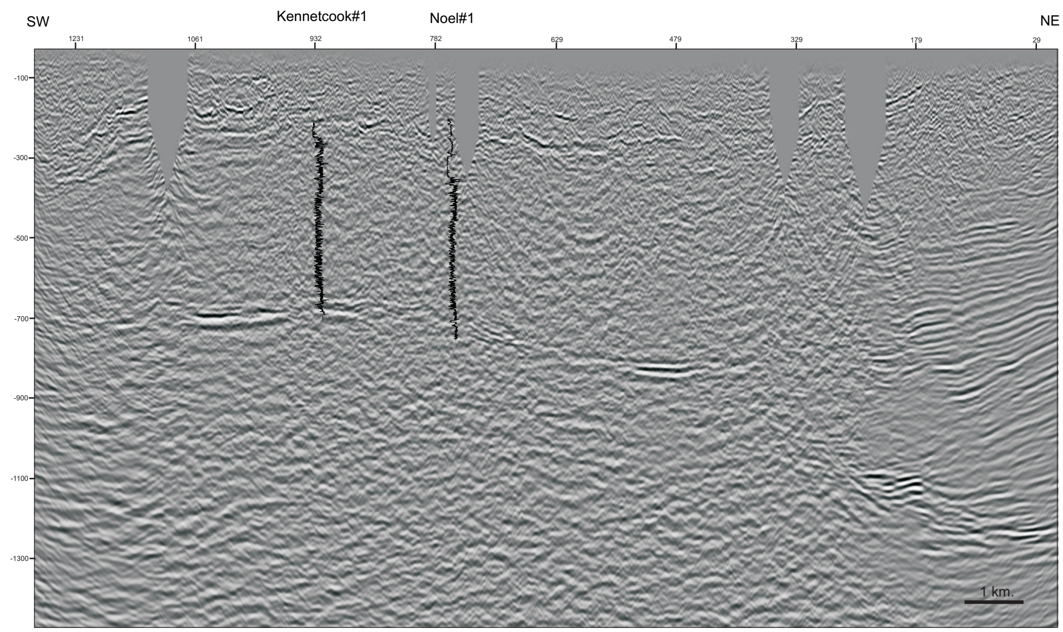


Figure 4.16: Uninterpreted NW-SE 2D seismic line WND00-007 (top). Interpretation (below) shows tilted fault blocks bounded by high-angle normal and inverted faults at the top of basement. Fault interpretation shows a flower structure (a) with the Horton Bluff Formation and an imbricate structure (b) in the Horton Bluff-Cheverie Formation.



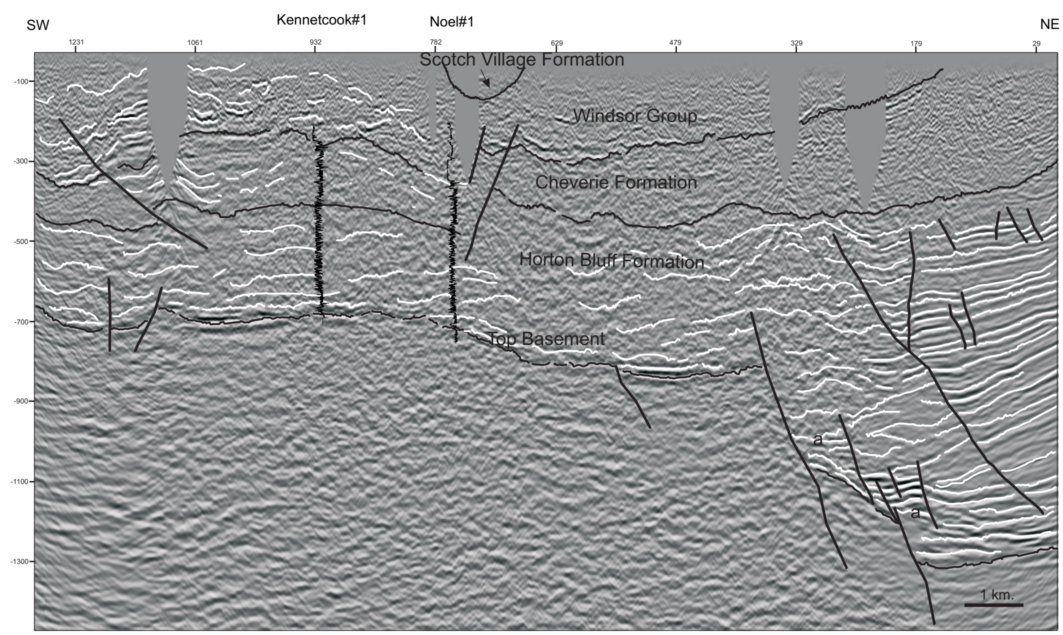


Figure 4.17: Uninterpreted NE-SW 2D seismic line NOL-01-002 (top). Interpretation (below) shows tilted fault blocks bounded by high-angle normal faults at the top of basement which is deepening towards the NE and provides half graben geometry. Gently dipping reflections (a) in the basal part of the Horton Bluff Formation downlap on the basement rocks in the lower right corner of the seismic profile.

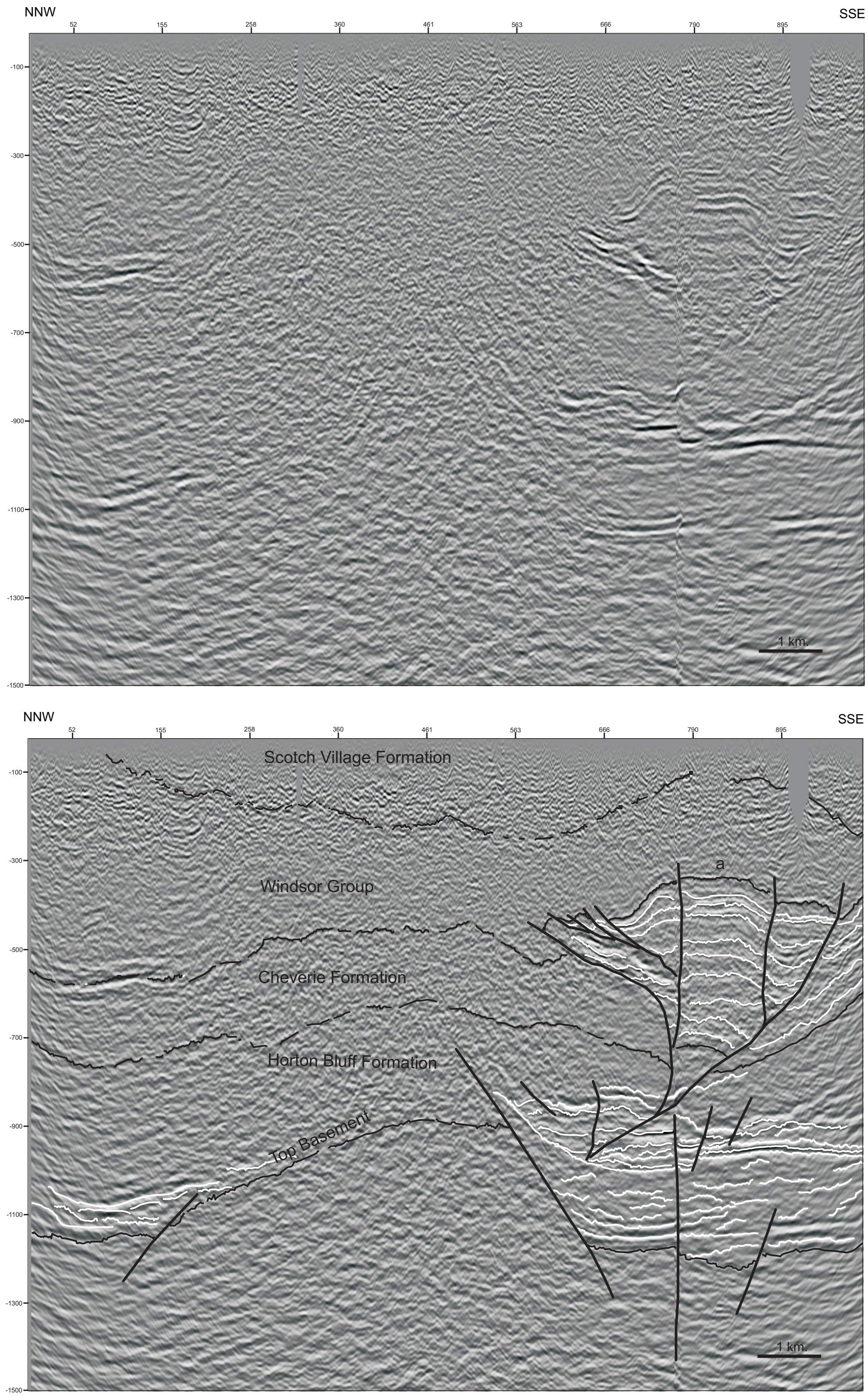
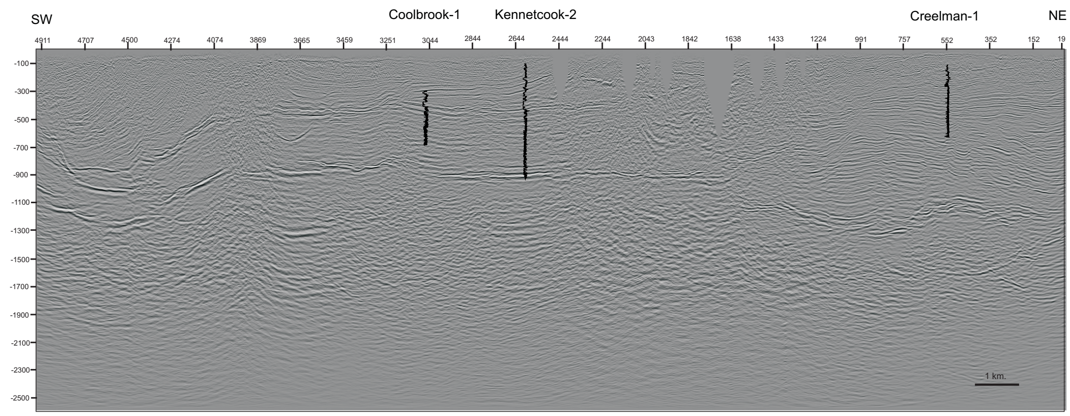


Figure 4.18: Uninterpreted NW-SE 2D seismic line WIND-02-003 (top). Interpretation (below) shows tilted fault blocks bounded by high-angle normal faults at the top of basement and a classical example of a positive flower structure (a) developed within the Cheverie Formation.



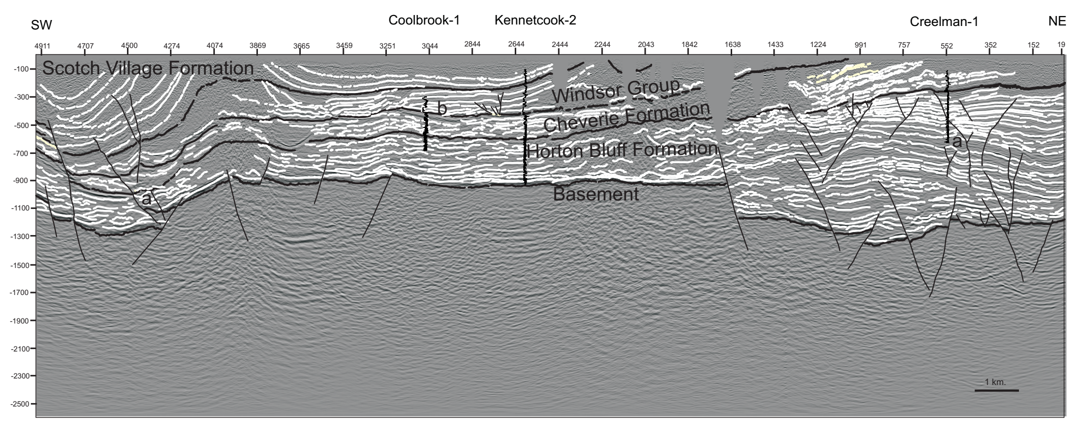


Figure 4.19: Uninterpreted SW-NE 2D seismic line WND00-001 (top). Interpretation (below) shows high-angle normal and reverse faults cutting through basement and the Horton Group rocks, pop-up structures (a) at the top of basement and within the Horton Bluff Formation. Gently dipping reflections (b) in the top part of the Cheverie Formation are truncated beneath the basal Windsor Group represented by the Macumber Formation.

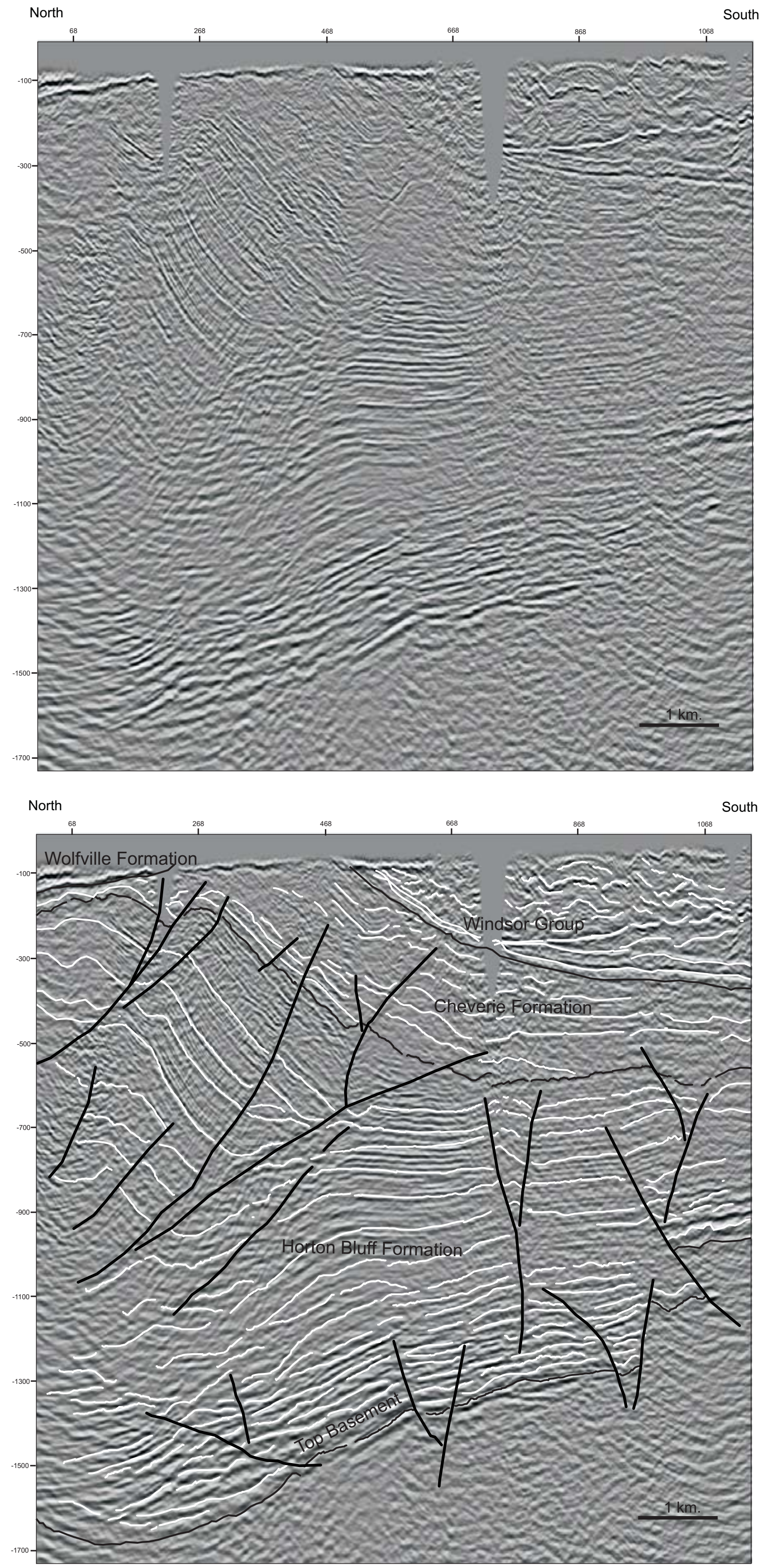


Figure 4.20: Uninterpreted N-S 2D seismic line Kenn-07-03 (top). Interpretation (below) shows high angle normal and reverse faults cutting through basement and the Horton Bluff Formation.

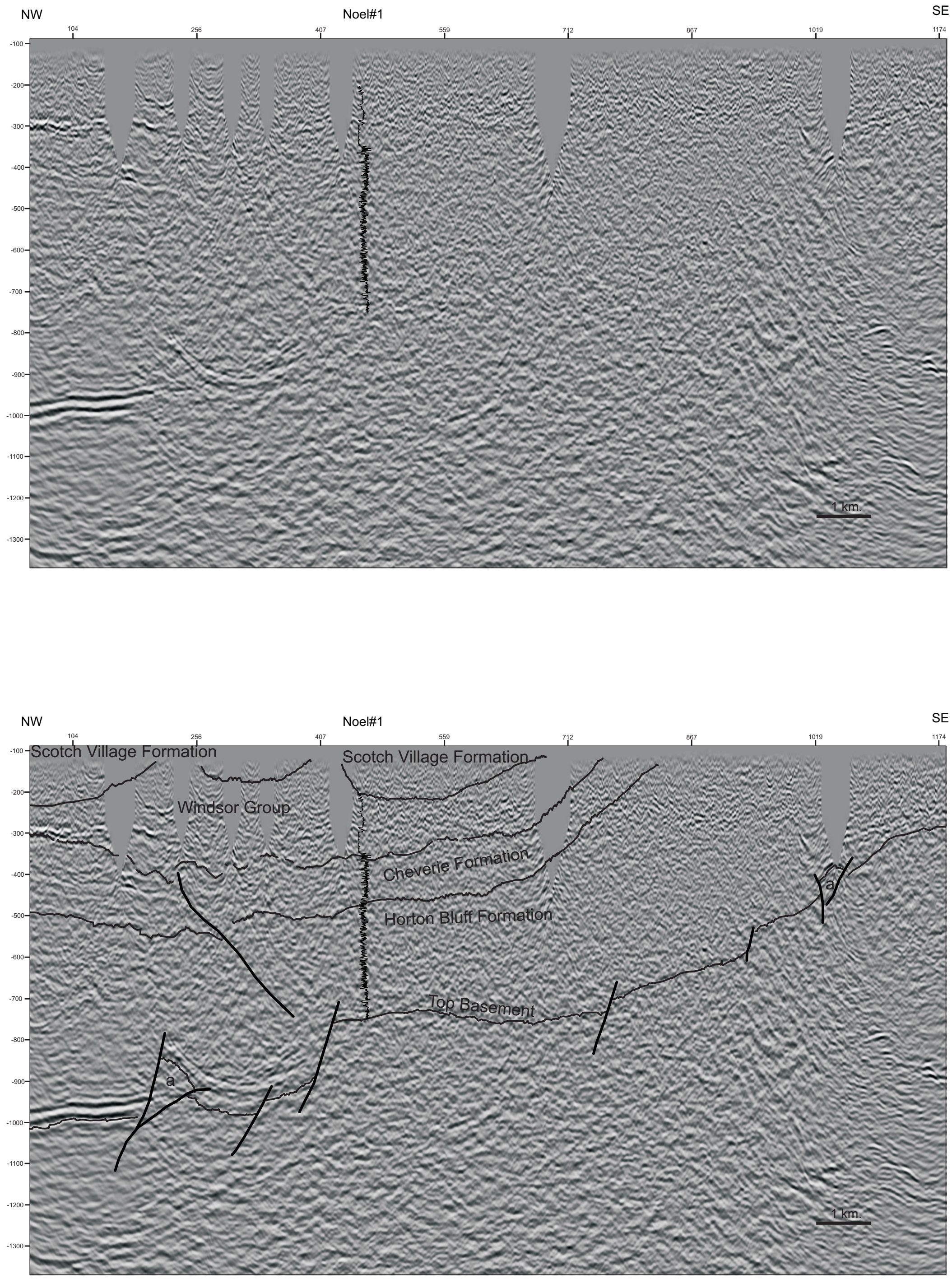


Figure 4.21: Uninterpreted NW-SE 2D seismic line WIND-02-002 (top). Interpretation (below) shows tilted fault blocks bounded by high-angle normal faults and pop-up structures (a) bounded by high-angle reverse faults at the top of basement.

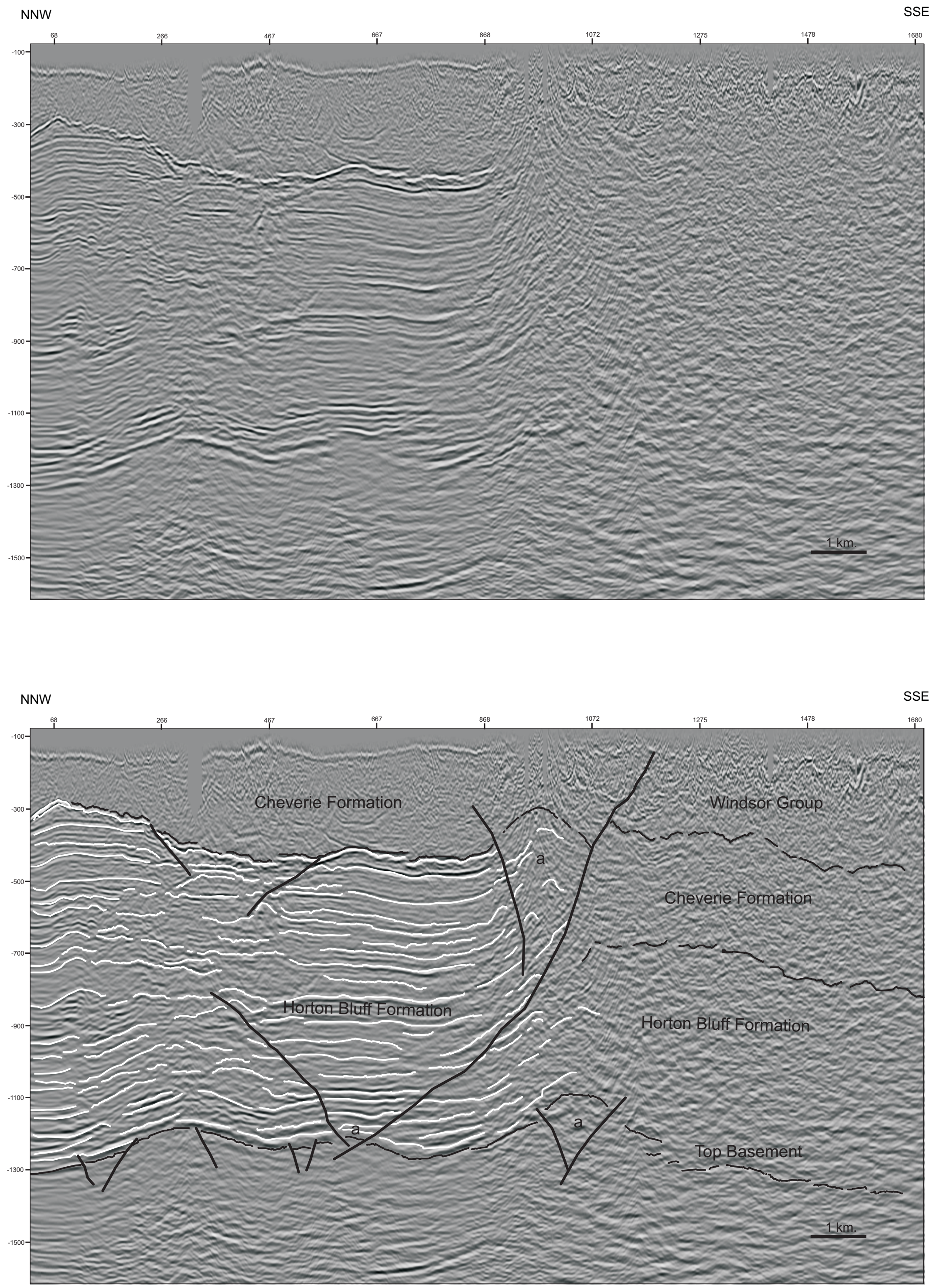
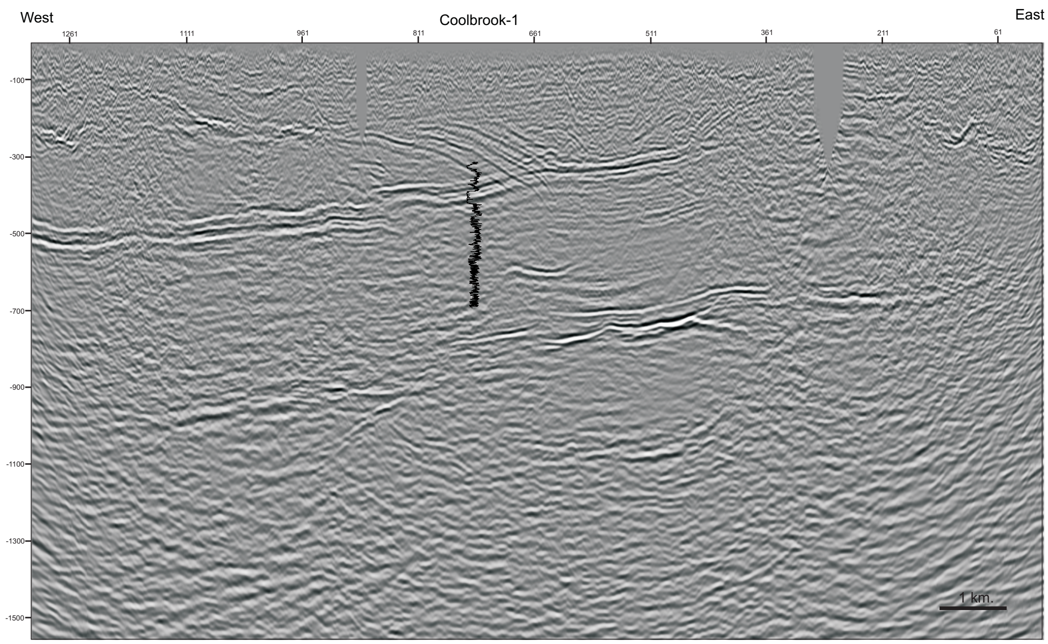


Figure 4.22: Uninterpreted NW-SE 2D seismic line KC-09-09 (top). Interpretation (below) shows tilted fault blocks bounded by high-angle normal faults and pop-up structures (a) bounded by high-angle reverse faults at the top of basement and the top of the Horton Bluff Formation.



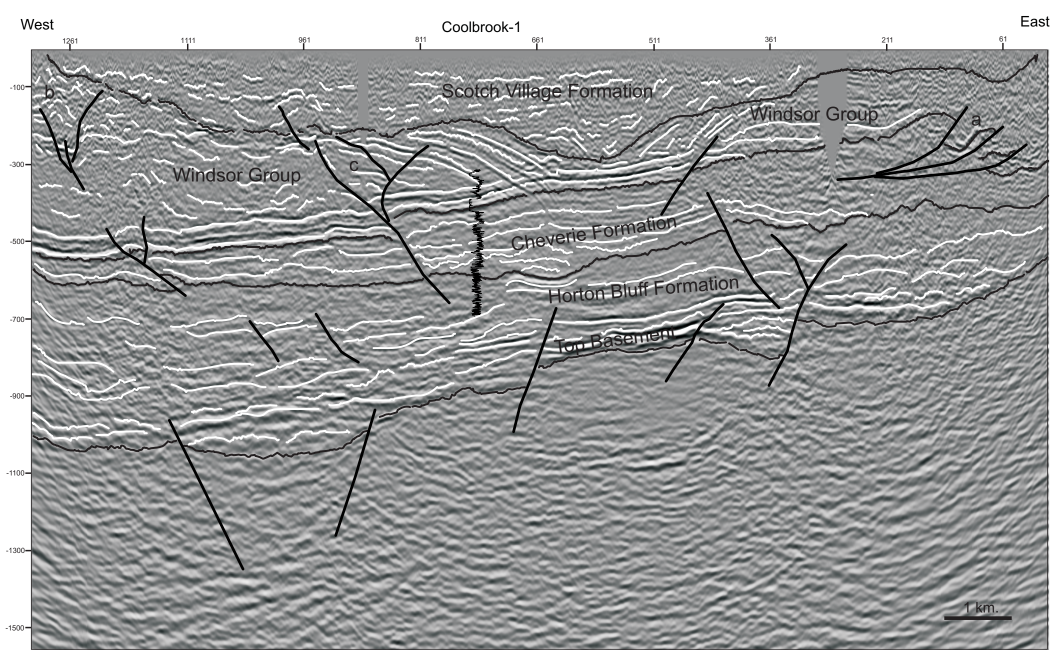


Figure 4.23: Uninterpreted E-W 2D seismic line NOL-01-001 (top). Interpretation (below) shows tilted fault-blocks bounded by high-angle normal faults at the top of basement. An imbricate structure (a) in the Cheverie Formation in the upper right corner; a salt diapir (b) in the upper left corner, and a positive flower structure (c) within the Windsor Group are interpreted on this seismic profile.

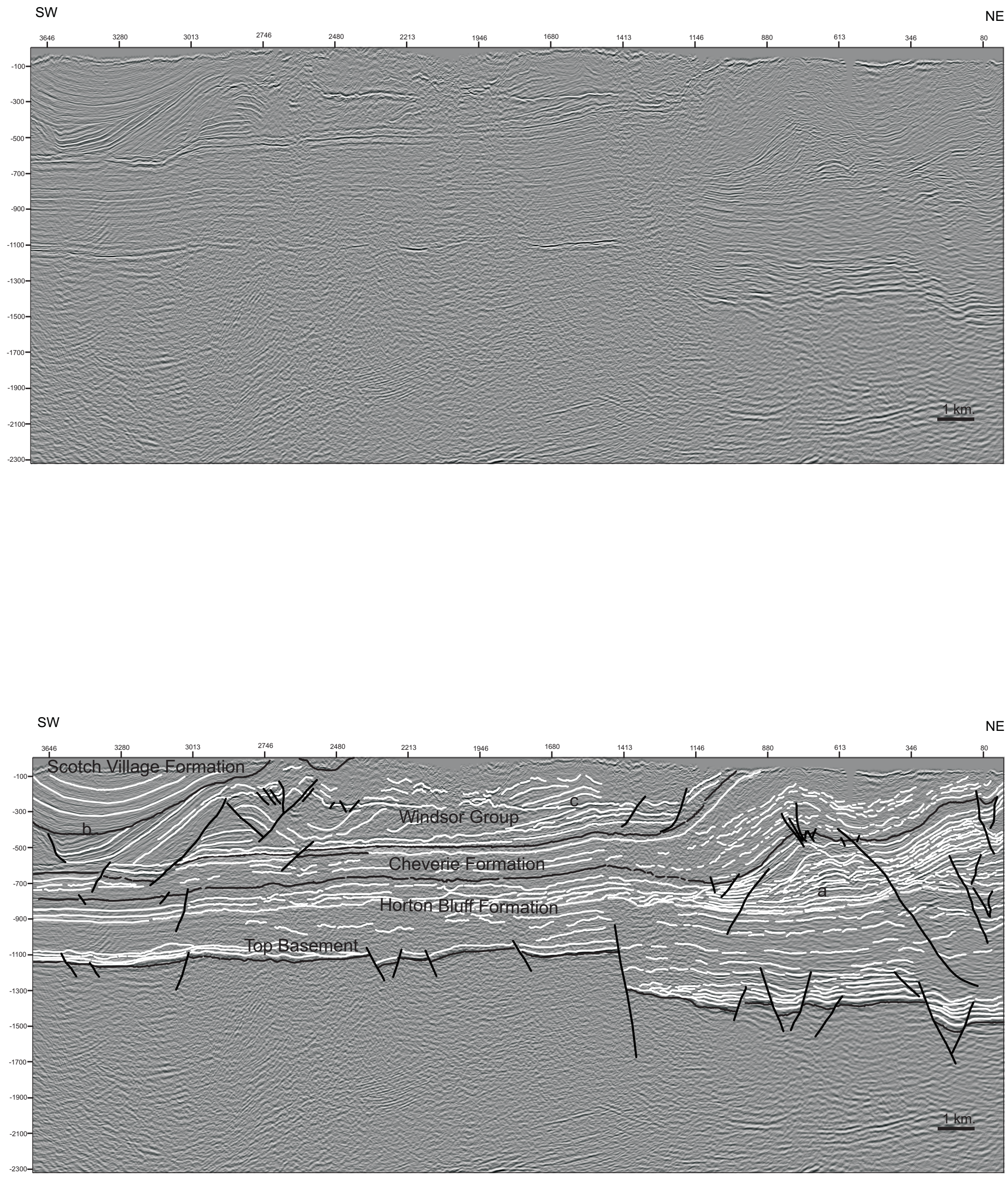


Figure 4.24: Uninterpreted SW-NE 2D seismic line Kenn-07-001 (top). Interpretation (below) shows a décollement structure (a) in the right upper corner within the Horton Bluff Formation. Discordant relationship (b) between the Scotch Village Formation and the underlying Windsor Group rocks in the upper left corner clearly indicates an angular unconformity. A very prominent nearly horizontal seismic reflector (c) with the Windsor Group indicate a possible detachment along which evaporite moved and caused structural collapse in the overlying strata indicated by down dipping seismic reflections.

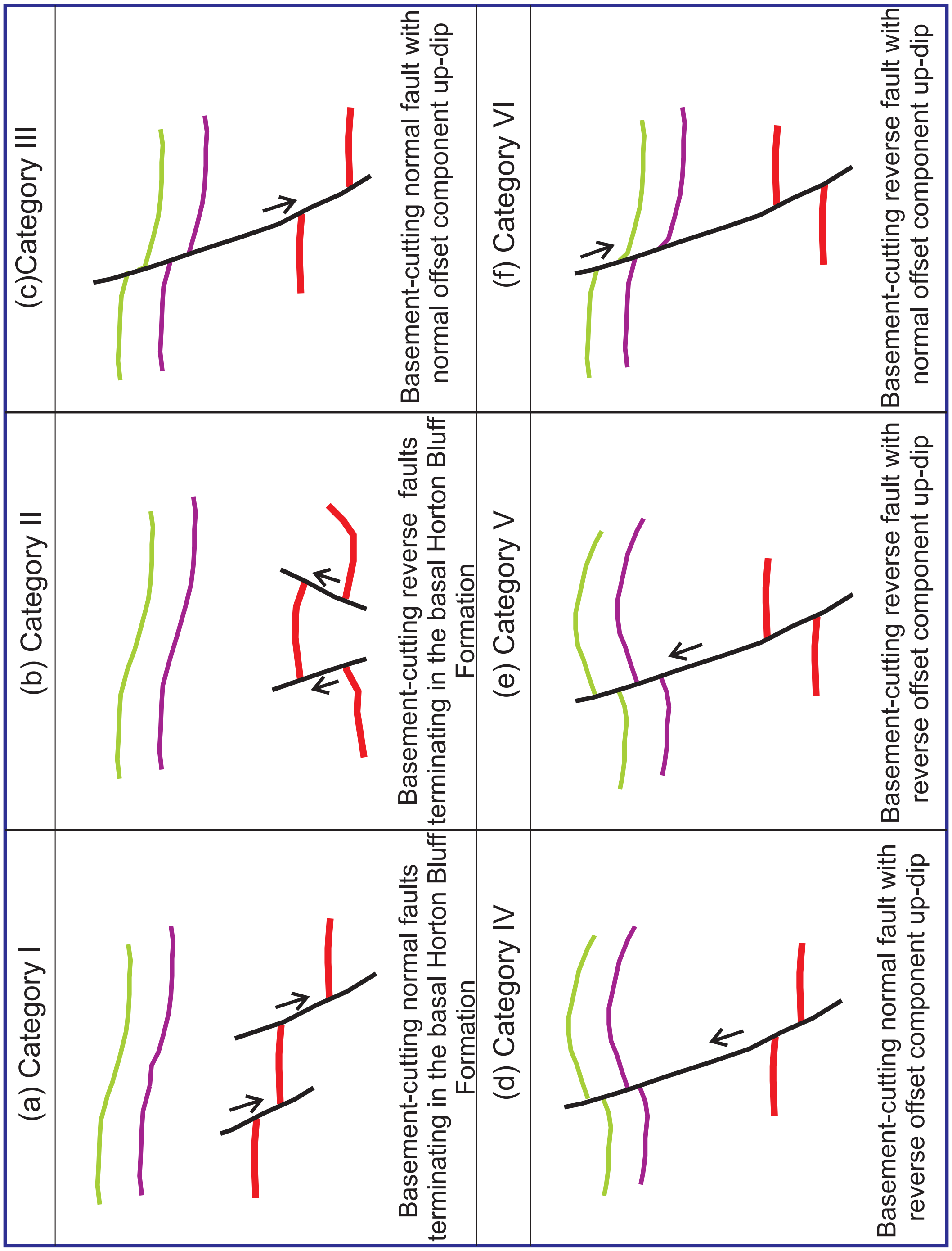


Figure 4.25: Categories of faults interpreted in the subsurface of the study area.

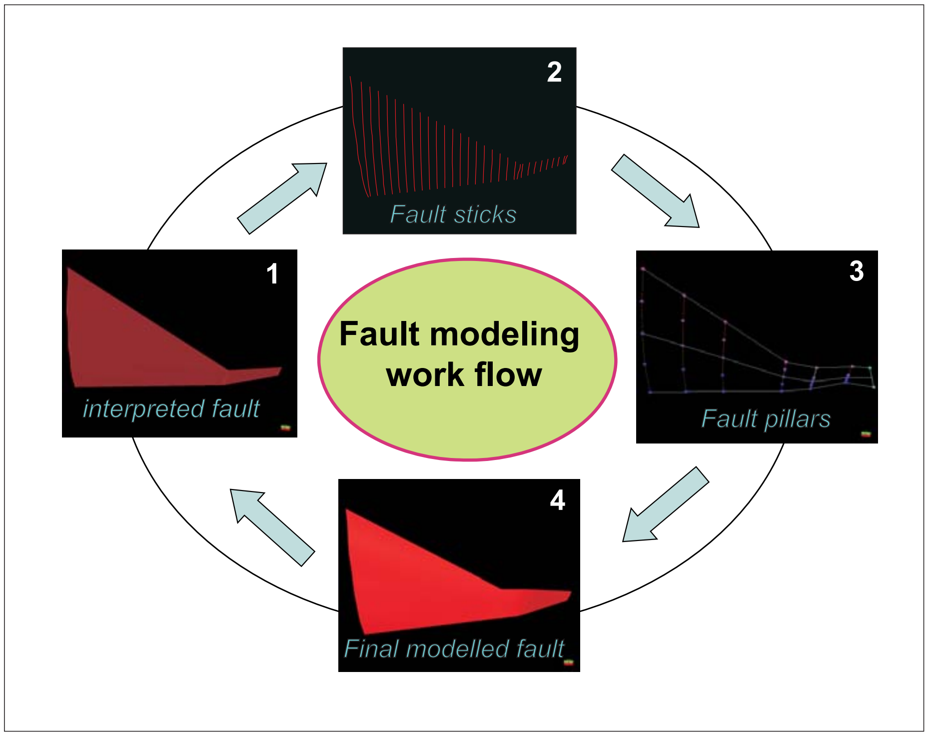


Figure 4.26: Diagram showing the fault modeling workflow in seismic interpretation.

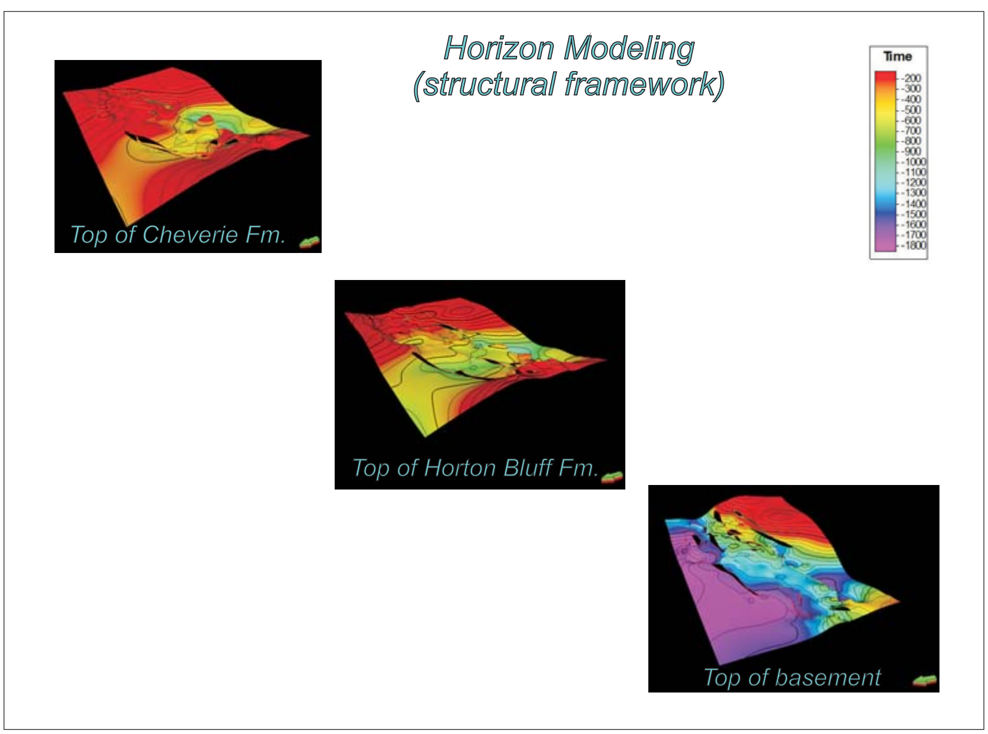


Figure 4.27: Result of the horizon modeling done in the structural framework for QC purpose.

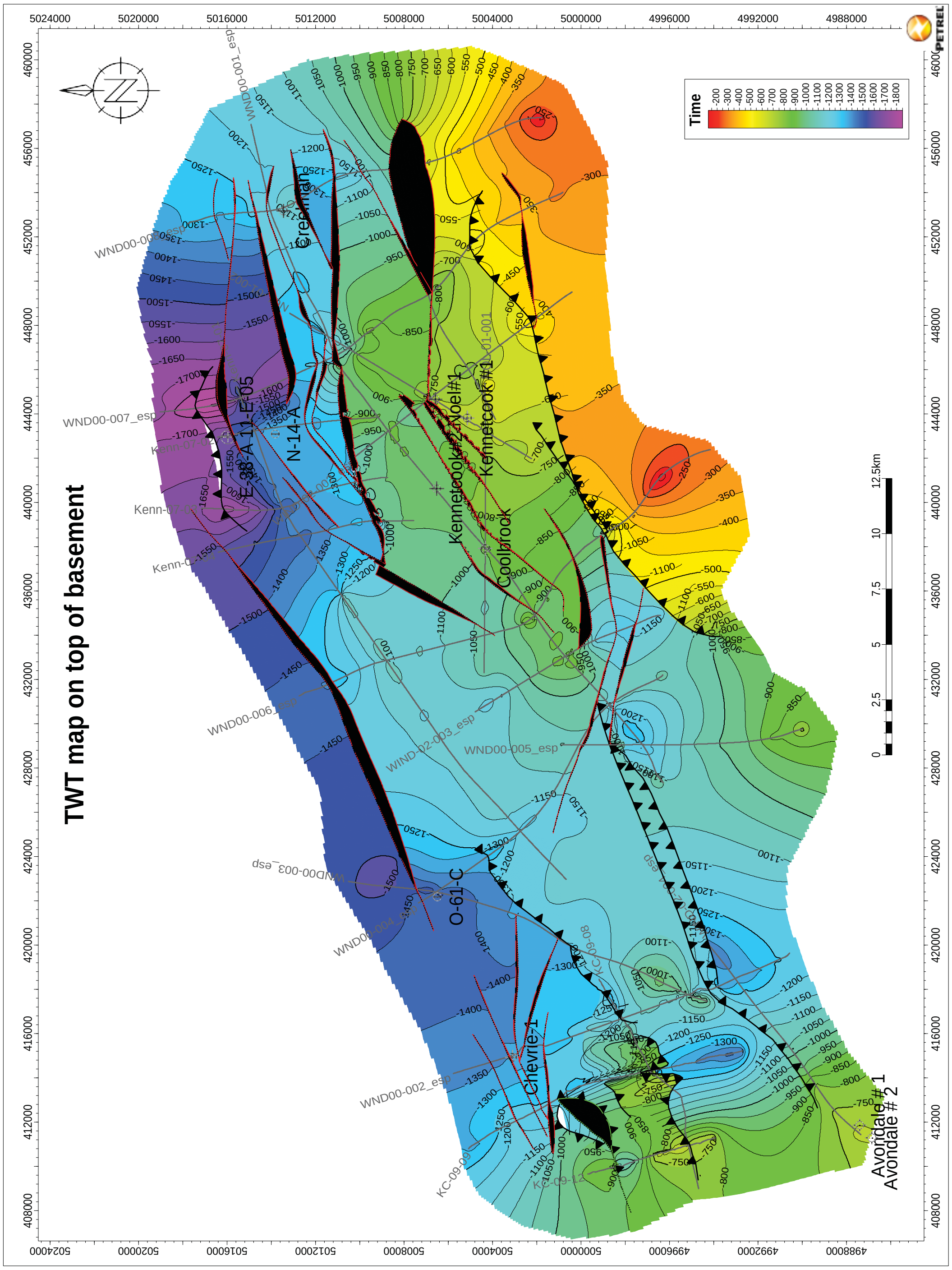


Figure 4.28: TWT structure map on the top of basement.

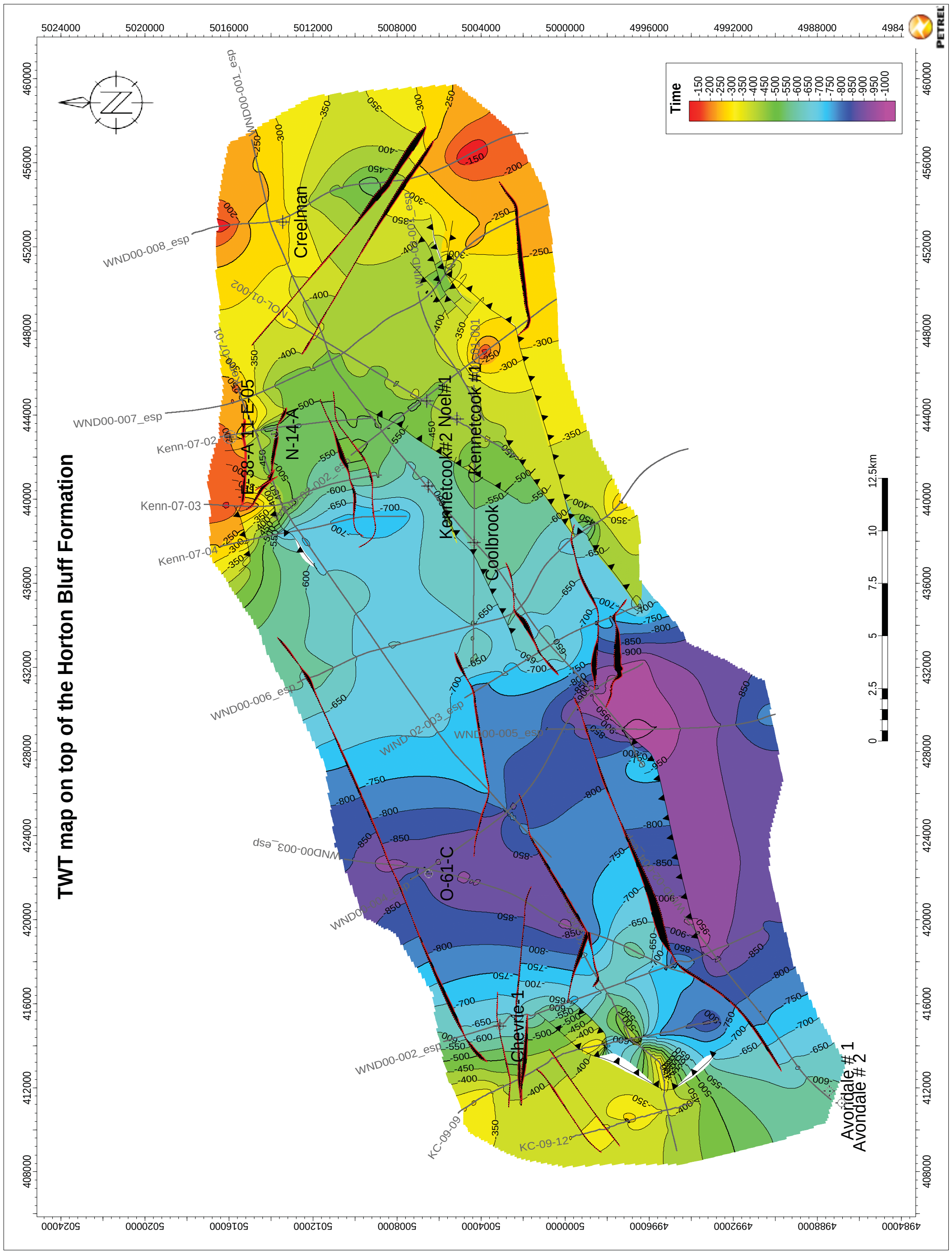


Figure 4.29: TWT structure map on the top of the Horton Bluff Formation.

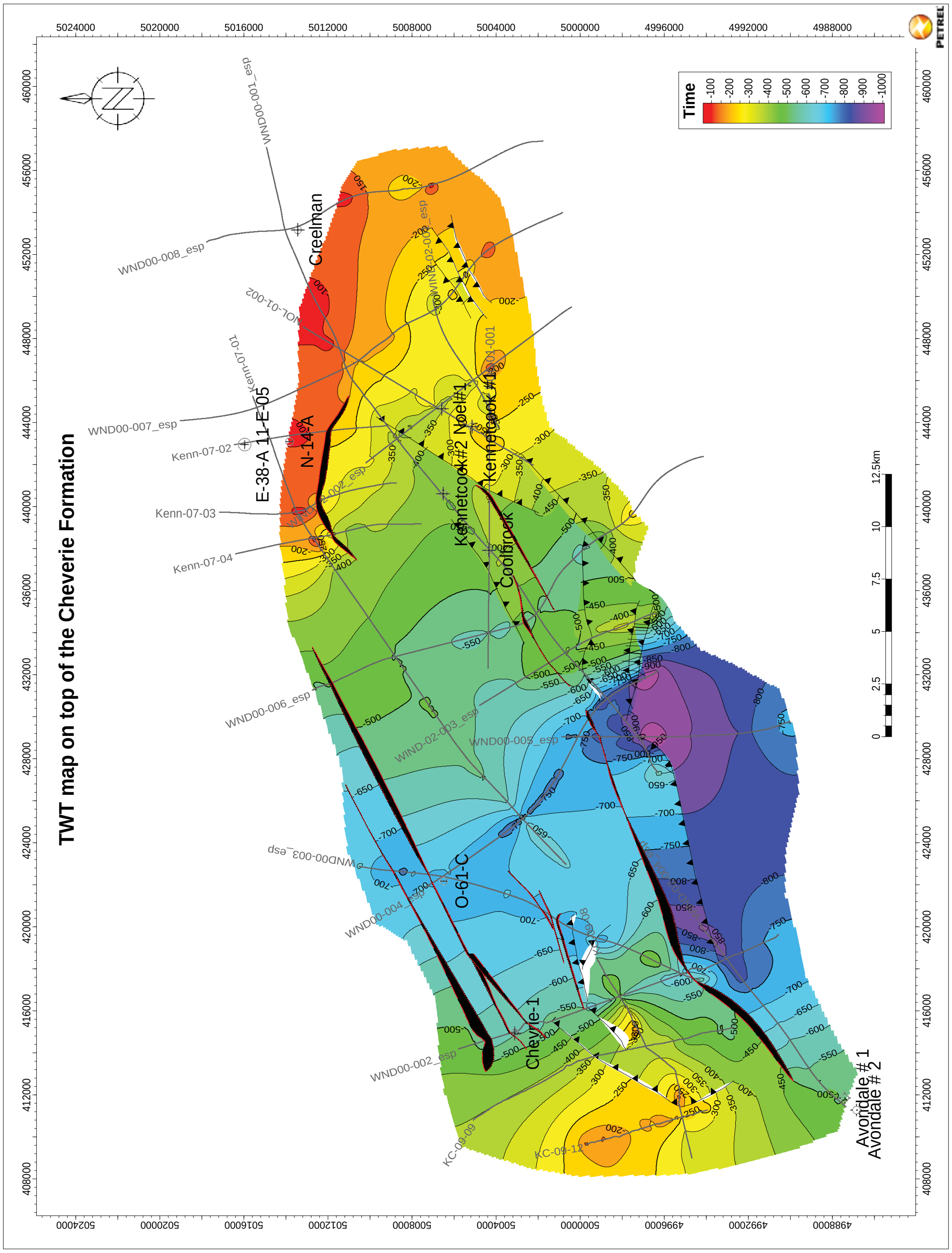


Figure 4.30: TWT structure map on the top of the Cheverie Formation.

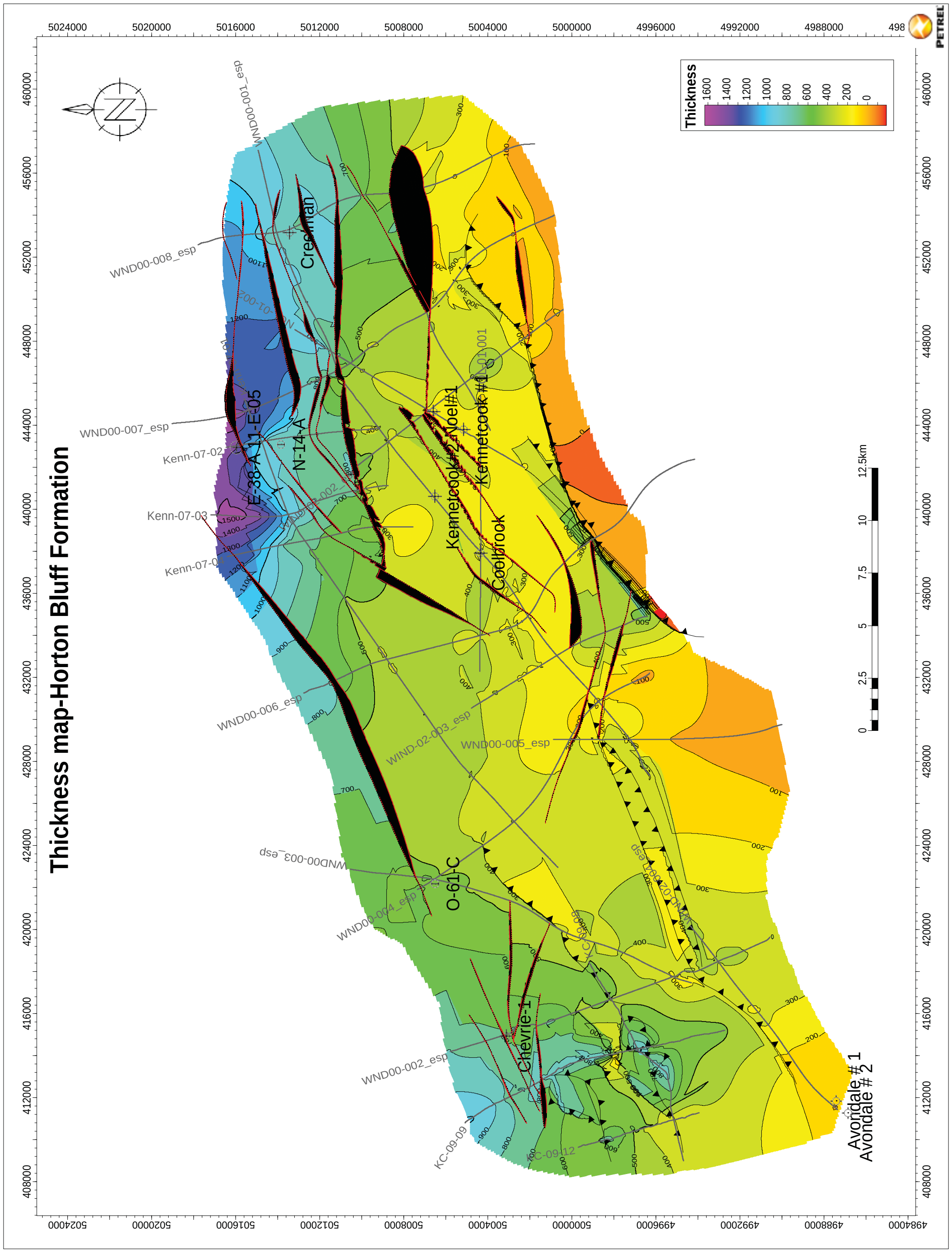


Figure 4.31: Thickness map of the Horton Bluff Formation.

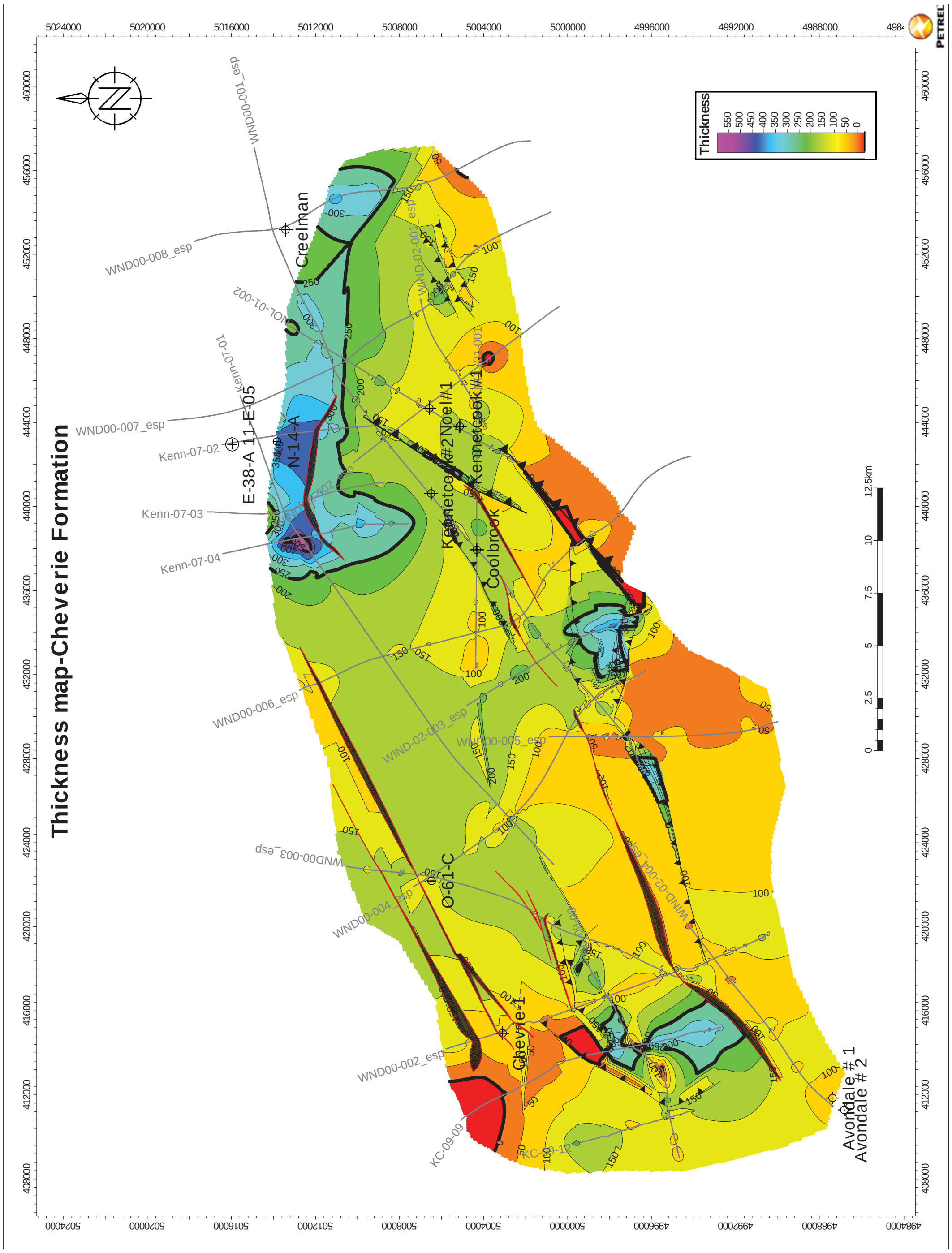


Figure 4.32: Thickness map of the Cheverie Formation.

5. Interpretation

The Kennetcook-Windsor basin (Figure 2.1) is a part of the large composite Maritimes Basin in Atlantic Canada. A variety of subsurface structures in the Kennetcook-Windsor basin have been mapped and interpreted on the available seismic dataset. Fault correlations and 3D modeling were completed prior to the generation of two-way-time (TWT) structure maps at the tops of basement, the Horton Bluff and the Cheverie formations. Thickness maps for the Horton Bluff and the Cheverie formations were also generated to estimate the thickest parts of both formations in the study area.

Subsurface seismic data indicate a very complex basinal history in terms of syn-depositional deformation and superimposition of numerous episodes of fault activation in the basin. Fault interpretations, correlation and mapping at the top of basement, the Horton Bluff, and the Cheverie formations and the top of Windsor Group add much information to the understanding of basin evolution.

5.1. Evidence for strike-slip setting

Most of the seismic profiles (Figures 4.1, 4.2, 4.8, 4.9, 4.15, 4.16, 4.18, 4.23) show both negative and positive flower structures within the Horton and the Windsor groups. These structural geometries are bounded by normal and reverse faults that are high-angle at deeper levels and become gentler and listric in up-dip sections. They are probably the products of multiple episodes of intense shearing that controlled the development and deformation in the basin. Transtensional episodes caused initial basin opening and subsidence. Category III and VI faults record transtensional episodes in the basin. These episodes are related to the oblique movement on the major boundary between Avalon and Meguma.

Transpressional episodes caused regional uplift and erosion across the basin and resulted in unconformable relationship with the underlying sediments. Category II, IV and V faults record transpressional events that caused inversion along the faults. These episodes are interpreted to be related to the oblique motion along a major basin-bounding fault. Each reactivation episode overprinted the earlier deformation and resulted in a complex behaviour of the subsurface faults through time.

5.2. The basement architecture

The TWT structure map on top of the basement (Figure 4.28) shows the gradual deepening of the tilted fault-blocks to the north and northwest. The reverse faults mapped in the south and west (Figure 4.28) have brought the top of basement at the shallower depth. The variable episodes of inversion along the basement-cutting faults caused the tilting of the top of basement. Faults mapped at the top of basement follow an array of stair-steps and provided graben and half-graben geometry bounding the tilted fault-blocks in the beginning of the basin history. Fault correlations and mapping at the top of basement show that there is a swing (bend) in fault strikes between the seismic lines WIND-02-003 and WIND-02-002. This change in the strike direction probably indicates the presence of a local stepover in which some flower structures developed (Figure 4.9). This subsurface structural geometry in the SW of the study area indicates that the oblique motion on the subsurface faults controlled the deformation in the Kennetcook-Windsor basin. This may be related to regional SW-NE faults which Hibbard and Waldron (2009) have suggested were dominant during Tournaisian time.

5.3. Discussion: Basin Evolution

5.3.1. Fault classification and implication

Seismic and well data integrated with the outcrop observations (Chapters 2, 3 & 4) in the Kennetcook-Windsor basin indicate an active tectonic history. On the basis of subsurface fault interpretation and correlations basement-cutting faults are classified into six broad categories evolved during the development of the basin and responded to the movement along the basin bounding-fault (Minas Fault Zone) located to the north. This regional fault marks the boundary between the Avalon and Meguma terranes.

The faults in the first category (Figure 4.25a) terminate in the basal Horton Group (Figures 4.3, 4.10, 4.12, 4.17, 4.23, 4.24) and mostly cut through the coarse alluvial fan deposits preserved in the basal part of the Horton Bluff Formation represented by bright seismic reflections that, on some seismic profiles, (Figure 4.3, 4.10, 4.17) show inclined geometries interpreted as downlap onto basement (chapter 3). The faults in this category mark an extensional phase and played their role only during the deposition of the Horton Bluff Formation as they do not extend up-dip into the Cheverie Formation.

The second category (Figure 4.25b) includes basement-cutting faults that also terminate within the Horton Bluff Formation but form localized pop-up structures and bound an array of tilted fault-blocks at the top of basement (Figures 4.16, 4.20, 4.21). The reverse offset along these faults indicate that contraction played an active role in the beginning of the basin development.

During the inversion of the category II faults, the category I faults, locally, could also have been inverted as indicated by the dipping and curved seismic reflections (Figure 4.1 & 4.3) present in the basal part of the Horton Bluff Formation. However, due to larger normal offset, inversion did not produce net reverse offset in these faults.

The third category of faults (Figure 4.25c) comprises those basement-cutting normal faults that cut almost the entire Horton Group and have a normal offset up-dip (Figure 4.2, 4.8, 4.15). These faults show variable offsets up-dip that may indicate episodic fault reactivation (Figure 4.2, 4.8). The normal offsets of faults in this category indicate that the Horton Group continued to be deposited in an extensional setting that controlled the subsidence in the basin.

The basement-cutting normal faults in the fourth category (Figure 4.25d) cut through the Horton Group, terminate in the basal Windsor group rocks and have reverse offset up-dip (Figure 4.2, 4.8). These faults show variable offsets which probably indicate multiple episodes of fault reactivation and inversion. Subsurface time structure-mapping at the tops of the Horton Bluff and Cheverie formations (Figures 4.29 & 4.30) show that these faults played an important role in controlling structural lows at the top of the Horton Bluff and the Cheverie formations.

Category III and IV faults are related as both have normal components at the basement level; some of them (category IV) were inverted in such a way that the reverse component during shortening phase exceeded the former normal component whereas inversion along other faults (category III) did not exceed the normal component resulting in net normal offset. As these faults (Category III & IV) extend up-dip and terminate in the basal Windsor group rocks they remained active at least until late Tournaisian to early Visean.

The faults in the fifth category (Figure 4.25e) have reverse offset at all horizons and terminate in the basal Windsor Group (Figure 4.2, 4.13, 4.14, 4.16, 4.22). These faults, mostly, form high angle pop-up structures and accommodated uplift of the Horton Group (Figure 4.14, 4.22). Termination of these faults in the basal Windsor Group indicates that they also played a role in the early Visean history of the basin.

Category VI faults (Figure 4.25f) comprises those that have reverse offset at the basement level and normal component up-dip (Figure 4.2, & 4.14). These faults also terminate in the basal Windsor Group. The normal component at the shallower levels indicates an extensional episode that occurred after the deposition of the Horton Group and after reverse motion on fault categories II, IV and V.

Category V and VI faults indicate a regional episode of inversion prior to the deposition of the Windsor Group, during which Horton Group suffered uplift and erosion. Some of the faults with larger normal offset underwent incomplete inversion. Faults of Categories III to VI remained active during the deposition of the Horton Group and some of the faults with normal offset at the basement level as well as the up-dip shallower levels show that Horton Group was deposited in an overall extensional setting. Also, faults in categories III to VI record at least two episodes of inversion during which basement-cutting normal faults were inverted at the basement and the shallower levels.

In terms of fault activation and timing during the history of the basin, the six categories of mapped faults discussed above can be recognized on the basis of interpretation of their subsurface terminations and offsets. Due to the complex array of faults, it is difficult to estimate which faults were inverted first and which later, as some faults show both normal and reverse components at shallower levels. Among the six categories, faults of categories V & VI are considered the most active faults that have reverse component at basement level and show both reverse and normal offsets at shallower levels. These faults played key roles even across the Tournaisian-Visean boundary in the development of subsurface structures and accommodated uplift of the Carboniferous strata.

Flower structures present in the subsurface probably developed during oblique movement on the subsurface faults interpreted in categories IV, V and VI. These structural geometries indicate the strike-slip setting responsible for the basin development. The oblique motion caused multiple episodes of extension and shortening in the basin as indicated by offsets and inclined reflections across the faults.

Multiple episodes of deformation played a key role in the basin development and subsurface structural geometries. Fault orientations, terminations and type of their offsets (e.g. normal and reverse) at different stratigraphic levels indicate multiple episodes which are discussed in a chronological order in the following sections.

5.3.2. Late Devonian-Tournaisian: Horton Group

5.3.2.1. Horton Bluff Formation

The Horton Bluff Formation mainly comprises fluvial sandstone and conglomerate, lacustrine-deltaic sandstone, siltstone and shale. Four members of the formation (Martel and Gibling, 1996) were deposited under braided-fluvial, fluvio-lacustrine, lacustrine and fluvio-lacustrine environments of deposition respectively. Deposition of the Horton Bluff Formation in an extensional setting represented by faults of category I marks the initial development of the basin and the first episode of extension (Figure 5.1a). The faults in the first category provided tilted fault-block geometry (graben or half-graben) where high gradient braided streams deposited coarser sediments along the basin margins.

The second category of faults marks a short break in the overall extensional setting that prevailed in the beginning of the basin development. Inversion along the basement-cutting faults (category II) indicates a second episode of deformation (Figure 5.1b) which was restricted to the basal part of the Horton Bluff Formation. Since the category I & II faults were restricted to the basal Horton Bluff Formation, they did not play any role in the remaining history of the basin

The TWT structure map on top of the Horton Bluff Formation (Figure 4.29) shows rising in the northeast, northwest and south. A broad regional structural low is present in the centre of the mapped area (between the seismic lines WND00-002 and WND00-006). The subsurface structural trends indicate that the subsurface faults mapped at the top of the Horton Bluff Formation suffered episodic and variable amounts of inversion during the history of the basin. Two fault-bounded structural highs at the Horton Bluff level are present in the western part of the mapped area between seismic lines KC-09-12 and WND00-002. These structural highs could be considered and tested as the future drilling prospects associated with the Horton Bluff Formation. In the subsurface, the Horton Bluff Formation thickens to the northwest and northeast (Figure 4.31) and follows the structural trends of the top of basement which steps down to north towards the Bay of Fundy. The half-graben geometry provided by the basement tilted fault-blocks accommodated much of the Horton Bluff sediments.

Mudlogs of Coolbrook-1, Kennetcook-1, -2 and Creelman-1 wells (tables 3, 4 & 5, Ch-3) show that there are lateral lithological variations in the Horton Bluff Formation which could be attributed to: 1) the position of the drilled wells in the basin; and 2) the post-depositional deformation that juxtaposed different fault-blocks, resulting in discontinuous facies relationship. However, the breakdown of the Horton Bluff Formation into members using the classification of Gibling and Martel (1996), which was achieved during this research project, shows that correlations are possible in the subsurface across the Kennetcook-Windsor basin.

5.3.2.2. Cheverie Formation

A third deformation episode (Figure 5.1c) that occurred after the deposition of the basal part of the Horton Bluff Formation provided an extensional setting that lasted throughout the deposition of the Upper Horton Group (Cheverie Formation). The faults in categories III and IV that controlled the deposition of the Horton Group during late Devonian to Tournaisian in the southern part of the Maritimes Basin were active during this third episode of deformation and responded to extensional and shortening episodes occurring in the basin. The Cheverie Formation was also deposited in a fluvial environment during which most of the half-grabens were filled by the Horton Bluff sediments. Lithological and mineralogical contrasts with the underlying Horton Bluff Formation indicate that climate and tectonic movements were the controlling factors during the deposition of the Cheverie Formation.

Lithological descriptions from the mudlogs of different wells in the study area indicate lateral facies variations in the subsurface. The Cheverie Formation, subdivided here into three intervals (tables 6, 7 and 8, chapter 3), indicates thickness variations and considerable erosion in the northeast. Its seismic signature and outcrop observations indicate a braided to meandering system during the deposition of the Cheverie Formation.

Category IV and V faults indicate reverse offsets at the tops of the Horton Bluff and the Cheverie formations. Inversion along these faults suggests that there was shortening and uplift in the basin after the deposition of the Cheverie Formation. Seismic data (Figures 4.2 & 4.8) show an angular relationship of the underlying Cheverie Formation with the overlying Windsor Group rocks (base of the Macumber Formation). Palynological data (*Colatisporites decorus – Schopfites claviger* Zone, Utting et al., 1989) also indicate a hiatus between the Horton Group and the Windsor Group. Utting et al. (1989) suggested that this hiatus may vary in different localities but would be more towards Cobequid Bay. This uplift and erosion of the upper part of the Horton Group marks the fourth episode (Figure 5.2d) in the basin.

The TWT structure map on the top of the Cheverie Formation also shows a structural low in the central part bounded between the seismic lines WND00-003 and WIND-02-003 (Figure 4.30). However, this structural low is narrower than that mapped at the top of the Horton Bluff Formation. The subsurface structural trend of the top of the Cheverie Formation also indicates the episodic and variable amounts of inversion along the faults which caused uplift and rising of the top of the Cheverie Formation much as with the Horton Bluff Formation. The TWT map on the top of the Cheverie Formation also shows two fault-bounded structural highs in the western part of the study area between seismic lines KC-09-12 and WND00-002.

The Cheverie Formation thickens in the southwest and northeast (Figure 4.32) and shows local thickness variations across the faults. Syn- and post-depositional fault reactivation controlled these regional thickness trends. Comparison between the thickness maps of the Horton Bluff and the Cheverie formations indicates that the Cheverie Formation shows less thickening in the north and northeast than the Horton Bluff Formation. This thickness comparison confirms that the half-graben geometry had already been occupied by the Horton Bluff Formation at the time of Cheverie Formation deposition.

5.3.3. Visean-Windsor Group

The limestone, gypsum/anhydrite and halite present in the Windsor Group indicate an entirely different style of deposition. A major transgression created restricted and hypersaline marine and lacustrine conditions (Gibing, 1995; Gibling et al., 2008) during middle-late Visean during which the Windsor and the Mabou groups deposited in the Maritimes Basin.

The Windsor Group in the study area shows much thickness variation due to the mobility of the evaporites present mainly in the basal part. High angle, discontinuous and chaotic seismic reflections within the Windsor Group indicate structural collapses triggered by the evaporite withdrawal. Fault interpretation and mapping at the top of the Windsor Group (Figure 4.7) show that faults strike SW-NE and SSW-NNE. This strike is different from the faults mapped at the top of basement, the Horton Bluff and the Cheverie formations; the faults at the top of the Windsor Group are rotated towards north as compared with the faults at other levels. This indicates a different episode of deformation across the Tournaisian-Visean boundary. The deformation in the Windsor Group was probably controlled by the evaporite mobility and the subsequent structural collapses.

Seismic reflection geometries that show tilted fault-blocks within the Windsor Group (Figures 4.2 & 4.15) indicate active tectonics. Timing of the fault activation and inversion within the Windsor Group is difficult to interpret due to the active role of the basal evaporites during the syn- and post-Visean history of the basin. Seismic data show that only one north dipping basement-cutting reverse fault has cut through the Horton and Windsor groups and terminated in the basal Scotch Village Formation (Figure 4.9). This fault has listric normal offset at the top of the Windsor Group. This fault shows multiple inversion history and formed a pop-up structure with a conjugate reverse fault at the top of basement, the Horton Bluff and the Cheverie formations interpreted on the seismic line WND00-005 (Figure 4.9). Due to strike-slip tectonics in the southwestern part of the study area, this pop-up structure merges eastwards with a graben at basement level as evident on the north-south oriented seismic line WND00-004 (Figure 4.8).

Most of the faults interpreted within the Windsor Group terminate within the group (Figure 4.16) and do not extend up-dip or down-dip into the older or younger sediments except some listric normal faults that extend up-dip and cut through the Scotch Village Formation (Figures 4.2, 4.8, 4.9, 4.10). Faults interpreted at the top of the Windsor Group (Figure 4.7) do not communicate with the faults in the Horton Group as most of them terminate in the basal evaporites and also their strike direction is rotated to the north as compared with those in the Horton Group. Deformation within the Windsor Group is attributed to a fifth episode (Figure 5.2e) in the basin. Presumably the Kennetcook thrust system (Waldron et al., 2010) developed during this episode.

5.3.4. Bashkirian: Cumberland Group

A continental fluvial environment prevailed during the deposition of the Cumberland Group (Scotch Village Formation). Fining upward channelized sandstone and siltstone were deposited by the braided river system. The siltstone, shale, and locally thin coal and plant debris represent floodplain deposits. In the subsurface, the Scotch Village Formation shows excellent, moderately continuous and uniform seismic reflections which are laterally traceable and show mild deformation as compared with the underlying Windsor and the Horton group rocks. Seismic data show that mostly the Scotch Village Formation in the basin occupies many minibasins created by the evaporite withdrawal within the Windsor Group. Inclined reflection geometries in the basal part of the Scotch Village Formation dip down on the top of the Windsor Group (Figures 3.18 & 3.20), which provided an uneven erosional surface for the deposition of the Scotch Village Formation.

This surface in the basin marks an angular unconformity between the Cumberland Group and the underlying Windsor Group. This regional angular unconformity in the basin separates underlying highly deformed Windsor Group rocks from the overlying mildly deformed Scotch Village Formation. No single reverse fault within the Scotch Village Formation is present in the subsurface seismic data. However, some listric normal faults, originating from the basal Windsor Group, cut through the Scotch Village Formation. This indicates that the deformation is related to an extensional episode (sixth, Figure 5.2f) and is post-Mississippian in the basin. It also indicates that all the other episodes were pre-Pennsylvanian.

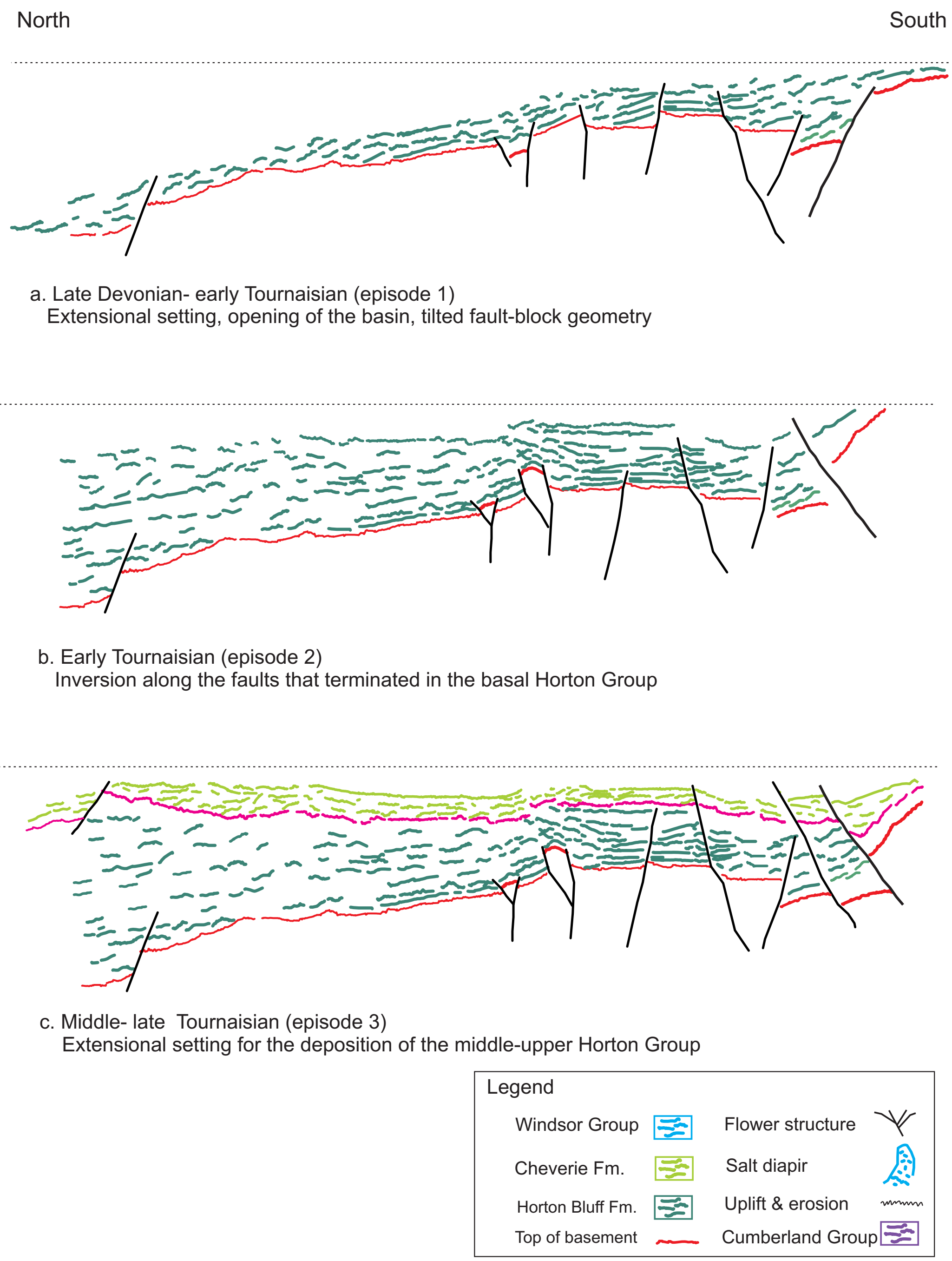
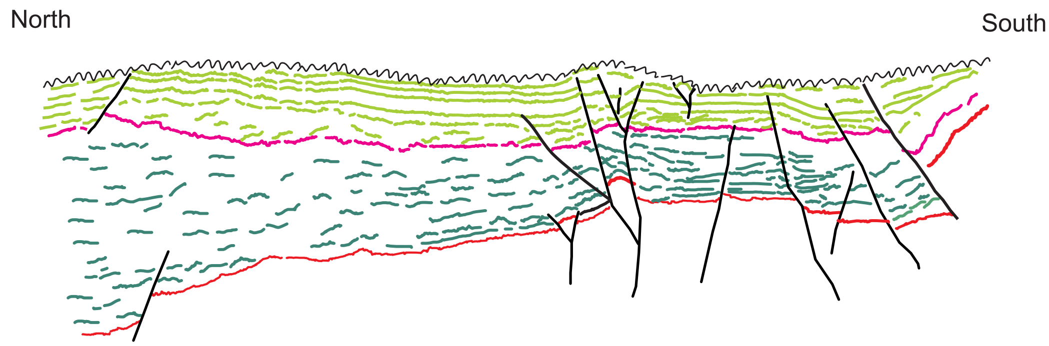
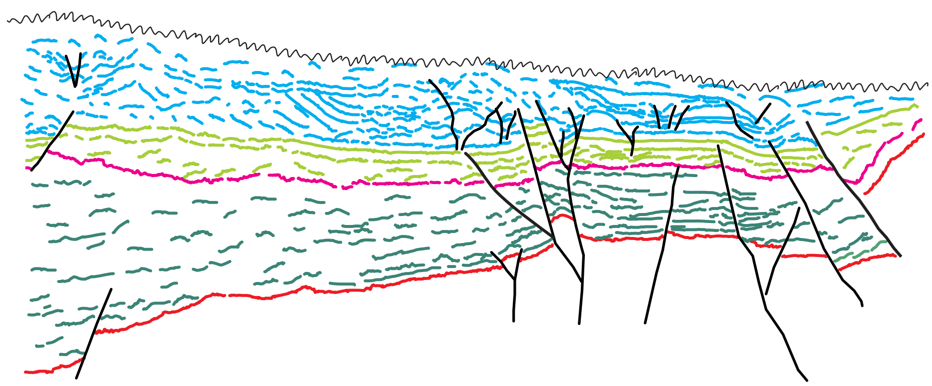


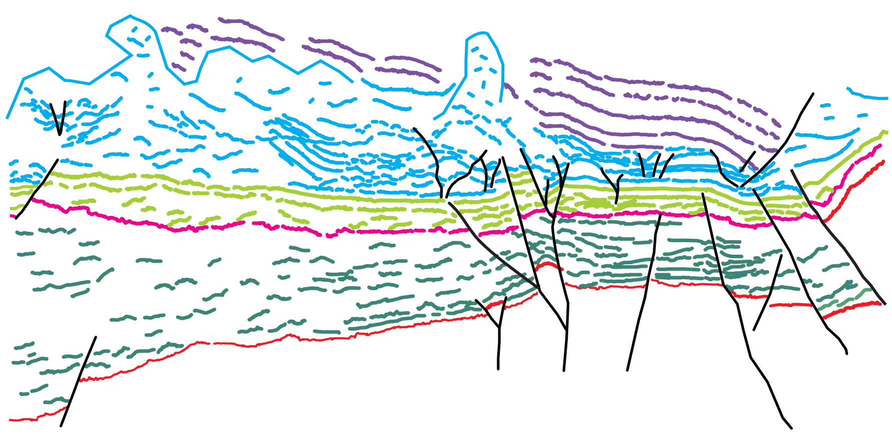
Figure 5.1: Schematic diagram showing the basin evolution through time (Late Devonian-Tournaisian).



d. Late Tournaisian-early Visean (episode 4)
Uplift, erosion, and flower structures in the Horton Group



e.Late Visean (episode 5)
Deformaion in the Windsor Group



f. Bashkivian (episode 6)
Deposition and mild deformation within the Cumberland Group

Figure 5.2: Schematic diagram showing the basin evolution through time (Late Tournaisian-Bashkirian). For legend, see figure 5.1.

6. Conclusions

Field observations along the wave-cut platforms exposed in the coastal areas between Cheverie and Selma (Figure 1.5) indicate intensely deformed Horton Group rocks. Structural data plotted on stereonets (Figures 2.5, 2.7, 2.9, 2.11, 2.13) indicate a general trend of the strike of the bedding planes and fold axes in SW-NE and WSW-ENE directions, with folds that plunge SW at 10^{o}-25^{o}. These folds represent the latest generation of folds that superposed on the earlier formed folds in the basin. This surface data plotted on the stereonet follow the strike direction of the subsurface faults modelled for the top of basement, the Horton Bluff and the Cheverie formations.

A variety of extensional and compressional structures is present in the subsurface of the Kennetcook-Windsor basin and has been interpreted in detail on the available seismic data. Subsurface structural geometries include: tilted fault-blocks bounded by high-angle normal and reverse faults at the basement level (Figures 4.2, 4.3, 4.10, 4.12, 4.17, 4.19, 4.20); both negative and positive flower structures (Figures 4.1, 4.9, 4.16, 4.18); imbricate structures bounded by overlapping listric reverse faults within the Horton Group rocks (Figures 4.15, 4.16, 4.23); structural collapses or dissolution features within the basal Windsor Group indicating evaporite mobility that initiated diapiric movement and caused angular reflection geometries within the Windsor Group (Figures 4.8, 4.15, 4.23, 4.24). Structural collapse features within the Windsor Group indicate a major post-Visean extensional episode in the basin that caused evaporite withdrawal and created accommodation space for the Pennsylvanian sediments in the basin. Flower structures mapped in the subsurface clearly indicate a strike-slip setting that remained active during the entire history of the basin and controlled the development and structures in the basin.

Time slices cut through the 3D seismic cube within the basement, the Horton Bluff and the Cheverie formations (Figures 3.6 & 3.18) indicate structural and stratigraphic features. Lineaments on the time slices indicate SW-NE strike of faults, which is consistent with the fault correlations and mapping results from the 2D seismic profiles. This subsurface trend is also nearly parallel with the Rawdon and the Roulston faults at the surface in the south of the Kennetcook-Windsor basin (Figure 1.5). Time slices cut through the basal Horton Bluff and the Cheverie formations show some concentric geometries which indicate the map view of inclined reflections. These inclined reflections are interpreted here as clinoforms that show progradation in the NE and NW direction and could be tested as a petroleum play if their topsets have preserved good quality sands. A high resolution 3D dataset is required that at least covers the area between Walton and Selma to delineate such stratigraphic prospects.

Subsurface faults in the Kennetcook-Windsor basin are classified into six categories based on fault interpretations, modeling and mapping. Six episodes of deformation, at least four during the deposition of the Horton Group (Late Devonian-Tournaisian) and two during Visean-Westphalian, are quite obvious from this seismic interpretation in the southern part of the Maritimes Basin. A time structure map on the top of basement shows deepening of the tilted fault-blocks towards the Bay of Fundy and rising towards south and southwest. Fault correlations at the top of the basement indicate NW-SE to NNW-SSE directions of extension controlling the opening and development of the basin immediately south of the Minas Fault Zone (MFZ). Time structure maps on the top of the Horton Bluff and the Cheverie formations show a regional structural low in the central part of the mapped area which indicates that the faults present in the northeast and the southwest were inverted more significantly and caused the uplift of both surfaces as compared with the faults present in the central part. A thickness map of the Horton Bluff Formation shows increasing thickness towards the Bay of Fundy and follows the deepening trend of the top of basement, whereas the thickness map of the Cheverie Formation shows increasing thickness SW-NE with the thickest parts preserved in the northeast of the study area.

Deformation and the consequent subsurface structural styles within the Kennetcook-Windsor basin were controlled by major dextral fault zones that were active during development of the Maritimes Basin. The E-W Minas fault to the north of the study area has many stepovers along its entire length (Murphy et al., 2011) and comprises numerous fault segments. Extensional episodes (i.e. I, III and VI) were related to the NE-SW faults and shortening episodes (i.e. II, IV and V) were related to E-W faults. These fault segments intermittently were active during the dextral movement along the Minas Fault zone and affected the area immediately to the north and south where the deformed Carboniferous rocks were brought to the surface.

Subsurface flower structures present in the subsurface of the study area confirm the structural model presented by Waldron et al. (2010) who assumed a regional positive flower structure cored along the Minas fault zone whose branching splays at the shallower levels transported the Carboniferous rocks to the north and south. Well data of Cheverie-1 and the field observations in the type section (west of Avon River) of the Horton Bluff and a few kilometres northeast around Cheverie and Walton where the intensely deformed Carboniferous rocks are present indicate the presence of an allochthonous sheet that was transported southward along the splays of this regional flower structure. The Kennetcook Thrust System (Waldron et al., 2010) that has a regional decollement surface in the basal Windsor evaporites played an important role in the distribution of the deformed Carboniferous rocks in a number of structural outliers towards the southern part of the Maritimes Basin; one of them is the Kennetcook-Windsor basin.

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