STRATIGRAPHY OF THE CHEVERIE FORMATION TYPE SECTION,

CHEVERIE, HANTS COUNTY, NOVA SCOTIA

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Submitted in Partial Fulfillment of the Requirements
for the Degree of Bachelor of Sciences, Honours
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April 2010

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DATE: April 26th /10

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TITLE: Stratigraphy of the Cheverie Formation Type Section, Cheverie, Hants County, Nova Scotia

Degree: BSc. Convocation: 2011 Year: 2010

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Abstract

Early Carboniferous strata of the Horton Group are excellently exposed in the Cheverie shoreline along the Bay of Fundy, Nova Scotia. The type section of the Tournaisian-aged Cheverie Formation disconformably overlies the Horton Bluff Formation and is overlain by the Macumber Formation of the Windsor Group. The section is part of a depocenter positioned in the Maritimes Basin. Sedimentation was controlled by continental-scale dextral strike-slip faults and thermal subsidence. Field work illustrates the stratigraphic domains of the Cheverie Formation, outlined in both a generalized stratigraphic column and in a set of three detailed subsections. Petrologic work from a suite of samples collected from the section examines details pertaining to lithology, provenance of grains, clasts and fragments, cement, porosity, and small-scale structures. In the outcrop, paleoflow direction and sedimentary structures are analyzed and facies are designated to intervals in the general section. The facies are interpreted as channel, floodplain and abandoned channel deposits. Overall, the Cheverie Formation best represents a meandering fluvial system that was experiencing a strong seasonality with arid to semi-arid conditions. Reactivation of faults in the Maritimes Basin have caused shortening, resulting in deformation of Cheverie Formation strata.

Key Words: Carboniferous, Caliche, Cheverie Formation, Horton Group, Macumber Formation, Maritimes Basin, Meander Fluvial System, Petrography, Stratigraphy

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Acknowledgements

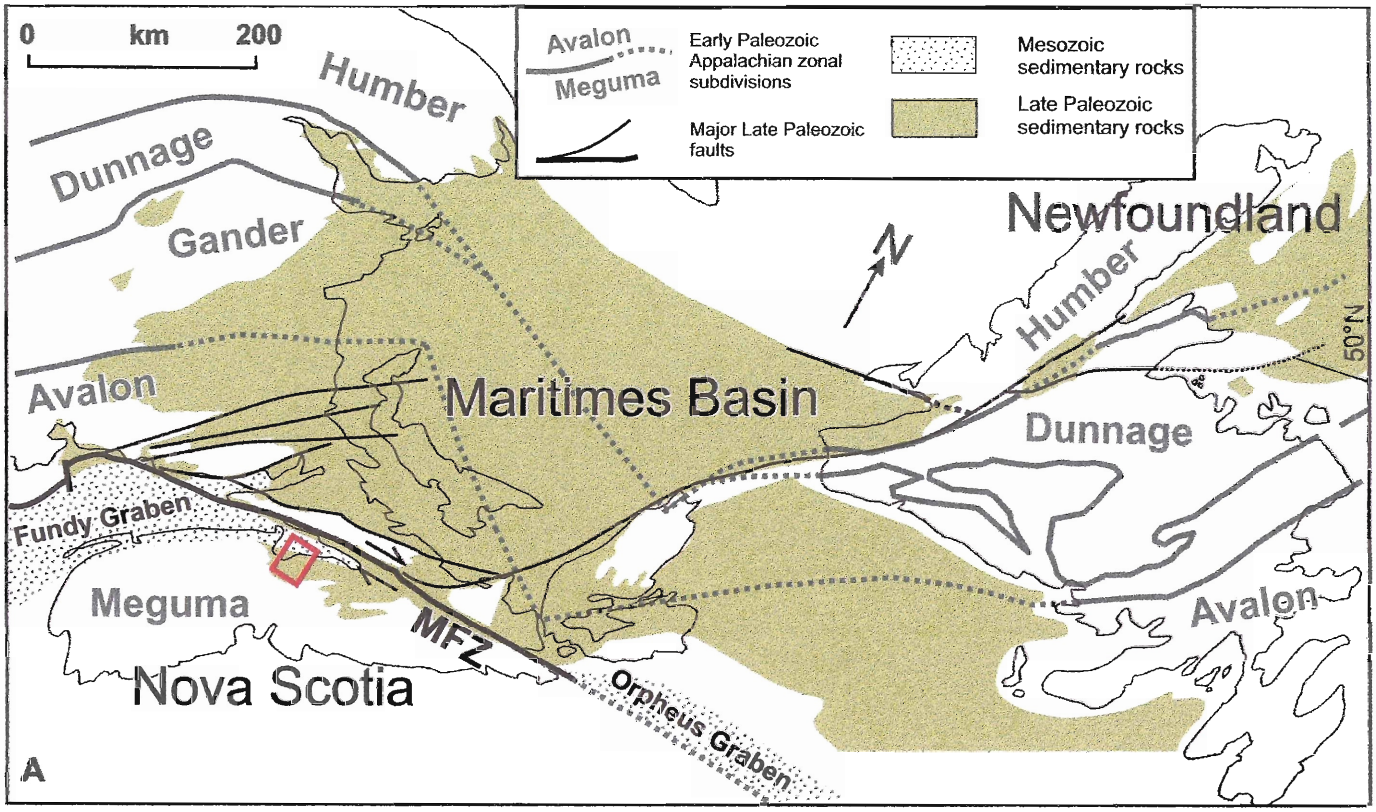
I would firstly like to thank my supervisor John W.F. Waldron for his enthusiasm in the field and bottomless knowledge of all things geological. He has been a great inspiration in every stage of this work. This research was initiated during a summer internship with Dr. Waldron, which was supported by a NSERC USRA. I owe this, and a great amount of my knowledge, to the dedication of my undergraduate professors at Dalhousie University. I would like to recognize Djordje Grujic, Isabelle Coutand, Rebecca Jamieson, Yana Fedortchouk, Grant Wach and Martin Gibling for giving me a strong and enduring foundation in the Earth Sciences. In particular I would like to thank Anne-Marie Ryan for her advice and commitment to teaching. Enrolling in her first year Geology class changed my life. I would like to thank my peers for their support and companionship. It's so rare to be surrounded by so many people who share the same passions. Lastly, I would like to thank my family and J-F.G. for their involvement and for teaching me to always test myself. Thank you!

CHAPTER 1 INTRODUCTION

The Maritimes Basin consists of Upper Paleozoic strata deposited over a period of 120 m.y. Over 12 km of material was laid down in fault-bounded depocenters spanning from southwestern New Brunswick to the continental margin on the eastern Grand Banks, and from the southern Grand Banks to offshore Labrador (Figure 1.1) (Gibling et al. 2008). Gibling et al. (2008) related the origin of the basin to the oblique convergence of Laurussia and Gondwana, due to the closing of the Rheic Ocean during late stages in the formation of the supercontinent Pangea (400 Ma). Rapid sedimentation resulted from uplift and subsidence caused by extension along NE-SW continental-scale strike-slip faults and was enhanced by salt migration and periods of thermally driven subsidence (Gibling et al. 2008). The basin fill is initially Fountain Lake Group, which includes volcaniclastics, flood basalts and intrusive bodies, and the clastic sediments of the Horton Group. The Carboniferous Horton Group was derived from established, adjacent upland terranes of the Atlantic Canadian Appalachians. An interval of marine transgression and regression led to deposition of limestones and evaporites that characterize the Windsor Group during the Viséan. The clastics of the Mabou, Cumberland and Pictou Group succeed the Windsor Group and are Pennsylvanian in age.

1.1 Purpose of Investigation

The division of the Horton Group into the lower, Horton Bluff Formation and the upper, Cheverie Formation was proposed by W.A. Bell (1929). As a result of his work in the summer field seasons of 1912 and 1913 Bell was able to describe the shoreline



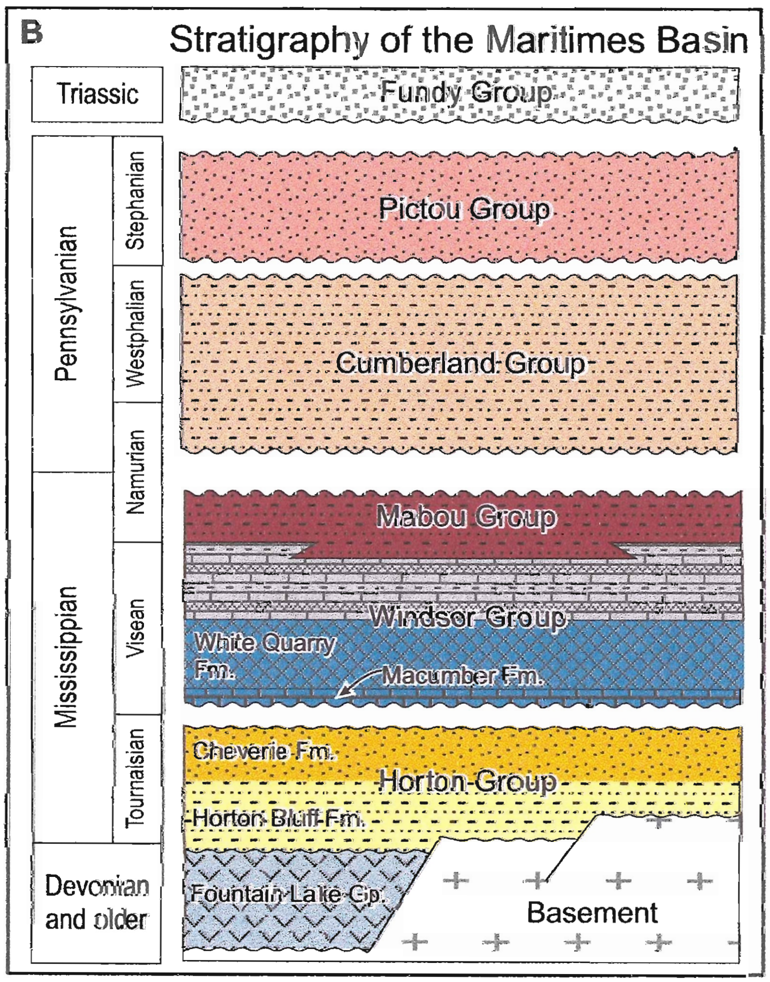


Figure 1.1 (a) Regional map of the Appalachians of Atlantic Canada, showing the major tectonic units and boundaries, modified from Waldron et al. (2007) and Gibling et al. (1995). MFZ = Minas Fault Zone. The red box outlines the study region shown in Figure 1.2 (b) Representation of the Maritimes Basin fill in a simplified stratigraphic succession. Stipple patterns: Clastic sediments. Brick patterns: carbonates. Hatching: evaporites. V-patterns: volcanics

between Cheverie and Summerville, Nova Scotia, as the type section of the Cheverie Formation. Subsequent stratigraphic work at Cheverie Point was completed by Freeman (1970) as part of several descriptions of Cheverie outcrop in his study of upper and basal lithologies in the section and their contact relationships.

My research is intended to provide a better understanding of the conditions at the time of deposition of the upper portion of the Cheverie Formation, at its exposure along the eastern shoreline south of Cheverie Point (Figure 1.2) (Figure 1.3). The work undertaken in this study includes the construction of a general stratigraphic section and the collection of three detailed subsections accompanied by petrographic descriptions. The sections detail sedimentary structures, Vegetation Induced Sedimentary Structures (VISS), paleoflow, and facies changes. Interpretation follows for the various facies including provenance, climate, and environment of deposition.

1.2 Method

Field work was conducted from August to November 2009. Measurement of the Cheverie section was done on the falling tide. This was necessary in order to maximize the time spent at the outcrops and in order to minimize the risk of being caught on wave-cut platforms during the 15 metre Fundy tidal rise. Measurements were taken by a standard measuring tape and Silva compass. The true vertical thicknesses of beds were calculated in the field and recorded at a 1:20 scale. Observations were accompanied by photographs and sketches. Another challenge that was encountered during the field work was interpreting abrupt facies changes that disrupted lateral continuity. The lateral facies changes were studied in some detail in order to trace them across fault block boundaries.

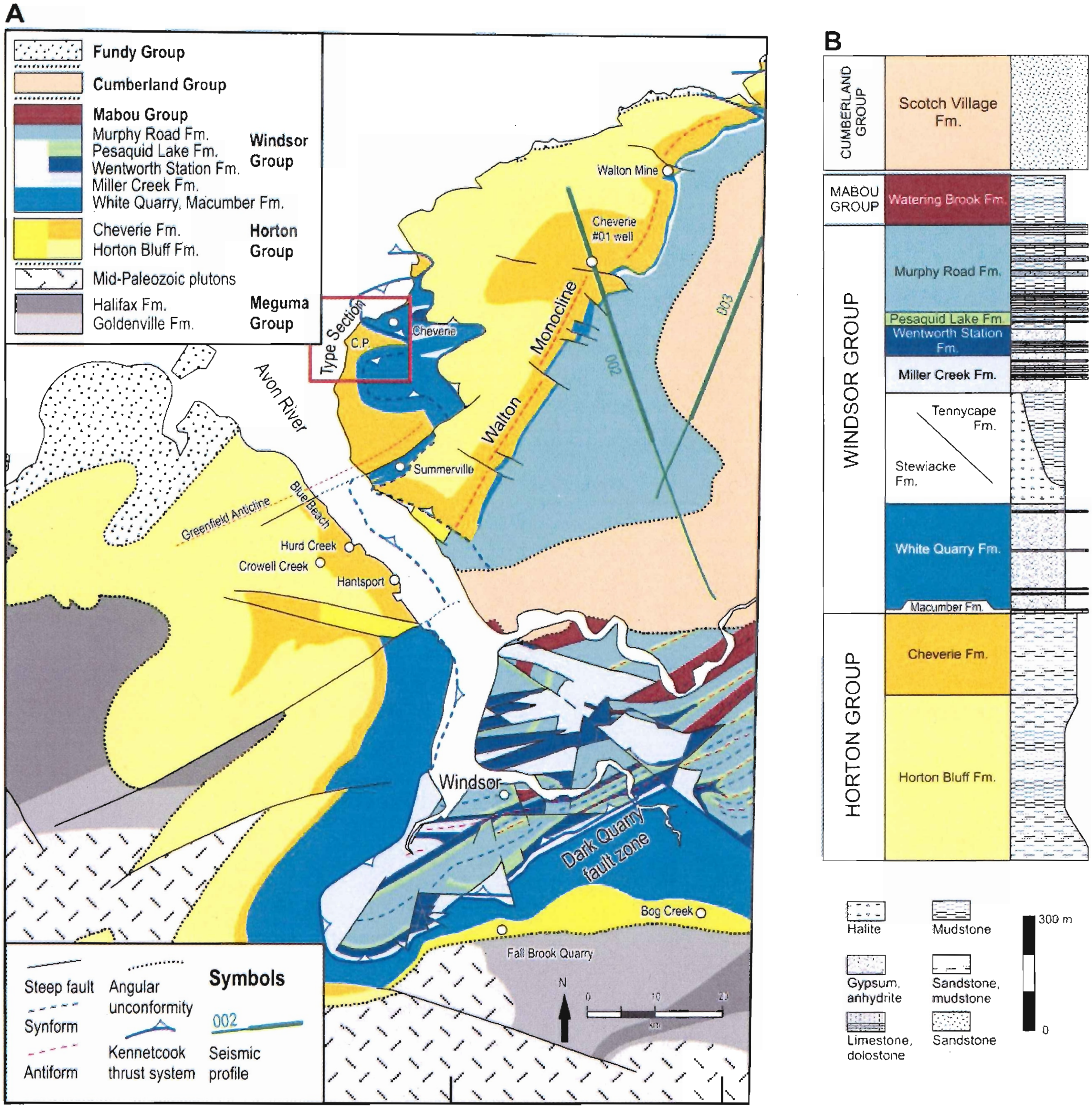
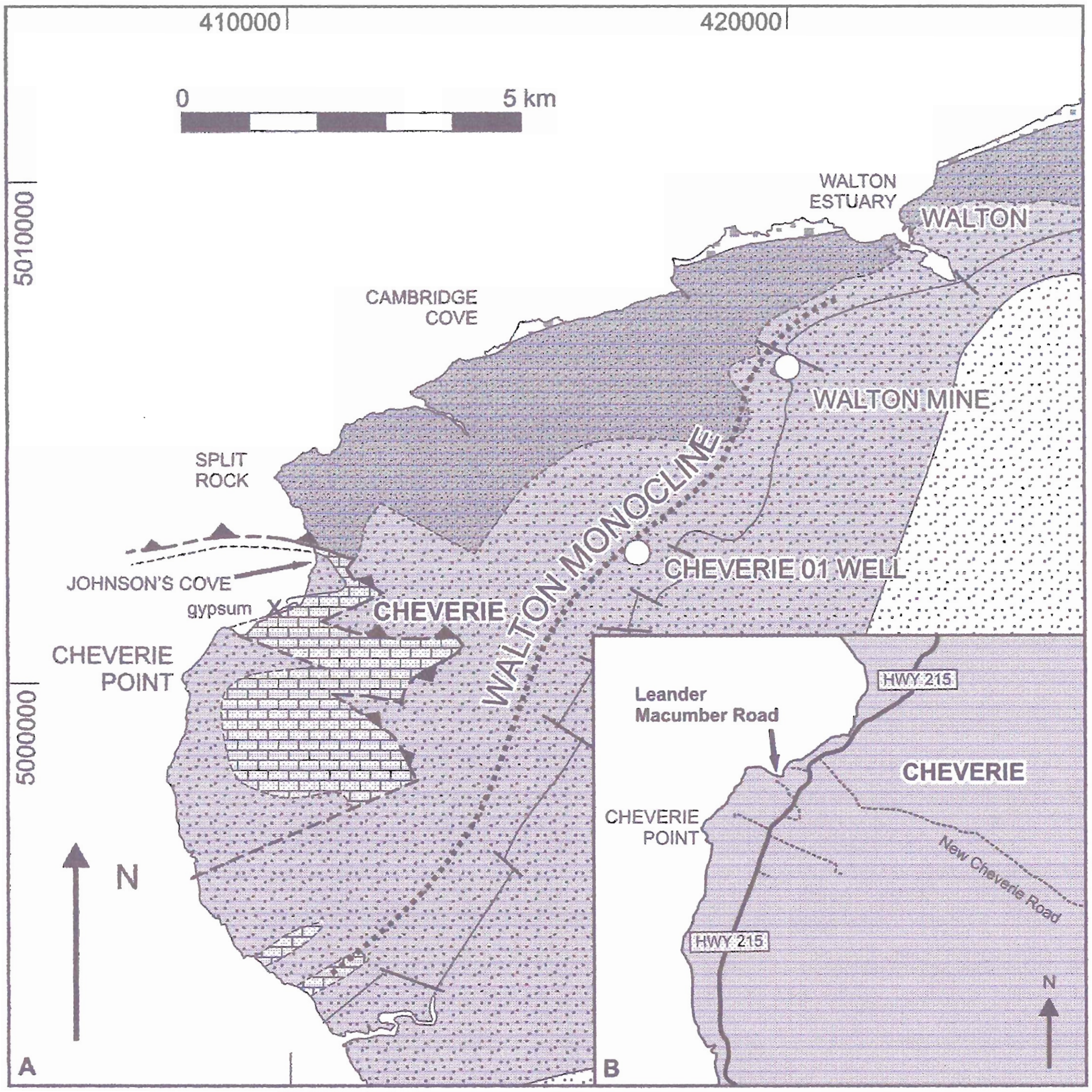


Figure 1.2 (a) Geological map showing part of the Kennetcook Basi around the Avon River and Cheverie region in Hants County, Nova Scotia. The map shows structural data and location of nearby seismic lines 002 and 003. The location of the Cheverie Formation type section is outlined in red. C.P.- Cheverie Point. (b) Simplified stratigraphic column of Devonian to Triassic aged formations within the area. Figure modified from Waldron et al. (2007).



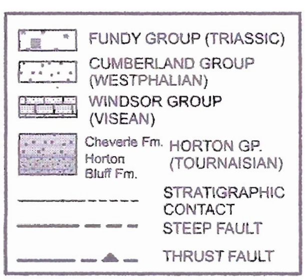


Figure 1.3 (a) Geologic map of the Cheverie coastline modified from Waldron et al. 2007 with information from Weeks 1948; Boyle 1957; Stevenson 1959; Crosby 1962; Ferguson 1983; Moore et al. 2000. Co-ordinates show Universal Transverse Mercator (UTM) grid. (b) Inset map showing the location of Leander Macumber Road and Highway 215 in relation to Cheverie Point.

The region of study is located on the shoreline of the Bay of Fundy at Cheverie, Hants County, Nova Scotia (Figure 1.2). Access to the type section of the Cheverie Formation is from the Leander Macumber Road, which branches off highway 215 (Figure 1.3). This route directly leads to several excellent beach and cliff exposures of Windsor Group lithologies. A 100 m walk from the access point on the western shore reveals a contact between the Windsor Group and Horton Group.

The area of interest is located in the Wolfville map area and corresponds to NTS map sheet 21 H 1. The most recent published geology map was completed by Moore et al. (2000) with the Nova Scotia Department of Natural Resources.

1.3 Stratigraphy

Sedimentary rocks of the Maritimes Basin in the Windsor Area sit unconformably on top of the lower Paleozoic basement rocks of the Meguma terrane. The Horton Group is Late Devonian to Tournaisian in age (Martel and Gibling 1995). The Horton Group and its equivalents span an area ~1000 km long by ~400 km (Sanford and Grant 1990). The Group is best exposed along the shores of the Avon River estuary near Wolfville and Cheverie, Nova Scotia, in wave-cut platforms and cliff sections. The Group was first described by Bell (1929) when he renamed it from its previous designation as the Horton Series. Bell split the Horton Group into a lower, predominately fine-grained Horton Bluff Formation and an upper, coarser-grained Cheverie Formation.

1.3.1 Horton Bluff Formation

The Horton Bluff Formation is formally divided into four distinct members that were first described by Martel and Gibling (1995) (Table 1.1). In addition to naming the

<table>
<tr><th>Bell 1929, 1960</th><th>Worth 1969</th><th>Ferguson 1983
Moore and
Ferguson 1986</th><th>Martel and Gibling
1995</th></tr>
<tr><td>Upper Member
120 m</td><td rowspan="2">Upper Sandstone
120 m</td><td rowspan="2">Upper Member</td><td rowspan="2">Hurd Creek
Member
300 m</td></tr>
<tr><td rowspan="2">Middle Member
(upper portion)
350+ m</td></tr>
<tr><td rowspan="2">Middle Sandstone
(middle shale
facies)
360 m</td><td rowspan="2">Middle Member</td><td rowspan="2">Blue Beach
Member
210+m</td></tr>
<tr><td rowspan="3">Middle Member
(lower portion)
200-650 m</td></tr>
<tr><td>Middle Sandstone
(Curry Brook
sandstone facies)
450+m</td><td rowspan="3">Lower Member</td><td rowspan="2">Curry Brook
Member
120+m</td></tr>
<tr><td rowspan="2">Gaspereau
Sandstone
90 m</td></tr>
<tr><td>Basal Member
180 m</td><td>Harding Brook
Member
100 m</td></tr>
</table>

Table 1.1 Stratigraphic evolution of the Horton Bluff Formation from previous authors, ending with the currently accepted nomenclature of Hurd Creek, Blue Beach, Curry Brook and Harding Brook Members. Offsets indicate differences in Member positioning during correlation, modified from Martel and Gibling (1995).

<table>
<tr><th>Bell 1929, 1960</th><th>Freeman 1970</th><th>Conrod 1987</th><th>This Paper</th></tr>
<tr><td>Upper Cheverie Fm.
180 m</td><td rowspan="2">Cheverie Fm.
(upper and lower
portions)
260 m</td><td></td><td>Cheverie Fm.
(upper portion)
176 m</td></tr>
<tr><td>Lower Cheverie Fm
30 m</td><td>Cheverie Fm.
(lower portion)
100 m</td><td></td></tr>
</table>

Table 1.2 Summary of the stratigraphic thicknesses of the upper and lower portions of the Cheverie Formation from previous authors.

formal members, a stratigraphic log was completed by Martel and Gibling. Braided fluvial sandstones characterize the basal Harding Brook Member (topmost Famennian), which overlies a paleosol derived from Meguma Group rocks. The Curry Brook, Blue Beach and Hurd Creek Members succeed the Harding Brook and are of Tournaisian age. The age ranges aforementioned were deduced from palynomorphs, megaflora and invertebrate fauna found in each interval (Martel and Gibling 1995). The Curry Brook Member is composed of shales and sandstones deposited in deltaic channels and interdistributary lakes. The Blue Beach and Hurd Creek Member shales and sandstones are representative of large, wave-dominated lakes and restricted marine bays (Martel and Gibling 1995).

1.3.2 Cheverie Formation

Maroon-red sandstones, siltstones and conglomerates of the Cheverie Formation overlie the Horton Bluff Formation. The contact has been argued to be both conformable and disconformable. Freeman's (1970) investigation of the type section of the Hurd Creek Member interprets the contact with the Cheverie to be conformable. This is inferred from a gradation of dark micaceous, arenaceous shales upward into arkosic siltstones, sandstones and conglomerates. However, at the Walton Estuary, Fall Brook Quarry, and Crowell Creek (Figures 1.2 and 1.3) Freeman (1970) interpreted a disconformable contact between the black shales of the Horton Bluff and pebble conglomerates of the Cheverie. Moore and Ferguson (1986) have shown the Cheverie Formation to overlap directly on the Meguma Group at highway 22 near exit 5. The field relations support an overall unconformable contact.

The Cheverie contains thick successions of arkosic pebble conglomerate and coarse-grained sandstones. Interbeds of siltstone and shale are common. The lithologies are dominantly red to maroon-brown in colour with few sections of grey sandstones and siltstones (Calder et al. 1998). The Cheverie has a low content of organic material compared to the organic-detritus-rich beds of the Horton Bluff. Thin paleosols, in which some *in situ* trees are preserved, have been documented by Conrod (1987). Bell (1929) and Freeman (1970) have noted there to be carbonate-rich conglomerate layers, described as kunkur beds, which sit above paleosols. In his memoir Bell (1960) lists the flora and fauna found at Cheverie (Table 1.3). Freeman interpreted the section as alluvial braidplain system, while Conrod (1987) and Bell (1929) associate the upper portion with a meandering channel system.

The deposition of the Cheverie marked a change from the underlying Horton Bluff Formation in terms of sediment provenance. The Meguma supergroup that had provided the sediment source of the Horton Bluff Formation became less pronounced as a source in the Cheverie lithologies (Bell 1929). The composition is more arkosic in the Cheverie strata and suggests derivation from the Devonian granitoid rocks of the South Mountain Batholith. Bell (1929) attributed the provenance change to heavy rainfall occurring in the uplands, which caused significant erosion and basin filling. Gibling et al. (2008) interpreted the change to be the result of major uplift, which occurred at the basin's margins.

Providing a complete stratigraphic section of the Cheverie becomes problematic at the outcrop scale. Two informal members, the upper and lower, are exposed at two different localities. The coarser-grained conglomerates and sandstone intervals of the

FAUNAL AND FLORAL LIST OF THE CHEVERIE FORMATION

Plants:

Lepidodendropsis corrugate (Dawson)

Triletes cheveriensis (Bell)

Asterocalamites scrobinculatus (Schlotheim)

Aneimites acadica (Dawson)

Sphenopteris strigosa (Bell)

Adiantites tenuifolius (Goeppert)

Trephyllopteris minor (Jongmans, Gothan and Darrah)

Sphenopteridium macconochiei? (Kidston)

Sphenopteridium sp.

Non-Marine Invertebrates:

Euestheria dawsoni (Jones)

Euestheria belli (Bell)

Asmussia alta (Raymond)

Eoleaia leaiaformis (Raymond)

Eoleaia leauicostata (Raymond)

Leaia sp. (Raymond)

Table 1.3 Faunal and Floral List of the Cheverie Formation from Bell (1960) lower Cheverie are best exposed at Blue Beach, while finer-grained conglomerates, sandstones and siltstones of the upper Cheverie Formation are best exposed north of Cheverie Point. The present study focuses on the stratigraphic section at Cheverie Point as outlined by Bell in his 1929 memoir, regarded as the type section, at least for the upper part of the Formation. Bell (1929) measured the thickness of the upper and lower portions of the Cheverie Formation at Cheverie Point and estimated them to be 180 and 30 metres, respectively (Table 1.2). However, Freeman (1970) was able to correlate a bed in the upper strata at Blue Beach with one in the lower strata at the type section to bring the Cheverie to ~260 metres overall.

1.3.3 Windsor Group

The contact between the Cheverie Formation and the Windsor Group limestone is best exposed at the north end of Leander Macumber Road in Hants County (Figure 1.3), which the Macumber Formation is named after. The terrestrial fluvial sediments of the Cheverie are overlain by thinly laminated muddy limestone of the Macumber Formation type section. The deposit found at the Leander Macumber Road site is approximately 2 metres; elsewhere in the Maritimes Basin the Macumber varies in thickness from 1 to 18 metres thick (Calder et al. 1998). The contact appears to be conformable with the underlying Cheverie sandstones with no differentiation in dip. Freeman (1970) records similar findings at Bog Creek (Figure 1.2) and Johnson's Cove (Figure 1.3). While the contact appears conformable, Martel and Gibling (1995) suggested that a hiatus may exist between the two. Utting et al. (1989) were unable to date the uppermost strata of the Cheverie and Windsor Group because the outcrop did not contain suitable lithologies for palynological samples. Currently there are no age constraints on the strata between the late Tournaisian Cheverie Formation and the Viséan Windsor Group.

At Cheverie the thin Macumber Formation is overlain by a localized thick deposit of a limestone breccia, the Pembroke Breccia. The large, angular limestone clasts originate from the underlying limestone unit and are lithified together with carbonate matrix. The depositional history of the Breccia is under debate. One scenario proposes the lithology as being the product of dissolution and formation collapse, while another suggest that the deposition was synsedimentary (Lavoie et al. 1995). One other possibility suggests that induced brecciation from large-scale fault-propagation folding of Macumber limestone created the Pembroke Breccia (Waldron et al. 2007). The overlying White Quarry Formation of the Windsor Group is seen at the cliff sections at Cheverie (Figure 1.3) as interbedded gypsum and anhydrite with limestone. The limestone interbeds are rich in organic matter and smell of hydrocarbons. They are thinly bedded and highly distorted within the gypsum and anhydrite. The deformation is related to localized thrust zones, which deformed the soft evaporites (Waldron et al. 2010). At surface, anhydrite is partially hydrating to gypsum (Lavoie et al. 1995).

1.4 Structural Setting

Bell's (1929) field work in Windsor-Horton District led him to the conclusion that a massive uplift event had taken place in the source region near the time of the deposition of the Horton Bluff and that the uplift must have been accomplished without destroying the general geographic relations in the basin. The uplift event led to an increase of Carboniferous material into the basin. The absence of regional metamorphism and magmatism during the basin filling period of 60-80 m.y. suggests that progressive extension and subsidence fostered conditions necessary for burial. It is likely that ductile deformation at depth is responsible for the large portion of extension in the Maritimes Basin as it is distinguished by a thinned continental lithosphere (Gibling et al. 2008). Seismic data revealed that the Horton Bluff and Cheverie are accommodated into a half-graben structure interpreted to have formed in a wide-spread dextral transtensional system (Hibbard and Waldron 2009).

Blue Beach

The Greenfield anticline (Figure 1.2) affects the strata across the Avon River Estuary at Blue Beach and includes the Blue Beach Fault which has thrust the Upper Middle Member of the Horton Bluff northeastward, over the Lower Cheverie Formation. Freeman (1970) postulated that the displacement along the Blue Beach fault is approximately 150 m. Smaller faults can be seen in the section, but commonly have a throw of less than one metre.

Cheverie Area

Strata at the Cheverie Formation type section are relatively undeformed with gently dipping beds at 10-20 degrees, which is in contrast to the Cheverie strata at Cambridge Cove and Johnson's Cove. In these areas the Cheverie Formation is part of a highly deformed succession of tightly folded, overturned strata (Figure 1.3). The strata in the wave-cut platforms at Cheverie Point have been displaced along fault blocks trending SW-NE. When they were encountered along the shoreline in this study, the throw between the blocks was generally less than 10 m, recording a dextral-sense of offset.

Fault-Propagation Fold

Near the top of the section at Cheverie, a blind fault has both thrusted and folded limestone strata of the Macumber Formation (Figure 1.4a). The blind thrust has offset the strata by approximately 0.5 m to the southeast. A stereographic projection done by Waldron et al. (2010) plotted the fold axis and slickenline orientation on the fault plane (Figure 1.4b), suggesting that folding and faulting occurred synonymously. Waldron et al. (2010) identified the structure as a fault-propagation fold, which recorded southeastward transport.

Seismic Images

Waldron et al. (2010) have interpreted migrated two-dimensional seismic reflection data, provided by Devon Energy Ltd., for the Cheverie area. Lines 002 and 003 (Figures 1.5 and 1.6) show the subsurface geometry near the type section. By following the main reflectors, map inferences, and well data, Waldron et al. (2010) were able to distinguish between the Meguma basement, Horton Group, Windsor Group, and the Scotch Village Formation of the Cumberland Group. For clarity, the Horton Group has been further divided in this paper to show the extent of the Cheverie Formation. This was accomplished by extrapolating the lithologic intervals from the Cheverie #01 well (which intersects Line 002) along a strong seismic reflector in the seismic profiles.

Inversion Structures

In Line 003 (Figure 1.6) there are several faulted areas extending through the Meguma-Horton Bluff contact. Many of these structures record a reverse-sense of motion and do not propagate far into the Horton Group. Waldron et al. (2010) has identified them to be inverted normal faults resulting from shortening on ENE-WSW trending faults. Inversion of the faults took place prior to the deposition of the Windsor Group in a half

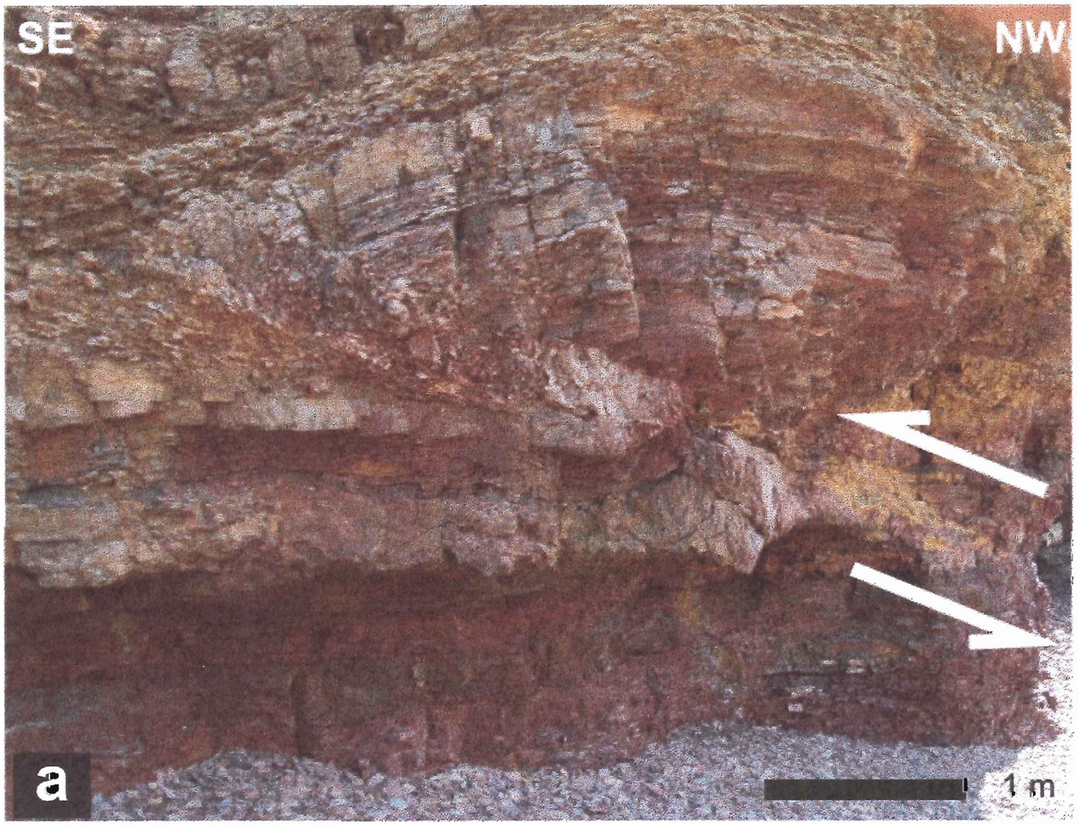
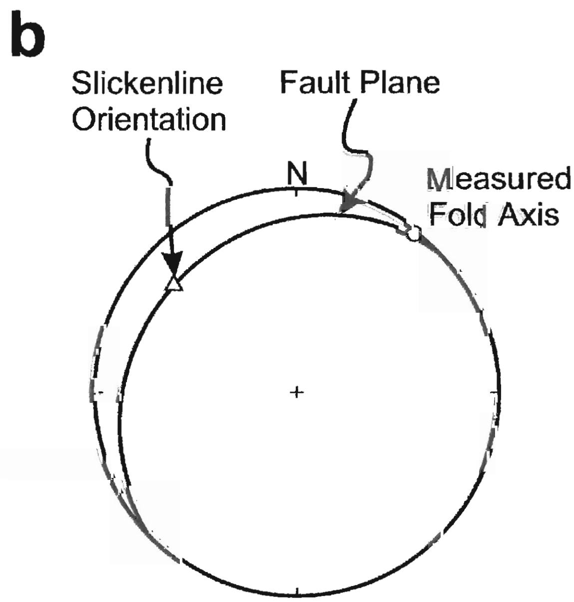


Figure 1.4

(a.) Fault-propagation fold at Cheverie Point in the Macumber Formation limestone following a blind fault. Sense of movement shown by arrows. Waldron et al. (2010)

(b.) Equal projection stereonet of the fault-propagation fold in [a.]. Fold axis and slickenline data plot on the fault plane. Waldron et al. (2010).



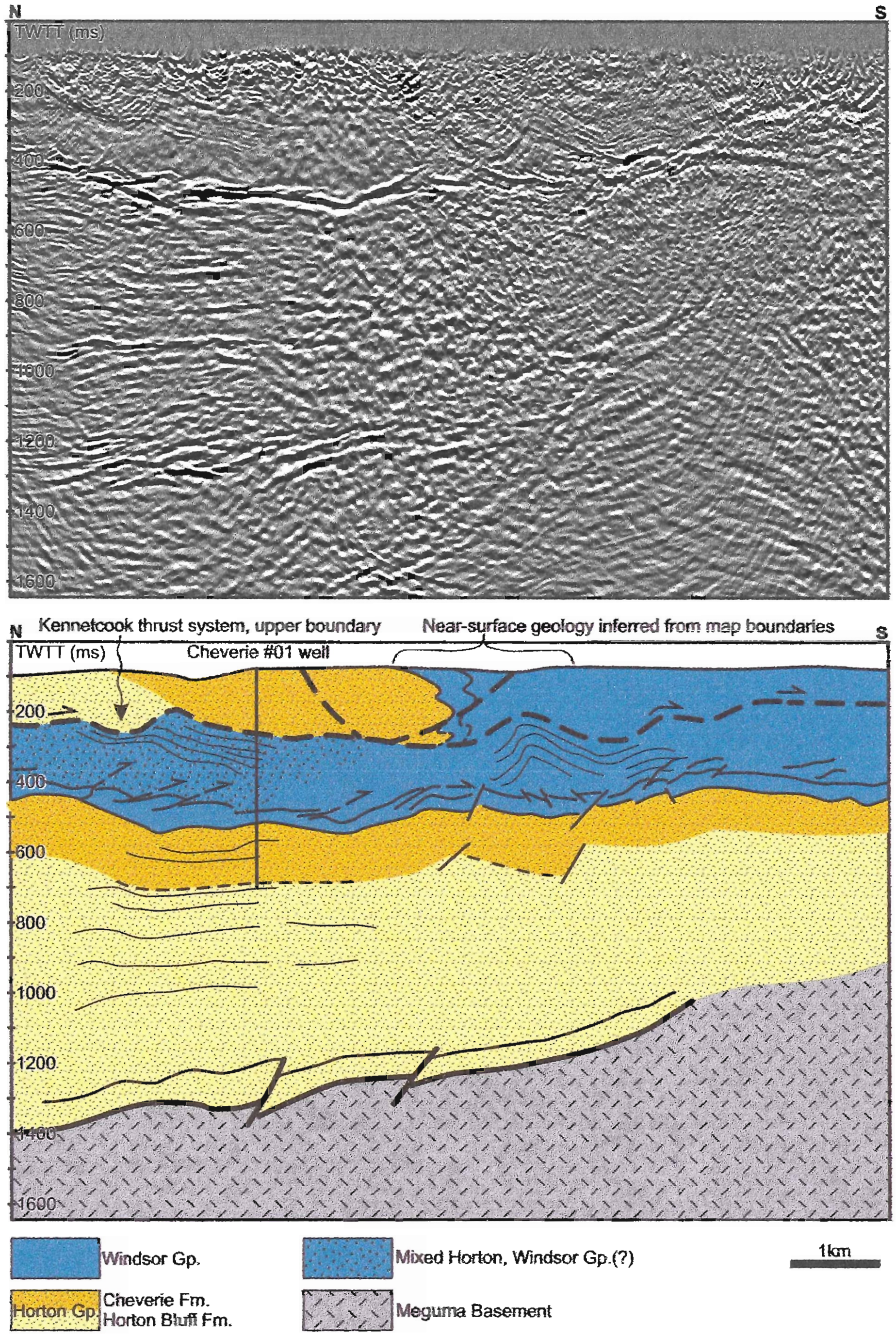


Figure 1.5 Seismic profile of Line 002 from Figure 1.2. Subsurface geology interpreted by Waldron et al. (2010). Kennetcook Thrust Upper Boundary shown as well as the location of the Cheverie #01 well. Seismic courtesy of Devon Energy Ltd. Modified from Waldron et al. (2010).

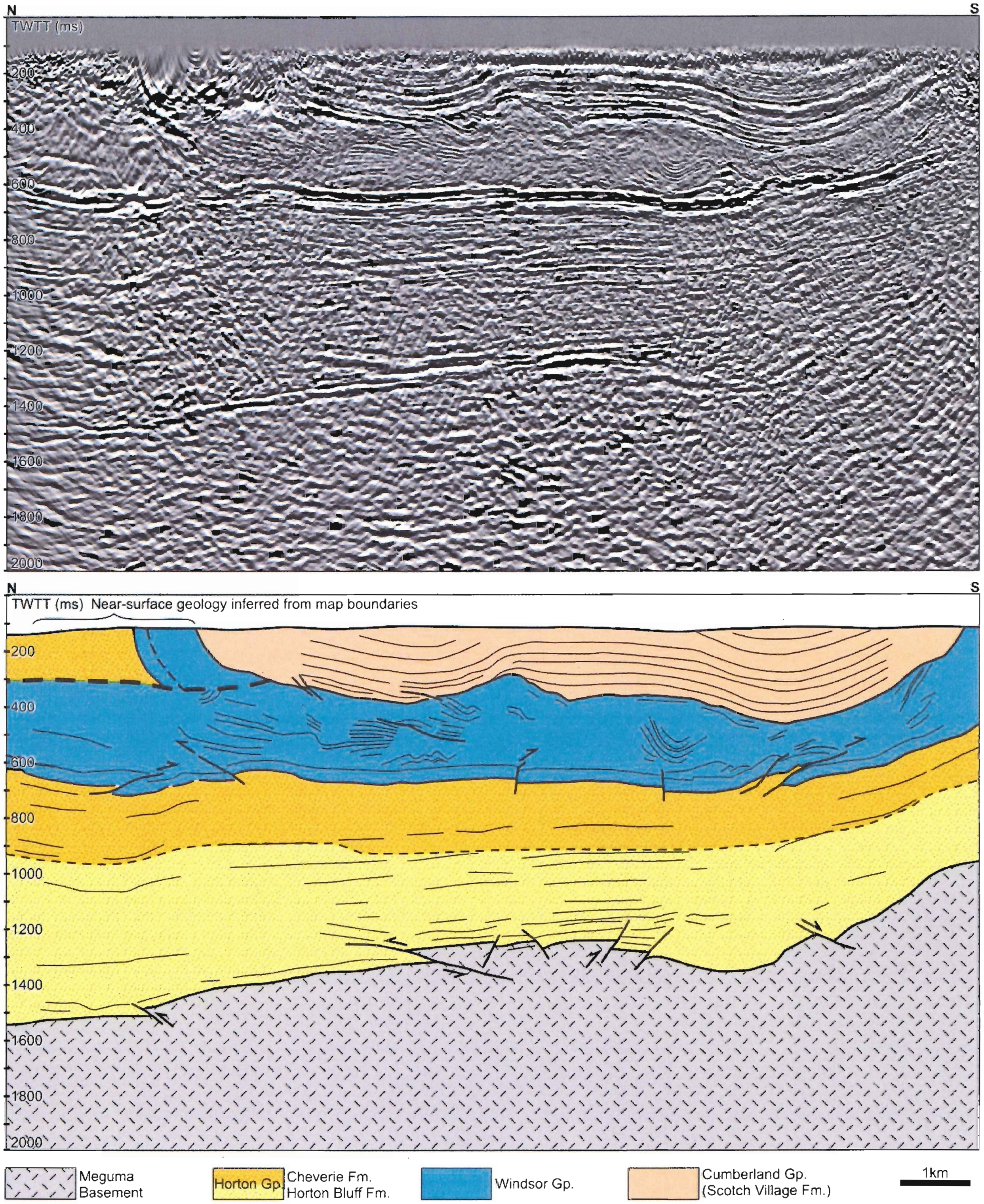


Figure 1.6 Seismic profile of Line 003 from Figure 1.2. Subsurface geology interpreted by Waldron et al. (2010). Kennetcook Thrust Upper Boundary shown as a thick dashed line. Seismic courtesy of Devon Energy Ltd. Modified from Waldron et al. (2010).

graben that was undergoing the effects of E-W dextral shear (Waldron et al. 2010, Gibling et al. 2008).

Kennetcook Thrust System

In the Kennetcook Basin (Figure 1.2) deformed lithologies located at the near-surface (Moore and Ferguson 1986) are underlain by sub-planar reflectors. At depth the seismic profiles can be used to map the upper boundary of the Kennetcook Thrust System through the Windsor Group, which is shown to be a sub-horizontal décollement surface (Waldron et al. 2010). The term Kennetcook Thrust was first applied in a tectonic map of Nova Scotia by Keppie (1982), but has since been recognized by Boehner (1990), and Moore et al. (2000) and was then designated by Waldron et al. (2010) as the Kennetcook Thrust System (Figure 1.2). In Line 002 and 003 Waldron et al. (2010) matched the surface geology to the underlying reflectors and found a repetition of Horton Group strata, which they attributed to the Kennetcook Thrust System. They proposed that allochthonous sheets of sedimentary rocks were thrust above younger Windsor Group evaporites.

CHAPTER 2 FIELD DESCRIPTIONS

The primary goal of the field work was to construct a stratigraphic column representing the strata of the Cheverie Formation type section. This was completed during the summer field season by measuring the lithologies by tape and compass and converting the intervals to true thickness. Figure 2.1 outlines the general stratigraphy in the Cheverie Formation along the type section shoreline and includes the locations of the three detailed subsections. The three subsections were chosen to represent strata at the base, middle and top of the formation. A series of fault blocks dominate the upper portion of the section and displaces the units by several metres horizontally (Figure 2.2). Correlation between specific bedding surfaces reduced the amount of repetition in the section.

2.1 General Section- 0-176m (Figure 2.1)

Measurements from Block A and B of subsection III along with the measurements taken at the bottom of the formation yield a total thickness of 176 m for the Cheverie Formation type section. The bottom portion of the section contains a thick sequence of crossbedded, very coarse-grained sandstones and pebble conglomerates between 0 and 30 m. At 30 m, the are strata are characterized by fining upward sequences of very coarse to fine-grained sandstone, interbedded with shale (termed "paleosol" in Figure 2.1), which repeats until 152 m. At the top of the section, near 152 m, the sandstones become coarser-grained and display fining upward sequences, which are thinner than observed in the middle portion. Carbonate nodules and conglomerate appear here as well. Fossil trees can be found at different intervals throughout the section.

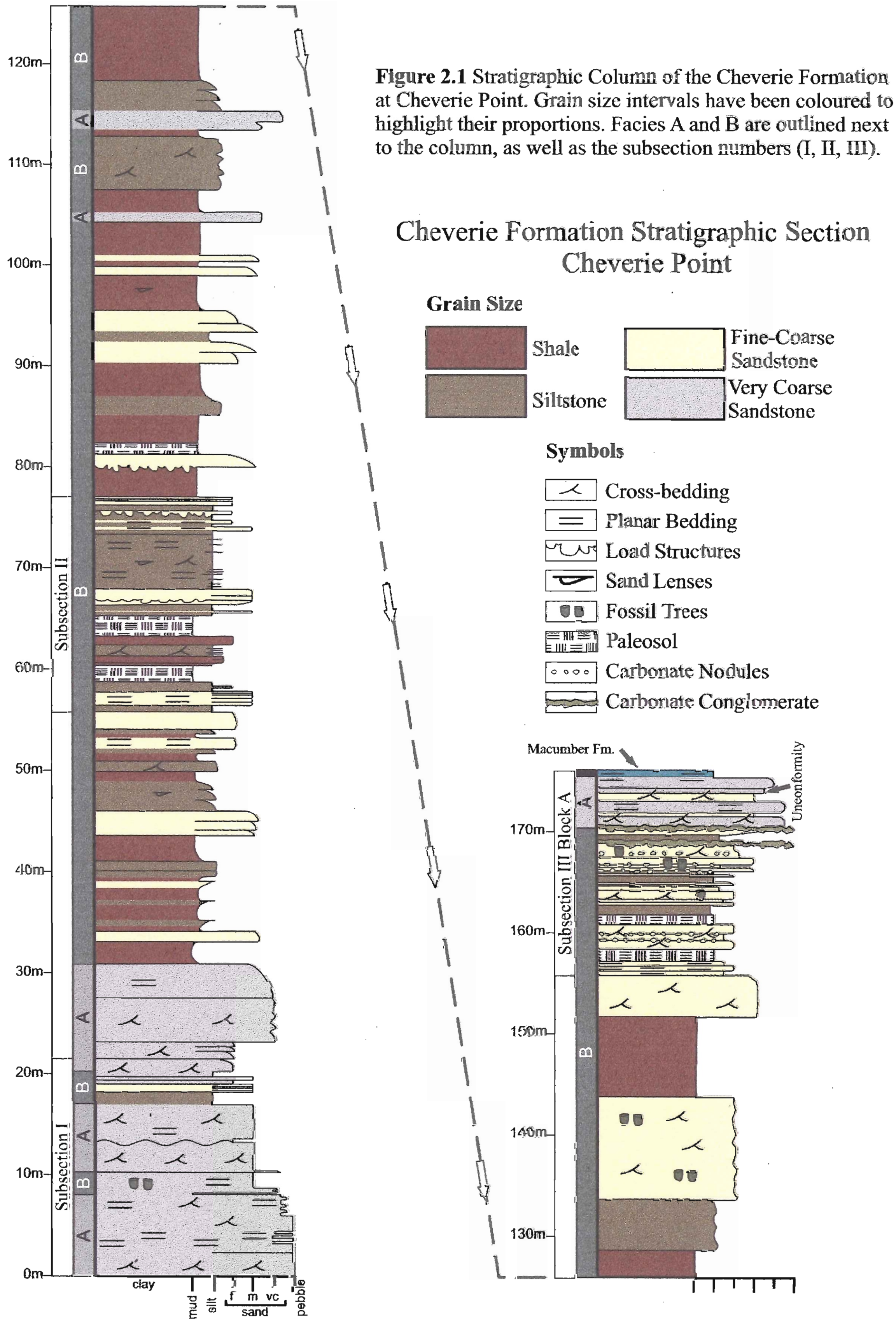


Figure 2.1 Stratigraphic Column of the Cheverie Formation at Cheverie Point. Grain size intervals have been coloured to highlight their proportions. Facies A and B are outlined next to the column, as well as the subsection numbers (I, II, III).

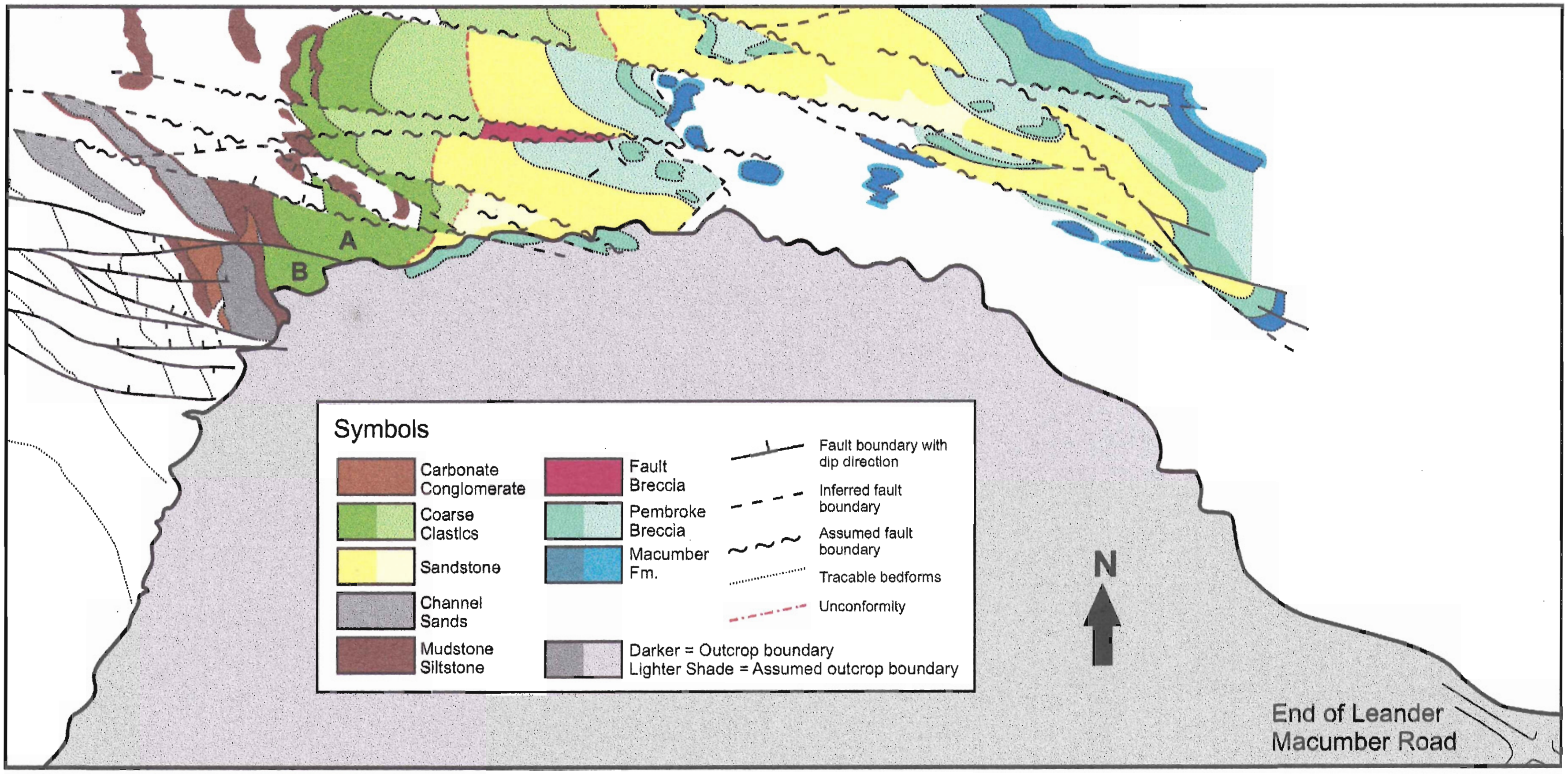


Figure 2.2 Structural map showing the location of fault blocks [A] and [B], and the unconformity from Subsection III. Leander Macumber Road ends east of the diagram. Scale is 1:20,000. Data provided by John W.F. Waldron.

2.2 Subsection I- 0-21m (Figure 2.3)

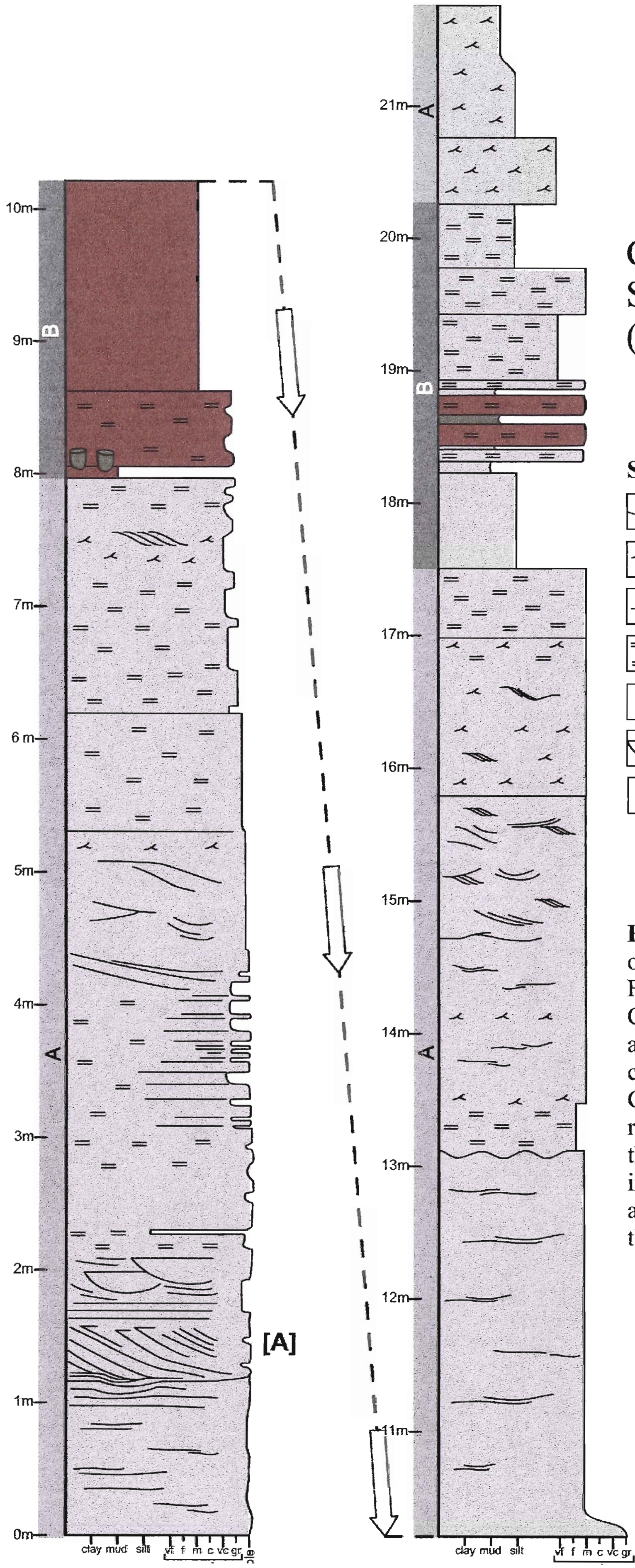
The lowermost beds of the type section are predominantly pebble conglomerates and coarse-grained sandstones. These sandstones and conglomerates are grey in colour and are largely composed of subangular quartz grains. The base of the subsection displays large-scale trough crossbedding and scouring surfaces of up to 1 m in length. At 8 m and 18.5 m there are maroon siltstones and medium grained sandstones, which at 8m contain a fossil tree horizon. The granule and pebble conglomerates are generally poorly sorted with the exception of one interval between 10.3 and 13 m, which consists of very well sorted quartz pebbles. The top of subsection I has planar and cross-bedded grey siltstone and sandstone.

2.3 Subsection II- 57-76m (Figure 2.4)

A mixture of maroon and grey beds is common in subsection II and is characterized by siltstones, medium-grained sandstones and mudstones. Thick successions of maroon mudstones contain carbonate material and have very little internal structure, but a distinct fracturing system was observed. Curved, bowl-shaped lower boundaries are present in medium grained-cross-bedded sandstone, which run continuously along the cliff face. The sandstones are underlain by maroon siltstone. The subsection generally displays planar bedding between the massive mudstone intervals. Crossbedding is observed in medium grained sandstones.

2.4 Subsection III- 157-176m (Figure 2.5)

The bottom of subsection III alternates between siltstone and medium-grained maroon sandstone. Three fossil tree horizons were observed above 164 m, which have

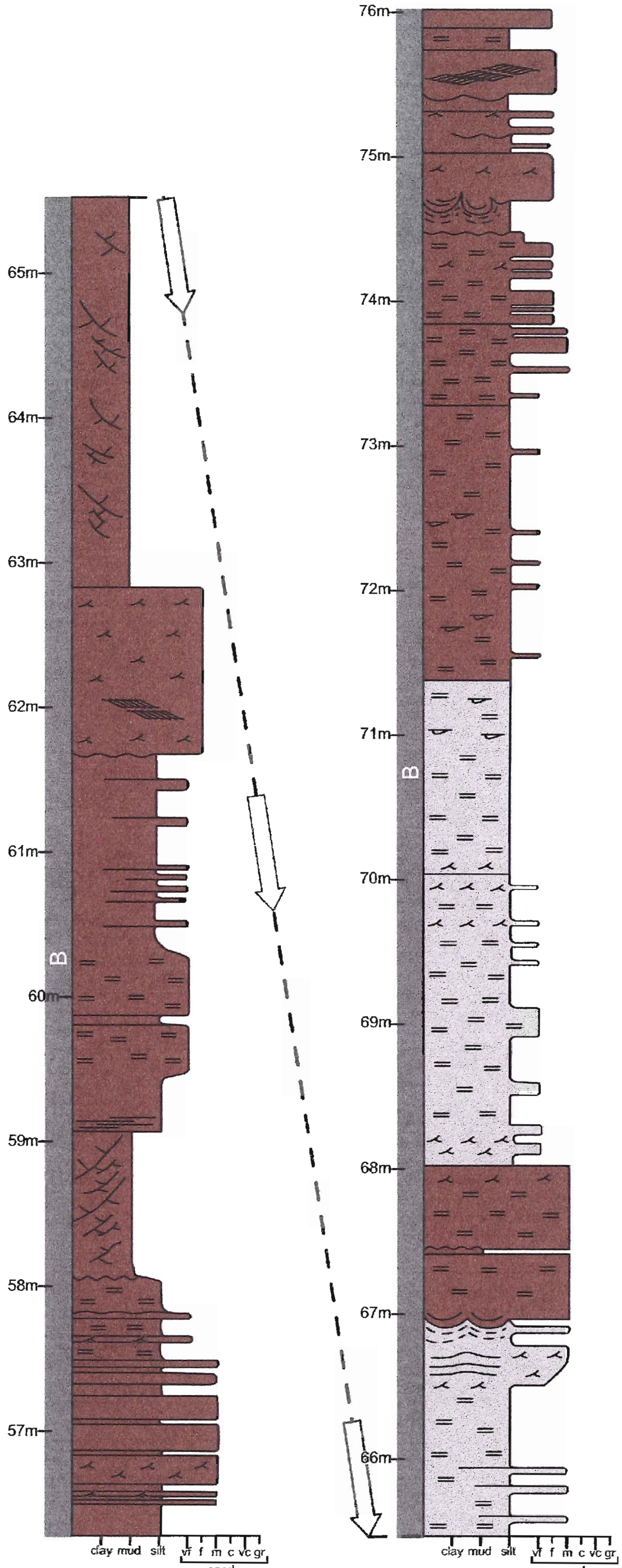


Cheverie Formation Subsection I (0-22m)

Symbols

Wavy Bedding
Cross Bedding
Climbing Ripples
Planar Bedding
[A] Antidune
Channel Body
Fossil Tree Interval

Figure 2.3 Detailed section of the lower Cheverie Formation at Cheverie Point. Coarse-grained sandstones and pebbly conglomerates characterize this subsection. Grey and maroon sections represent colours recorded in the field descriptions. The intervals containing Facies A and B are indicated next to the columns.



Cheverie Formation Subsection II (56-76m)

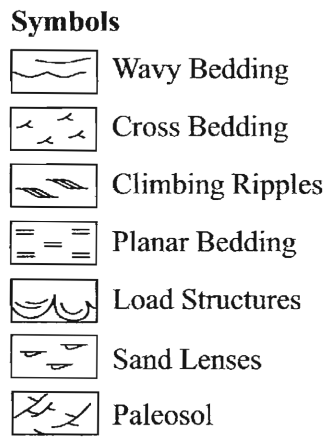
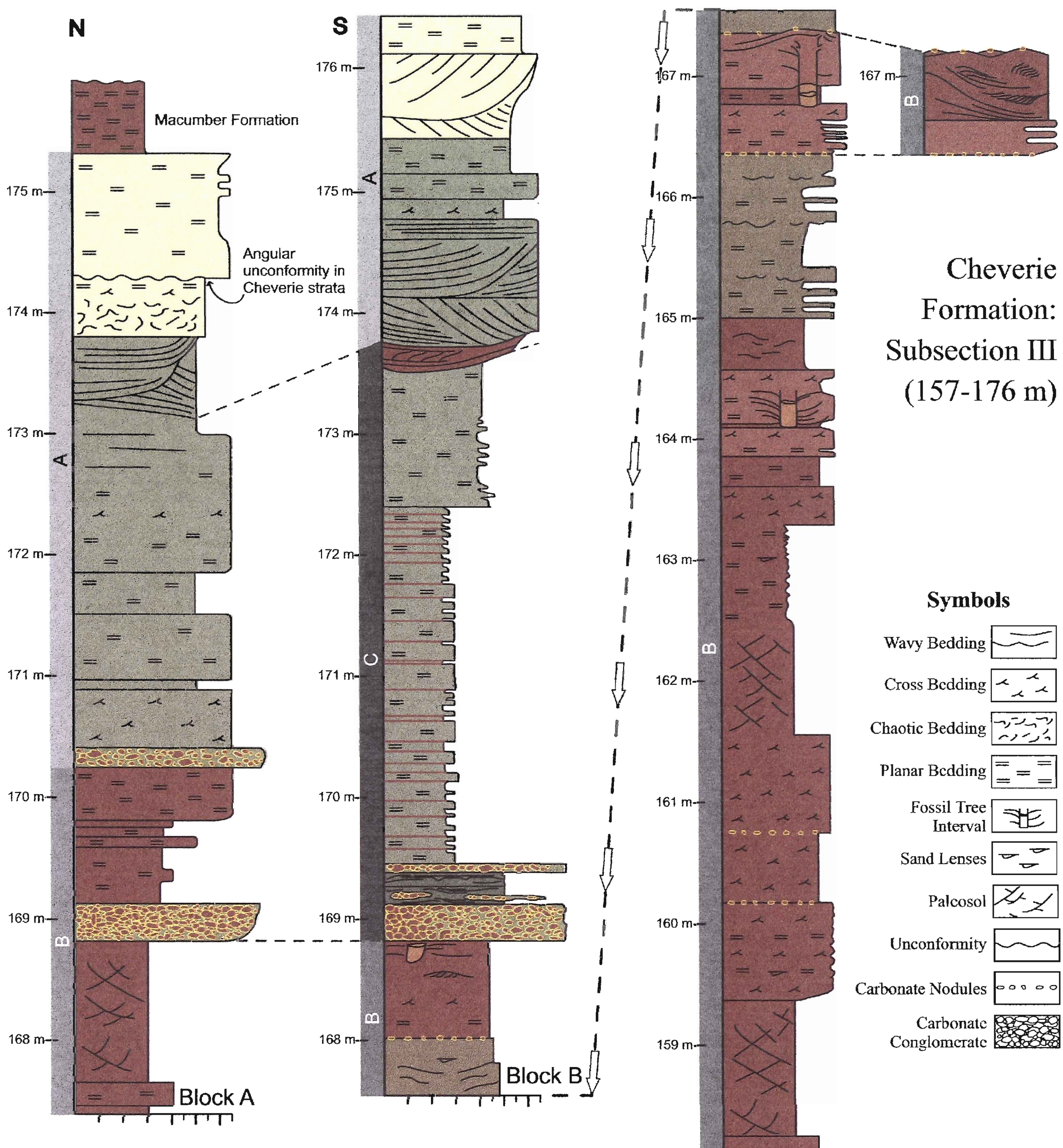


Figure 2.4 Detailed section of the middle Cheverie Formation. Medium-grained sandstone, siltstone and mudstone are the main lithologies. Grey and maroon sections represent colours recorded in the field descriptions. The strata coincide with Facies B, which is indicated next to the columns.



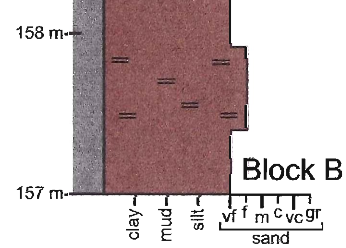


Figure 2.5 Subsection of the uppermost Cheverie Fm. Lateral variations are shown between fault blocks; A and B. Block A also illustrates the Windsor-Cheverie unconformity and Macumber Fm. contact. Block B shows carbonate nodules, carbonate conglomerate, fossil tree horizons, large trough cross-beds, maroon mudstone intervals, and large truncating feature (167 m). Maroons, greys and browns represent the colours recorded in the field descriptions. Solid lines represent lithology boundaries and distinct bedding planes.

trees preserved in the upright position. They can be traced into maroon, very fine-grained sandstones where they terminate. Trees were entombed within medium-grained sandstone beds. A large, half metre deep, cross-cutting feature is observed truncating older successions of maroon beds.

Carbonate nodules can be found *in situ* and as clasts in conglomerates. Nodules occur at the top of siltstone and very-fine-grained sandstone units along with desiccation cracks. Up-section from the carbonate nodules and maroon sandstones, at 169 and 170.3 m, are thick carbonate conglomerates. The clast size generally reduces to the south and the unit pinches out towards the cliff face.

Interbedded with the caliche conglomerate are thinly bedded organic-rich siltstones and mudstones. They are dark grey in colour and contain large amounts of plant debris. Between Block B and Block A in subsection III these grey units disappear. It is likely that they pinch out to the north.

In Block A coarse-grained to granule conglomerates occur at 170 m to 174 m where they are succeeded by into calcareous sandstones and pebble conglomerates. These sands occur either as chaotically bedded intervals or sub-planar beds. An angular unconformity was observed in the calcareous sands in the uppermost portion of the Cheverie Formation in Block A (Figure2.6). The unconformity is exposed on the beach less than 1 m below the contact of the Macumber Formation (basal Windsor Group) and has sulfide enrichment above this surface. The contact separates very coarse-grained sandstone from pebble conglomerate. Groups of bivalve casts were recognized on the tops of two separate beds near 175 m in the calcareous sandstones (Figure 2.7).

Figure 2.6 Unconformity near the top of the Cheverie Formation. Angular discordance between sandstone beds with sulfide enrichment occurring for approximately 5 cm above the contact. The unconformity is approximately 1m below the Macumber Formation limestone.

CHAPTER 3 INTERPRETATIONS

Three different facies can be recognized in the section: Facies A, B and C. These are interpreted as channel and overbank deposits, floodplain, and abandoned channel strata. The facies boundaries are outlined in the stratigraphic type section (Figure 2.1).

3.1 Facies A

The lower boundary of Facies A is defined by a layer of massive pebbly conglomerate which is overlain by moderately well-sorted crossbedded sandstone. The type section of the Cheverie Formation has two thick intervals of Facies A: one that defines the base of the measured section at Cheverie Point and the other, which occurs below the Cheverie-Macumber Contact. Two minor intervals of Facies A occur within the middle of the section, near 105 m and 114 m.

3.1.1 Sedimentary Structures

Conglomerates

The lowermost portion of the measured section consists of coarsely-grained grey strata (Figure 2.3). Distinct bedforms are hard to locate in the lowest package of pebbly conglomerates. A few planar surfaces and troughs are visible when the grain distribution is closely examined, but for the most part, the conglomerate is structureless. The composition is mainly quartz granules and pebbles that are densely packed in a grey-green sandy matrix, giving the outcrop its colour. The boundary between this package and the overlying granular conglomerate is wavy.

Cross-stratified siliciclastics

Along the cliff face at the bottom of the section there are numerous occurrences of cross-cutting and planar strata above the pebbly conglomerate. Continuous outcrop in the cliff face allows observation of the lateral continuity of the features (Figure 3.1). Several complex flow structures are preserved within the granule and pebble conglomerates and in some instances whole bedforms could be traced for several metres. At 1.5 m the outcrop displays an excellent example of the cross-cutting relationship between sequences of planar bedding and inclined strata. The boundaries of individual features are defined by the strata that truncate against younger beds. In the vertical sequence thick sets of semi-planar beds cut across the tops of the down-dipping strata and thicken laterally into curved structures. These are subsequently crosscut by a new sequence of down-cutting beds (Figure 3.1).

In Block A between 173 and 173.8 m is a section of very coarse-grained sandstones to pebbly conglomerates showing large trough cross-stratification. On the curved surfaces there are sets of small normal faults with orientations in two directions, 161-02 and 150-11, and current lineations trending approximately north. Kink bands were also observed within the strata and have an orientation of 350-13. This section is coeval with a package of thicker clastics in Block B at 173.8 m. Here, grey cross-stratified deposits overlie fine-grained, red sandstone that conforms to the curve of the bottom bed.

The pebble cross-bedded conglomerates are composed of carbonate clasts, quartz and metasediment clasts. The clasts are sub-rounded and range in size from very coarse sand to pebbles. The conglomerate continues until 175 m where it grades into planar grey beds of medium sandstones and granule conglomerates. Another cycle of cross-stratified beds resumes at 175.4 to 176.2 m and ends with coarse-grained laminated sandstone.

Figure 3.1 Lower section of the Cheverie Formation showing large continuous sand packages and cross-cutting features.

Calcareous sandstone

Above the trough cross-bedded sandstones in Block A is a unit of chaotically bedded carbonate-cemented sandstones (Figure 3.2a). The wave-cut platform has exposed a section of steeply dipping strata truncating the chaotic calcareous sandstones at 174 m (Figure 2.5 and 3.2b). This sandstone grades into a more ordered calcareous sandstone unit exhibiting well defined linguoid ripple marks with a SW paleocurrent (Figure 3.2c).

Well sorted sandstone

The intervals from 3 to 8 m, 10 to 18 m and 19 to 22 m (Figure 2.3) contain large packages of well sorted to very well sorted, light grey medium-grained sandstone. Small-scale cross-sets 5 to 20 cm high are prominent and are often accentuated against the pale grains by thin, red oxidized laminae. Successive sets of cross-laminations are obliquely stacked in the sandstone packages and are interpreted to be climbing ripples (Figure 3.3). Where the laminations are wavy to planar they become difficult to observe in the very well sorted sand.

Antidune

A large-scale structure in very-coarse sandstone at 2 m displays inclined bedding with an opposite sense of dip in relation to the surrounding strata (Figure 3.4). The bedding of the structure diverges westward above a planar base and develops a primary incline of approximately 15°. For nearly 4 m the beds continue to thicken westward before they are crosscut by the base of a sweeping unit of very coarse sand. The truncated beds define a structural crest, as well as a down-dipping slope on the far west side, which expands the feature for an additional metre in length. Overall this feature reaches

a.) Chaotic and ordered carbonate sandstone beds of sub-section III occurring in the topmost section of Block A. The top portion is also defined by linguoid ripple marks. Hammer = 30 cm

b.) Possible slump surface (centre of photograph) in the carbonate sandstone beds. With ordered beds above and chaotic beds below. Measuring tape = 1m

c.) Foreset of channel trough in sub-section III showing current lineations in very coarse grained carbonate sandstone.

Figure 3.2

Structures found in the carbonate sandstone beds in subsection III.

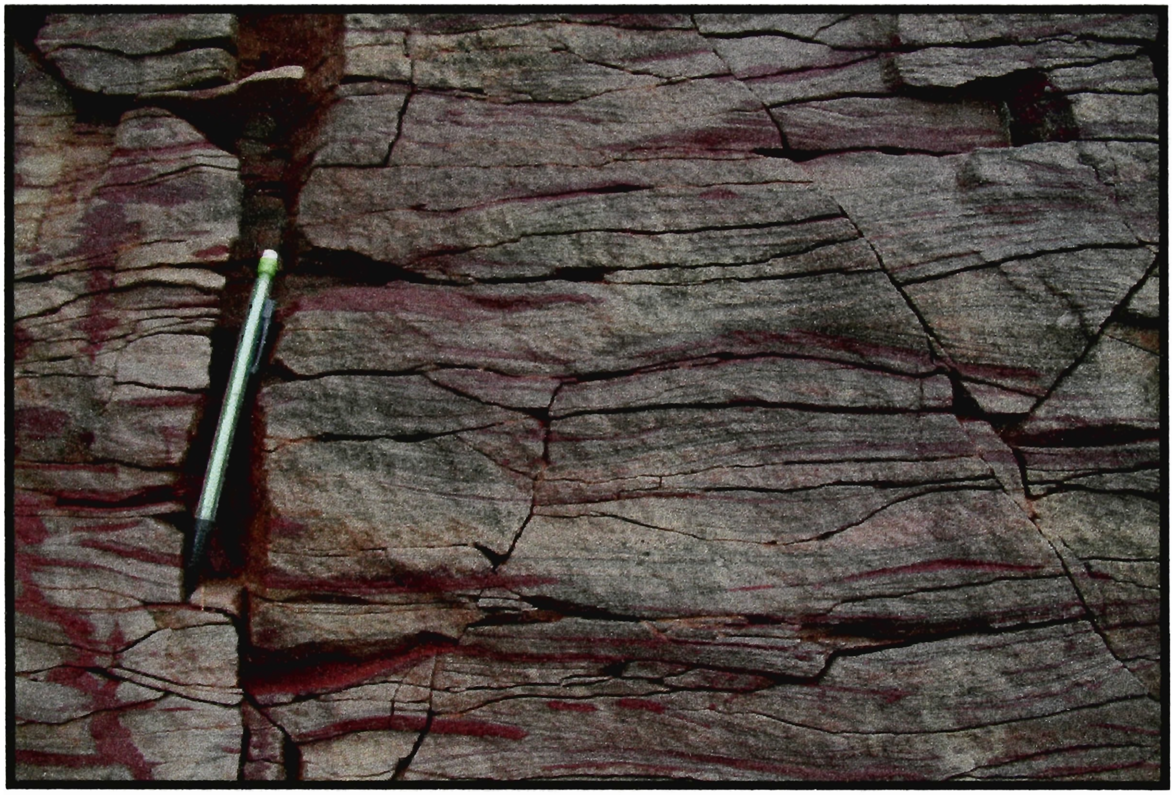


Figure 3.3 Elongated ripples in well sorted sandstone, highlighted by oxidation. Pencil = 14 cm.

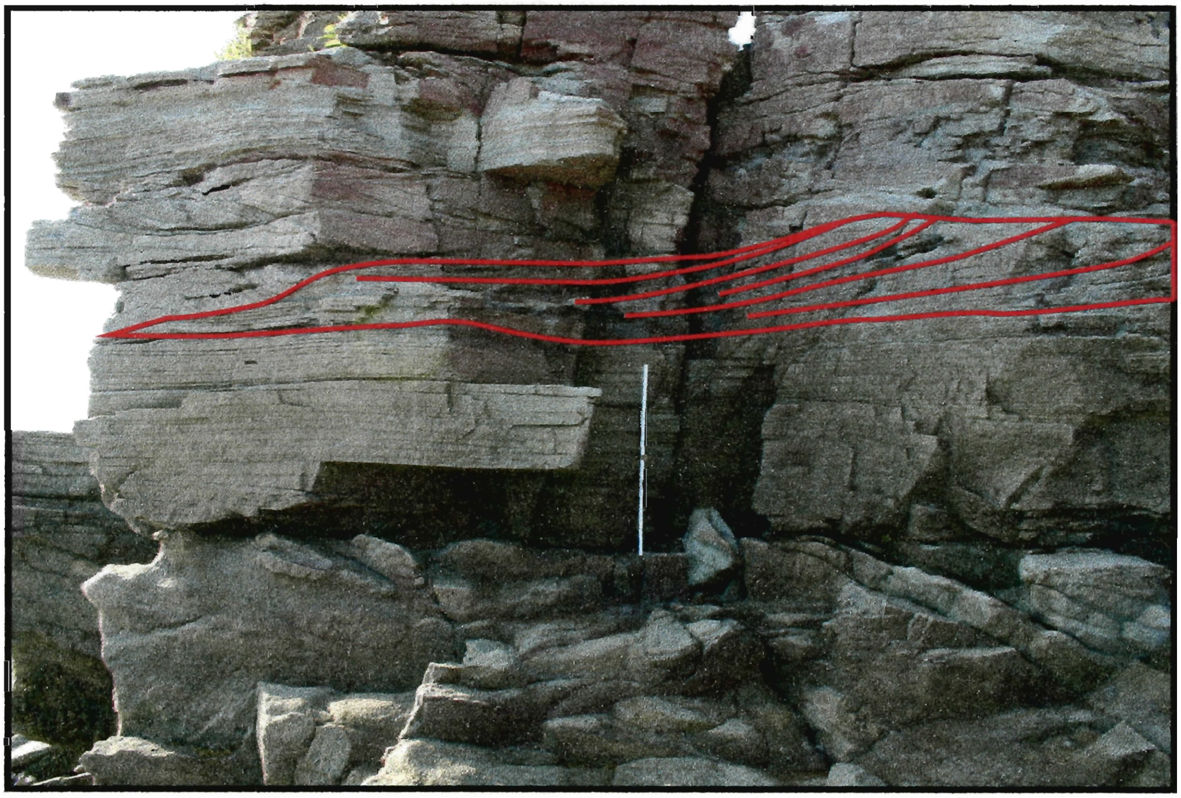


Figure 3.4 Antidune structure in the lower portion of the Cheverie Type Section. Indicating high flow strength conditions. Metre stick for scale. Photo by M.R. Gibling.

approximately 0.5 m in height. It is interpreted to be an antidune because of its size, coarse-grained nature and bedding orientation.

3.2 Facies B

The Cheverie Formation type section is dominated by thick successions of maroon mudstones, siltstones, and sandstones, which make up Facies B. The bedforms are mostly planar or display small-scale cross bedding in sediment that is generally well sorted. Carbonate nodules and fossilized trees are also common features throughout Facies B.

3.2.1 Sedimentary Structures

Maroon mudstone beds

The middle section of the Cheverie is largely characterized by 2 m intervals of massive, maroon mudstone and siltstone (Figure 2.4 & 2.5). These mudstone and siltstone packages are located at 58, 63 158, 162 and 168 m in the section. Although they do not display evidence of primary structures, there is a distinct penetrating fracture pattern (Figure 3.5a). These fractures curve and interconnect with one another, propagating throughout the unit. In some instances calcareous material has accumulated in the pore space. These intervals are interpreted as horizons of paleosol.

Cross laminated fine to medium maroon sandstone

From 157 to 169 m (Figure 2.5) there is a succession of coarser grained maroon beds occurring between the massive silt and mudstone packages. The composition of these very fine to medium-grained sandstones is both micaceous and arkosic. Where the strata displayed small-scale cross-stratification there are typically desiccation cracks and *in situ* carbonate nodules at the top of the beds. The maroon mud, silt and sandtone layers are interpreted as dry floodplain deposits.

***In situ* carbonate nodules**

Carbonate nodules are developed in-place within the strata of this section. *In situ* nodules occur at the top of maroon siltstone and red very fine-grained sandstone units that are often associated with desiccation cracks and hummocky bed surfaces. They are discrete and are nodular to stringy in appearance (Figure 3.5d). Where they are exposed on the wave-cut platforms, the nodules can be cleanly removed from the tops of argillaceous beds, because they are much harder than the sandy matrix. The individual nodules range from 1 to 2 cm in diameter. Exposure of the carbonate has weathered it to an orange-yellow colour.

Load Structures

The bottom contacts of several sandstone beds in sub-section II display large, adjoining, bowl-shaped depressions. They are a continuous feature along the bedding plane separating underlying siltstone from the medium-grained sandstone. The curvature of the depression on the bottom contact is reflected in the orientation of the siltstone fabric. The sediment converges towards the point where two bowl structures meet (Figure 3.6). Additionally, the depressions have many internal cross-laminations. They are interpreted as load structures.

Fossil Trees

Four intervals of fossil trees are present in the section at 8, 164, 167 and 169 m (Figure 2.5). The tree casts were preserved upright within medium-grained sandstone beds. However, they are rooted in horizons of maroon siltstone and very fine-grained

A. Close up of paleosol fracturing patterns. Carbonate material was present in the massive maroon paleosols.

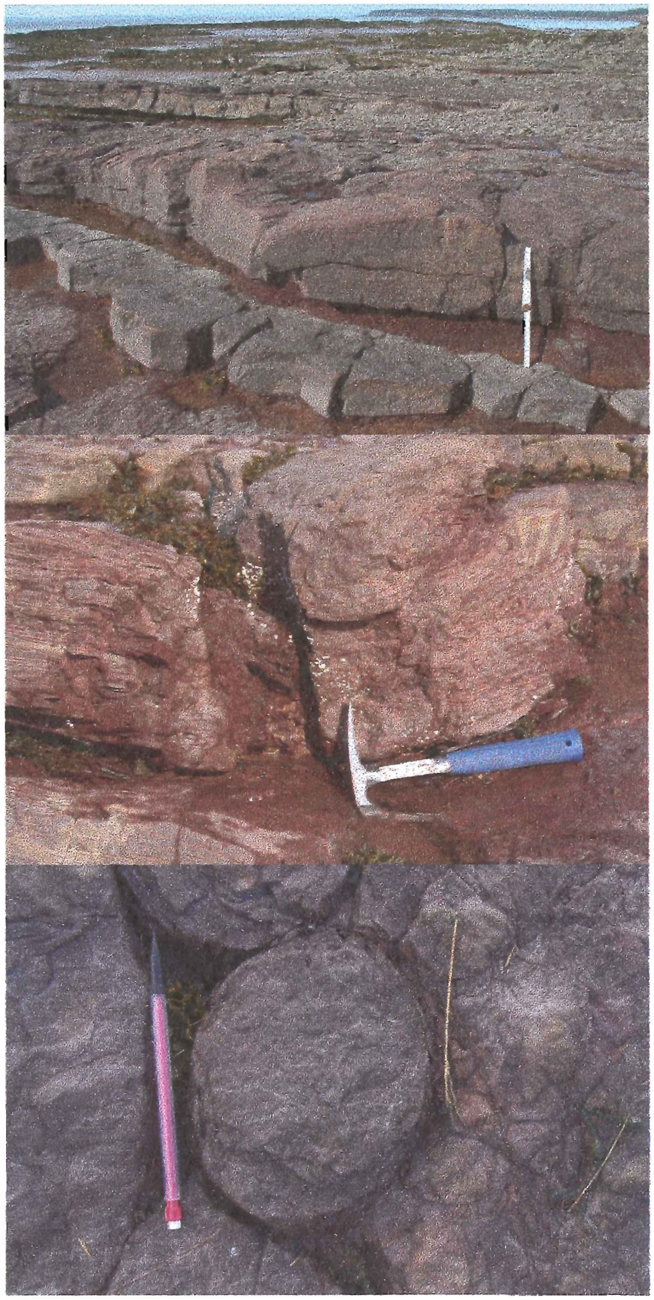
B. Thinly bedded grey unit of siltstones and sandstones with large amounts of preserved plant debris, overlaying red mudstones.

C. Reworked caliche conglomerate. It is not laterally extensive and pinches out into grey siltstones and sandstones 5m south (right of photograph).

D. In situ caliche material found at the tops of maroon siltstone to fine grained sandstone beds. Desiccation cracks also feature prominently on the tops of these surfaces.

Figure 3.5 Carbonate and organic occurrences in the Cheverie Type Section

Figure 3.6 Load structures found in the maroon silt and sandstone successions.
Hammer= 40 cm



a.) Siltstone and sandstone succession of forested interval. Topmost bed shows bowl-shaped depressions caused by fluid scouring at the base of *in situ* trees. Metre stick for scale.

b.) Vegetation Induced Sedimentary Structure (VISS) preservation in the bedding around *in situ* trees. Hammer = 30 cm

c.) Cross sectional view of the top bedding surface from photo E. An in situ tree is the center of the depression. Pencil = 14 cm

Figure 3.7 Images showing the forested tree horizon located in the upper portion of the Cheverie Type Section.

that are about 10-20 cm in thickness (Figure 3.7a). The trees themselves are preserved as casts of medium-grained sandstone, which are surrounded by downward-dipping sandstone beds that are truncated against the trees on either side (Figure 3.7b). The average height and diameter of the casts is 20 cm and 9 cm respectively. The tops of the sandstone units appear to be hummocky such that the troughs of the depressions are in-line with the tops of tree casts (Figure 3.7c). In areas where the sandstone has completely filled the space above the trees there are no depressions on the bed surfaces. The tree fossils are interpreted to be pith casts, which are the lithified remains of tree cores that have decayed and infilled with sediment. The pith casts do not have any defining textures, but are most likely to be Lepidodendropsis corrugate.

Bed truncations

At 167 m a large truncating feature has incised 0.5 m into a forested tree interval. The internal structure of the feature shows down-dipping successions of cross laminations that are truncating medium-grained planar beds, which are laterally equivalent to the beds of the entombed fossil trees (Figure 3.8). The top of the structure appears hummocky and contains *in situ* carbonate clasts that also correlate to the top of the fossil tree horizon in Block B. The truncating feature is interpreted to be a crevasse channel.

3.3 Facies C

Facies C is the final facies described here and is defined in the section by reworked carbonate nodules, creating a carbonate conglomerate, overlain by organic-rich grey siltstones and sandstones. Facies C is quite different from Facies B because it is thinly bedded, rich in fine organic plant debris, and is not highly oxidized.

Figure 3.8 Crevasse channel incising into forest tree interval at 167 m. Hummocky top has *in situ* caliche deposits and continues laterally to the measured section of Block B to the right.

3.3.1 Sedimentary Structures

Organic grey beds

Above and between the two beds of carbonate conglomerate in Block B are thinly bedded organic-rich sandstones, siltstones and shales. They are dark grey in colour and contain large amounts of coalified plant debris (Figure 3.5b). The lower section exhibits wavy bedding transitioning to planar bedding. The grey beds are interbedded with maroon mudstone beds approximately 2 cm thick and thin maroon laminae at 15 cm intervals. The plant debris is concentrated on the tops of the grey beds and ranges from mm-scale clustered amorphous fragments to large (>30 cm) discrete plant segments. These beds contrast strikingly with the thicker maroon siltstones and sandstones of Facies B below, which show little plant preservation, with the exception of the *in situ* tree stump casts. Correlation between the northern and southern blocks reveals that the dark grey unit pinches out to the north between thicker packages of maroon siltstones and sandstones. Likewise, the succession of carbonaceous grey beds in Block B does not appear in the northern Block. Instead they are replaced laterally by thick grey packages of medium-grained sandstones to granule conglomerate. This interval is interpreted as being part of an abandoned channel sequence.

Carbonate Conglomerate

Near the base of Facies C are two distinct deposits of carbonate conglomerate (Figure 3.5C) that occur in both Block A and B. The beds have thicknesses up to 40 cm with rounded to sub-rounded clasts ranging from 1 to 3 cm in diameter. The conglomerate is largely clast-supported and the matrix is a carbonate-rich grey to maroon mudstone. Five metres south of Block B both the size and density of the clasts decrease laterally within the beds. The conglomerate becomes thin and matrix-supported and pinches out towards the western cliff face. There are locations between the two main conglomerate beds where the deposits are discontinuous. The carbonate conglomerate is interpreted as having reworked caliche clasts from paleosols.

CHAPTER 4 PETROLOGY

Fourteen thin sections were prepared from a suite of samples collected at the Cheverie type section. They were cut and impregnated with blue epoxy by Gordon Brown, thin section technologist at Dalhousie University. The thin sections, cuttings and hand samples were examined to find the modal composition of each rock, along with the percentage of major and minor constituents, matrix and cement. Structures and textures of each sample were also recorded. Optical mineralogy work was performed using a standard petrology microscope and the detailed descriptions for each sample are available in the appendix. Table 4.1 gives a list of the sample numbers, hand sample characteristics, depth and facies assemblage.

4.1 Granule and Pebble Conglomerate

Pebble conglomerates are poorly sorted with clast sizes ranging from fine gravel to very coarse gravel. Overall these samples do not display any structures or preferred orientations in thin section. The matrix between the gains and fragments is composed of clay and/or calcite. Quartz in the samples averages 37% and exhibits flat to undulose extinction. The clasts are mainly rock fragments, including; polycrystalline quartz and calcite, siltstone, mudstone, and volcanics. The bulk of the fragments are sedimentary in origin.

In subsection I there are large amounts of calcite lithic fragments that have developed as pseudomorphs of granitoid clasts. At the centre of these fragments there is muscovite and quartz surrounded by calcite, which entrain smaller quartz grains. The pebble conglomerates of subsection I also contain 3% average modal detrital orthoclase.

Sample	Describing Features from the Hand Sample	Depth (m)	Subsection	Facies
MR012A	Macumber Formation Limestone	175.30	III	none
MR012B	Very Coarse-Grained Sandstone, Above the Unconformity	175.25	III	A
MR007A	Pebble Conglomerate, Quartz-Rich, Block B	174.60	III	A
MR012C	Granule Conglomerate, Above the Unconformity	174.30	III	A
MR010A	Very Fine-Grained Sandstone, Below Channel	173.45	III	A
MR011A	Calcareous Pebble Conglomerate	171.40	III	A
MR011B	Granule Conglomerate, Quartz-Rich	170.90	III	A
MR006A	Caliche Pebble Conglomerate, Block B	169.10	III	C
MR004A	Maroon, Very Fine-Grained Sandstone, Base of a Fossil Tree Horizon	166.80	III	B
MR022A	Maroon, Fine-Grained Sandstone, Cross-Bedded	75.60	II	B
MR022B	Maroon, Fine-Grained Sandstone, Cross-Bedded	74.40	II	B
MR017C	Light Grey, Medium-Grained Sandstone, Well Sorted	14.30	I	B
MR016A	Medium-Grained Sandstone, Porous	3.40	I	A
MR013A	Pebble Conglomerate, Porous & Permeable	0.65	I	A

Table 4.1 The sample numbers listed above are applicable for both hand samples and thin sections taken from the study area. The general features observed in the hand sample are listed in the second column, followed by the depth, subsection number and the facies classification of the sample

In subsection III the pebble conglomerate clasts are composed of volcanic, quartz and polycrystalline quartz fragments. In subsection I there is an average of 22% open space (Figure 4.1a), while in subsection III there is less than 2% pore space, representing primary porosity. The difference in percentages from the sampled conglomerates occurring between the top and bottom of the section is due to the amount of secondary porosity created by fractures. Where the original conglomerate contained clay matrix or calcite cement, such as in subsection III, it has been almost completely removed in subsection I, leaving the pebble conglomerate to be largely clast-supported, creating additional pore space.

4.2 Coarse and Medium-Grained Sandstone

A medium-grained sandstone taken from subsection I was found to be a poorly sorted lithowacke characterized by subangular and subprismoidal quartz grains. Subtle gradational layering defines thick laminations in the thin section with grain sizes varying from fine to very coarse sand. Quartz is the most abundant mineral at 60%. Detrital garnets (2%) are angular with many small quartz inclusions. Lithic fragments include: volcanics (4%), polycrystalline calcite (4%), siltstone, and mudstone (5%). The volcanic fragments are subrounded, but are also strongly cracked and broken. Several have radiating calcite replacing the internal lath structures. Anhedral calcite cement defines a mosaic texture between grains totaling 25% of the sample and closing any pore space.

The sandstones in subsection III are very well sorted, medium-grained sublithic to quartz arenites (Figure 4.2b). Spherical to subspherical quartz is the most prominent grain type with an average of 72%. They have very few lithic fragments (>5%) in relation to subsection I, but in contrast there is significant porosity in the samples with only small

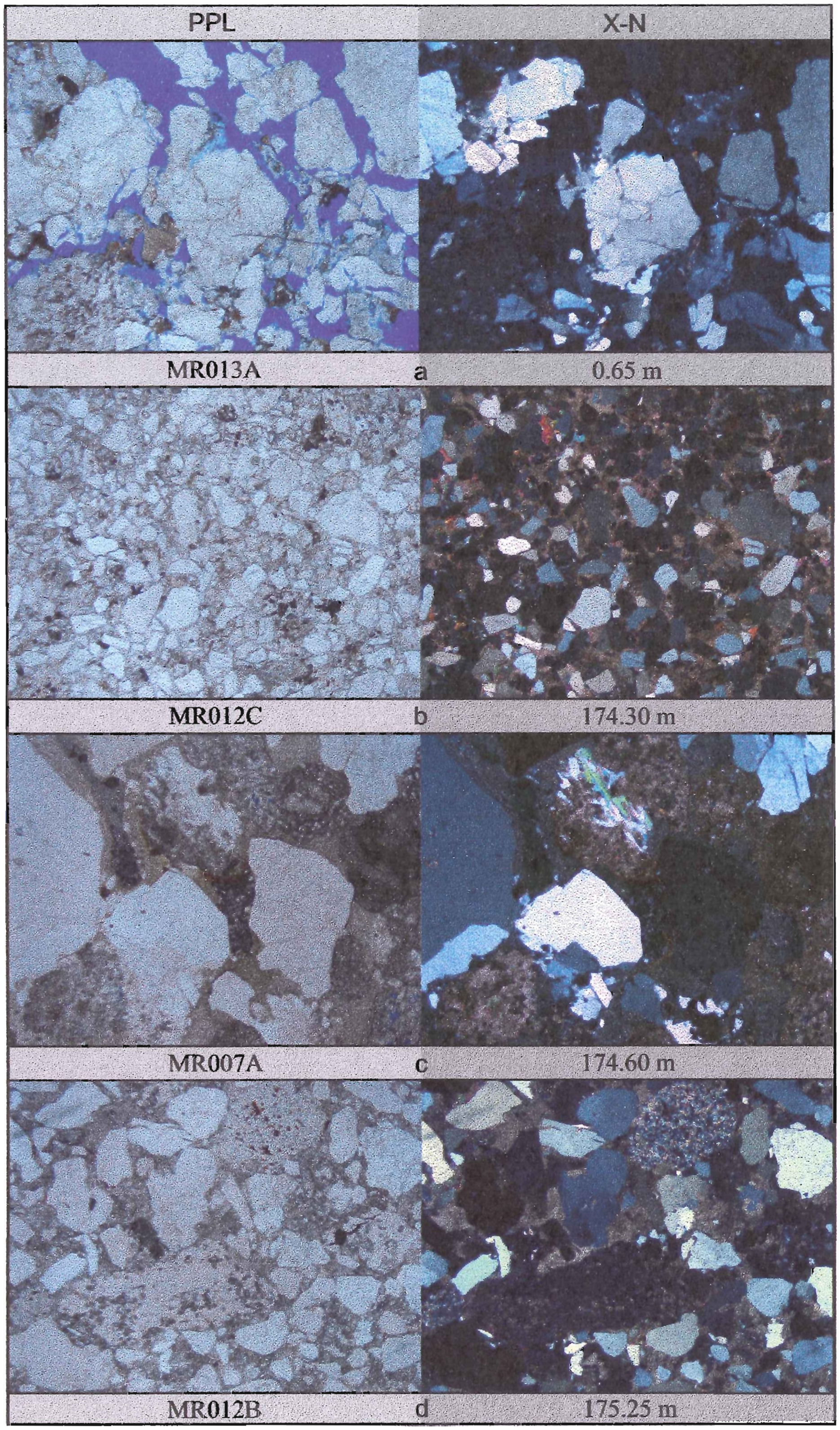


Figure 4.1 Thin section photographs of granule and pebble conglomerates taken in Plane Polarized Light (PPL) and Cross-Nichols (X-N). The field of view is 6.25 mm. Large grains in [c] and [d] are granitoid fragments and volcanic fragments respectively.

amounts of clay (>8%). Biotite, tourmaline, epidote and zircon can be identified with fractions totaling less than 2%. Muscovite and biotite grains are strongly kinked around the quartz grains, which either display undulose extinction or subgrain development. Secondary quartz has precipitated along the boundaries of quartz grains, partially filling the pore space.

4.3 Very Fine-Grained Sandstone

Four fine-grained sandstone samples from subsection II and III can be classified as either arkosic wackes or quartz wackes. Even though the percentage of quartz varies between the samples the amount of matrix and cement fluctuates, giving high normalized quartz percentages. The intergranular space averages 33% and consists of either clay or cement. Epidote and chlorite appear in subsection II, while the modal percentages of clay, muscovite, and iron oxides remain similar between the two subsections. Texturally, the sandstones are well sorted, with subrounded grains that are subspherical to subprismoidal. Elongated muscovite grains are kinked around surrounding quartz grains.

There is a low amount of porosity in the sample and probably little to no permeability. Laminations in the thin sections are defined by areas rich in clay alongside areas dominated by calcite cement. Planar and cross-laminations are present. Sinuous boundaries divide areas of high clay content from sediments dominated by anhedral calcite cement. Muscovite and chlorite tend to be more abundant in the clay regions.

4.4 Caliche Conglomerate

Caliche clasts compose 73% of this pebble conglomerate and vary from 5 to 40 mm in diameter, with a mean size of 14 mm. Most of the clasts contain laminations defined by quartz grains that are fine to coarse-grained. When the internal quartz grains are found to have a planar distribution, they coincide with the long axis of the clast, while others show sweeping and even truncating patterns. The matrix contains micrite with mud particles (20%) and minor sparite (1%) in which clasts are suspended. Circumclastic cracks are observed in the sample, especially around larger clasts, creating secondary porosity and probably permeability. Some clasts have thick, asymmetrical micritic grain coatings that can be easily confused with the matrix. Inserting the tint plate accentuates a sweeping extinction pattern, indicating that the coating has a lattice preferred orientation, which is unlike the matrix micrite. Fine to medium-grained detrital quartz grains located in the matrix (6%) have angular edges.

4.5 Macumber Formation

The Macumber Formation sampled at the section is a pelitic limestone with a micrite matrix. Under Folk (1974) classification the limestone is a pelmicrite. In hand sample the Macumber is fine-grained, maroon in colour and thinly bedded. In thin section the peloids are visible and are roughly spherical, composing 70% of the sample with an average diameter of 0.4 mm. The sample is composed of thinly laminated layers of peloids, which are entrained in a muddy micritic matrix (20%) with sparite (10%). The matrix contains clay particles that obscure the boundaries between the peloids and micrite. A stylolite was observed in the thin section that was accentuated by the accumulation of opaque material.

Several valves of recrystallized ostracod fossils were discovered in the thin section. The valves were positively identified against a complete specimen figured by Scholle (2003). The valves have recurved terminations and a shell structure formed of rod-shaped calcite crystals, which were orientated perpendicular to the shell outline and showed a sweeping extinction pattern in cross-polarized light.

4.6 Interpretations

Pebble Conglomerates and sandstones

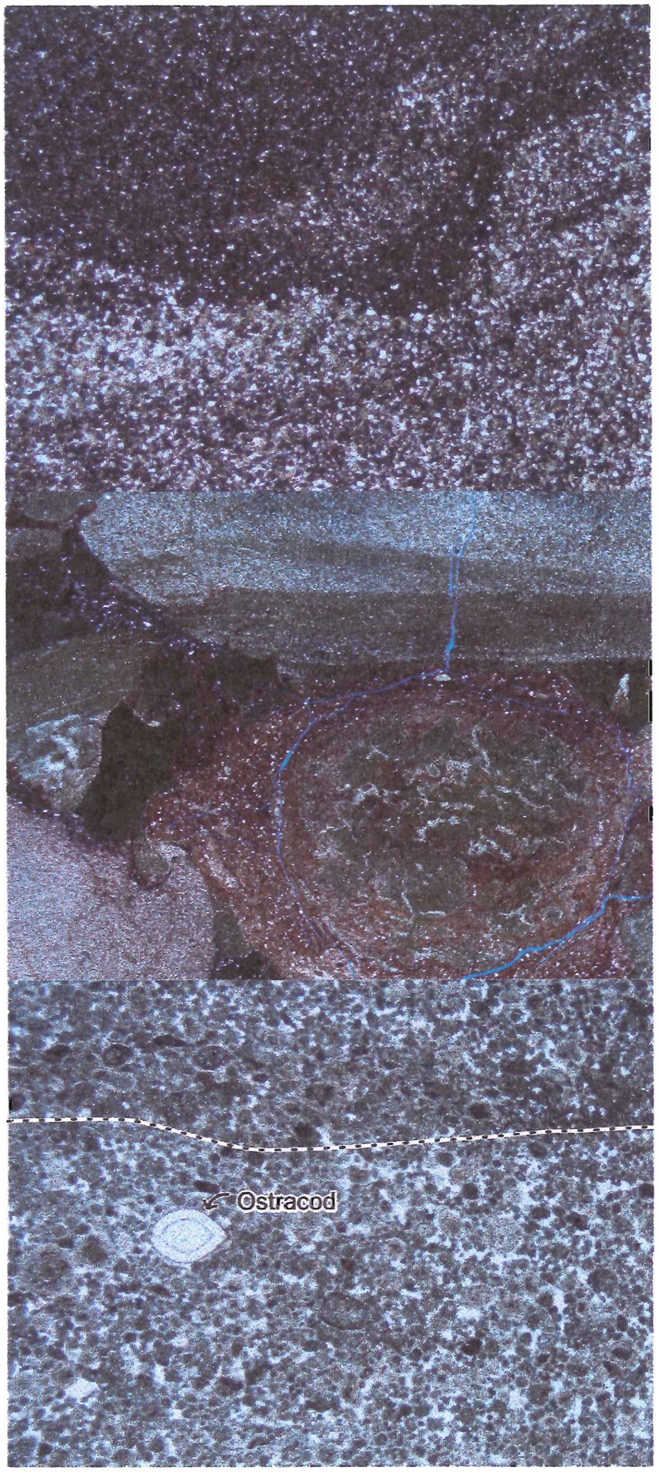
The average sandstone contains only 15% lithic fragments with an average amount of detrital clay of 5% (Blatt 1982). The sandstones of the Cheverie have large portions of intergranular clay nearing the middle of the section, which indicate that these sandstones are texturally submature, while well rounded and well sorted sandstones with little clay to no clay are texturally mature (Folk 1974). It is likely that feldspars from subsection III have altered to clay, especially those occurring in oxidized floodplain deposits. Sandstones whose detrital grains are composed mainly of quartz may have clay content attributed to diagenesis. Secondary clay can be recognized in the thin section as a film occurring around grain boundaries.

The polycrystalline calcite fragments displaying pseudomorphic textures are relicts of felsic granitoids. The internal structures show a replacement of muscovite and plagioclase by calcite, creating quartz inclusions (Figure 4.1c). The volcanic fragments may also contain plagioclase that is being internally replaced by small calcite growths (Figure 4.1d). Biotite in the sample has been altered to chlorite.

Pore filling causes the rock to become more rigid, such as in samples dominated by calcite cement or secondary quartz precipitation. More ductile material, like the sheet silicates identified in thin section, have developed kinks from grain compaction during burial. Volcanic fragments are inherently less ductile than ones that are sedimentary derived. In thin section, mudstone and siltstone fragments are more fractured and well rounded than adjacent volcanic fragments. Even in the caliche carbonate, larger grained nodules have gouged and settled into finer grained nodules. Overall the effect of compaction and chemical alteration has made it difficult to distinguish between detrital grains and primary or secondary matrix.

Meteoric cements precipitate in areas where there is low capillary potential (Scholle and Ulmer-Scholle 2003). When water cannot be held or transported between the grains it gradually evaporates, leaving cement. The laminations preserved in the finer grained sandstones provide a good example of how the finer grained sediments vary in diagenetic processes. Small-scale porosity and permeability associated with laminae containing high clay content tend to resist calcite growth. These are juxtaposed with highly cemented laminae with low clay content. Displacive growth of intergranular calcite has been restrained by densely packed clays, which are incorporated into the micritic matrix, with coarser-grained calcite cement crystallizing as a response to increased porosity and permeability (Scholle and Ulmer-Scholle 2003).

Sinuous boundaries were found in fine-grained sandstone collected directly from the base of a tree cast. The irregularly curved nature of the boundary defines a contact between sediments with high clay content and sediments with anhedral calcite cement (Figure 4.2a). The calcite along the contact is thicker than the interior cement, which may indicate that an originally planar bed was disturbed, but detrital terrigeneous sediments are too subrounded to conclude if there was any realignment of grains during deformation. The internal fabric of the sandstone is interpreted to be disturbed by fluid circulating in the sediments around the base of fossil trees.



a.) MR004A- 166.80 m
Very fine-grained sandstone with sinuous boundaries. The amount of calcite cement varies between the clay-rich and clay-poor areas.
Field of view = 6.25 mm

b.) MR006A- 169.10 m
Caliche conglomerate showing circumgranular fracturing, pesoid structure and crossbedding
Field of view = 6.25 mm

c.) MR012A- 175.30 m
Macumber Formation fossil-bearing pelmicrite. Thinly laminated beds (shown as a line) of peloids in micritic matrix with minor sparite. Ostracod specimen labeled.
Field of view = 6.25 mm

Figure 4.2 Thin sections showing carbonate crystallization.

Caliche conglomerate

The caliche conglomerate sample shows a floating texture, indicating that fine-grained overbank sediments have been partially replaced by micrite and minor sparite around the clast boundaries, which are prone to fracture. In the matrix, the detrital quartz grains are altered along their edges giving them an angular appearance. This is because calcite has displaced the area around the quartz grains as it grows (Tandon and Narayan 1981). In some cases brecciation of the quartz grains has occurred and sparry calcite has crystallized between the boundaries.

We can interpret the planar inclusion trails that are aligned to a clast's long axis as recording the original orientation of the *in situ* caliche nodule in a floodplain deposit (before reworking) because the long axis of an *in situ* caliche nodule develops parallel to the bedding (Tandon and Narayan 1981). The quartz inclusions are also useful in identifying the types of bedforms in the originating strata. When studying the thin section, the presence of gradational bedding and small-scale cross-beds are preserved in the grain size distribution of quartz. The varying grain size between clasts indicates that the clasts came from several different caliche sources.

Mature *in situ* caliche nodules develop irregular asymmetric grain coatings with abundant inclusions of detrital terrigeneous silt and sand, called pesoids (Scholle and Ulmer-Scholle 2003). The micritic grain coatings described in the thin section are interpreted to be pesoids originating from floodplain strata in the vadose zone, which is the region of water infiltration and percolation above the water table (Figure 4.2b). Pesoids develop as a type of meteoric alteration brought on by water droplets clinging to the undersides of clasts (Scholle and Ulmer-Scholle 2003). Frequent hydration and evaporation form micro-stalactitic cements, such as micrite, which elongate the clast downward, creating pesoid structures.

Macumber Formation

A limestone that is composed principally of peloids and micrite is most likely to have been deposited in an environment with low kinetic energy. Low flow strength conditions have a better chance of preserving finer-grained sediments, such as clay particles, and incorporating them into a micritic matrix (Blatt 1982). The thin planar beds of the Macumber Formation also suggest that the environment of deposition experienced lower flow regime conditions. Peloids may originate as recrystallized shell fragments or accumulations of fecal pellets, but the paucity of shell fragments in thin section suggests that the peloids are not formed by recrystallization processes (Figure 4.2c).

CHAPTER 5 DISCUSSION

The Cheverie Formation is part of the fill of the Kennetcook Basin, which is part of the larger Maritimes Basin. The type section has three distinct facies composed of clastic sediments derived from nearby sources. The interpretations of the sedimentary structures found in facies A, B and C, support a meandering fluvial depositional model. Post depositional deformation in the Cheverie Formation is recognizable in the regional seismic profiles and at the outcrop scale.

5.1 Cheverie Formation in the Maritimes Basin

The Carboniferous fault-bounded Maritimes Basin provided accommodation space for the creation of several periodically connected depocenters such as the Kennetcook Basin where the Cheverie Formation was deposited. Overall, Atlantic Canada is within a zone of dextral shear which characterized the collision forming Pangea, at the end stages of the Acadian Orogeny (Gibling et al. 2008). Faults on the continental scale were mainly strike-slip and were the main control on local sedimentation.

5.2 Facies A Interpretation

The large trough crossbeds and fluvial structures, defined here as Facies A, at the top and bottom of the measured section represent channel fills. While the geometry of the channels was never entirely visible they were shown to have been actively migrating as they truncated earlier packages. As the meanders in the channel were becoming more sinuous the point-bars accreted laterally, creating thick sand deposits in the form of high angle cross-stratified beds (Figure 5.1) (Prothero and Schwab 2004). The point-bar

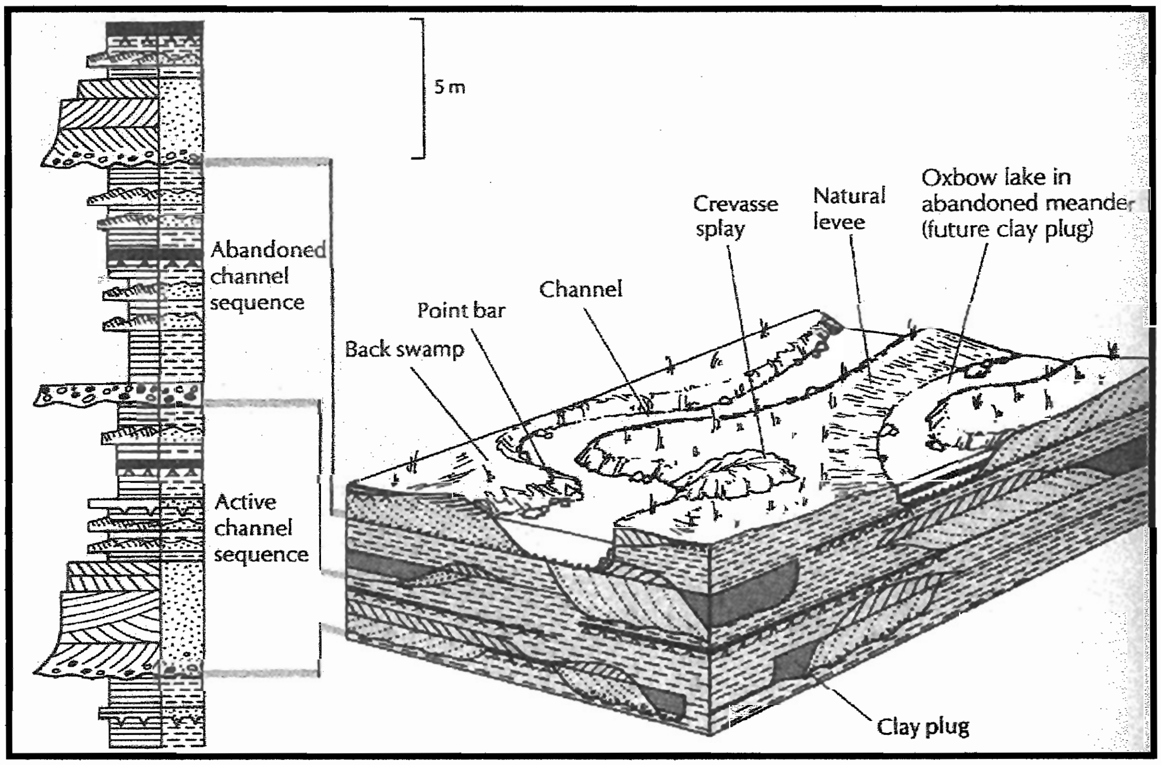


Figure 5.1 Schematic drawing of a meandering fluvial system. Abandoned channel and active channel sequences are shown to the left in an ideal stratigraphic section (Prothero and Schwab 2004). The base of the active channel sequence is a conglomerate lag deposit, followed by crossbedded sands in a fining upwards sequence. The abandoned channel sequence is dominated by silts muds and minor crossbedded sands resting on a channel lag.

sequences are best seen in subsection I where they prominently overlap one another over a space of several metres and up section they are truncated by younger point-bar sequences. All the point-bar deposits seen here sit on a thick channel lag of pebbly conglomerate. This section represents a meandering channel environment with inclined stratifications (Thomas et al. 1984). Further up in the section the trough crossbeds transition into thick successions of well sorted sand with bedforms that are dominated by ripple cross-laminations. Oxidized silt laminae are characteristic of areas displaying climbing ripples. Where there are equal portions of sand and silt the strata show wavy bedding. Higher flow velocities were required to produce the ripple cross-laminations and well sorted nature of the sand packages. It is possible that they were deposited close to the floodplain margins.

The opposite-trending structure in the lower section is a well preserved antidune. An antidune is an Upper Flow Regime structure that adequately records that the lower Cheverie was undergoing rapid flow conditions (Figure 5.2) (Prothero and Schwab 2004). In order for the antidune to form a unidirectional current with high flow strength was required to deposit the sand on the upstream side of the bedform (Fielding 2006). Antidunes are a rare occurrence in the rock record because they are often reworked during burial when the flow strength falls, but an antidune of this size may have survived if the flow conditions changed abruptly (Fielding 2006). The rapid fall in flow power would be typical in a river body experiencing major seasonal variation in discharge. If antidunes were a prominent feature in this channel system, we would see them cross-cutting over other antidunes as they migrated upstream. Observations from the outcrop

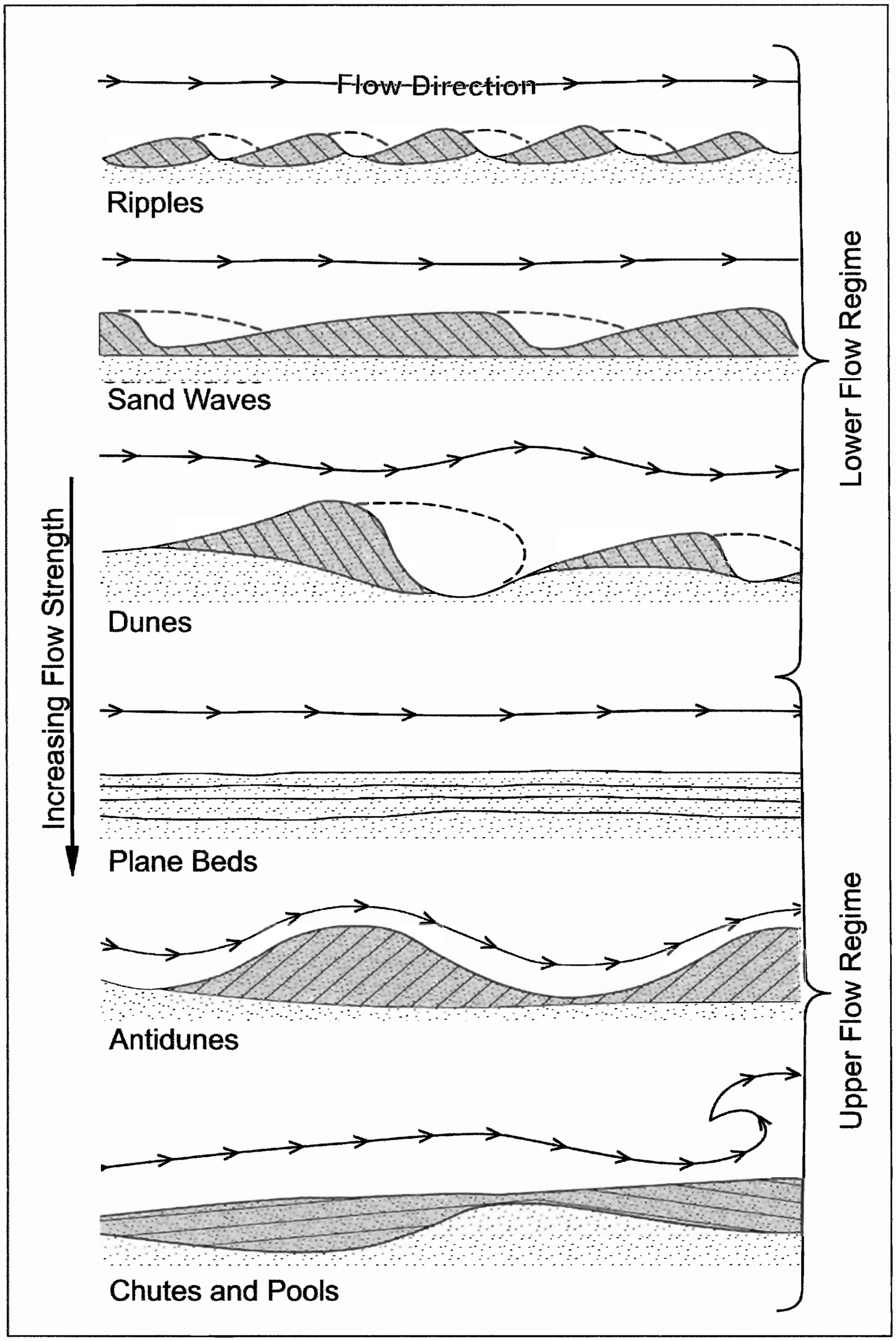


Figure 5.2 Line drawing showing the division between Lower and Upper Flow Regime structures in relation to increasing flow strength. Ripples, sand waves, dunes, plane beds, antidunes and chutes and pools complete the succession. The individual bedforms are scale-independant. Modified from Prothero & Schwab (2004) and Fielding (2006).

suggest that antidunes were not common as they were not found to be in closely spaced the sets (perhaps because they were not well preserved). Since high flow states were achieved, underlying planar beds are interpreted to have formed under upper flow regime conditions just under the flow strength required to form the antidunes (Figure 5.2).

The chaotic bedding found above the channelized sands is likely a soft-sediment deformation feature caused by small-scale slumping within a chute. This could have happened if a new channel formed between two limbs of a meander, inundating and scouring previous scroll-bar sediments (Prothero and Schwab 2004). Following flooding, the channel sides were exposed, which initiated slumping into the chute. This reworked the previous structures in the scroll-bars and incorporated the sediments into a chute-bar sequence. Before the slumping occurred, the chaotic sands may have had lingoidal ripples, much like the ones observed in the overlying strata.

As the channel filled with slumped material at one point, the flow in the cut-channel may have stabilized between flooding events, especially if the main meander remained open. In this case, both sediment and fluid would have become constrained to the area above the chaotic sands. Wind-generated currents would have then been able to rework the upper sediments forming the more organized packages of planar beds of coarse-grained calcareous sandstone above. These beds are relatively undeformed because they are resting on top of a foundation of reworked point-bar sediments. A decrease in water depth led to an aqueous current that was able to generate lingoidal ripples. Since the sand is largely coarse-grained, this area may not be far away from the original point of channel diversion.

5.3 Facies B Interpretation

Facies B, consisting of maroon mudstone and sheet sandstone, is interpreted to represent well drained floodplain assemblages. The strata represent levees, splays, paleosols and floodplain fines that accumulated in an arid to semi-arid climate under oxidizing conditions (Davies and Gibling 2003). The preservation of plant material was low, with the exception of tree casts.

Facies B represents an area rich in floodplain paleosols, which are represented by the thick maroon silt and mud layers. Overall, both the amount of clay and the fracture system allow classification of the paleosols of the Cheverie as vertisols (Wilding *et al.* 1984). The hydration and dehydration of clay particles produced the cracks in the paleosol, thereby recording the climatic conditions in the soil. The expansion and contraction of the soil occurred periodically and allowed the cracks to travel deep into the sediment. Vertisols occur in arid to semi-arid regions and usually occupy depressions or broad plains (Flügel 2004). The region where the Cheverie paleosols developed must have been well drained and seasonal in order to develop the vertisol fractures. Another feature that supports seasonal conditions is the presence of pedogenic trace carbonates. They would have formed from the accumulation of precipitated calcium carbonate in the unconsolidated carbonate-rich soils (Flügel 2004). Carbonate is a common feature in soil profiles, often precipitating within the cracks of the paleosol after each hydration period (Flügel 2004).

The carbonate nodules appearing on the tops of beds are interpreted as authigenic caliche deposits, which have formed from a combination of cementation, replacement and displacement of precipitated calcite within the pore space or on existing calcite particles of the host rock (Prothero and Schwab 2004). Caliche commonly develops in carbonate-rich soils in regions where rainfall is between 200 and 600 mm per year, when more evaporation is occurring than precipitation (Tandon and Narayan 1981) and where there is a supply of carbonate-rich groundwater (Flügel 2004). Nodules, and other forms of caliche, can grow over one or more drying cycles (Flügel 2004) over tens of thousands of years (Steel 1974). The *in situ* caliche at Cheverie was found to have developed on the tops of silt and sandstone beds, but not throughout the strata. The caliche horizons can be interpreted to have been located below the capillary-rise zone in the floodplain sediments, in which scattered to clustered pedogenic carbonate can develop (Steel 1974) (Tandon and Narayan 1981). For the nodules to form, the groundwater must have greatly fluctuated in the capillary-rise zone when the calcite accumulated so that the caliche horizon was hydrated in brief cycles. Since the caliche nodules formed in the red floodplain strata, the sediments were likely oxidized before burial. We can therefore interpret the caliche horizons as areas on the floodplain that have been well drained as a result of arid to semi-arid conditions. The *in situ* caliche found at Cheverie can be classified as Type 1, which describes irregularly shaped nodules that are 1-6 cm in diameter and compose less than 10% of the host rock (Steel 1974).

Soft-sediment deformation created the load structures observed in Facies B when sand was quickly deposited over silt. This caused the soft substrate to dewater and caused the disruption of the original planar bedding (Prothero and Schwab 2004). This process would have occurred while the sand was accumulating; indicating that there was a sudden influx of sediment, perhaps from a nearby splay or from levee building.

The trees grew close to one another as each horizon was marked by several pith casts spaced less than 1 m apart. Pith casts can be formed after a tree dies and begins to decay (Degges et al. 1989). The core of the plant fills with sediment that is later lithified to form an internal cast. Another way a pith cast can form is when the centre of the stem develops as a hollow during the plant's growth. This creates a large cavity that can be infilled at burial, such as in the late Carboniferous species *Calamites* (Rygel et al. 2004). The defining features such as bark, vascular and cortex tissue are not preserved in the measured section, which makes it difficult to identify the tree type.

The trees grew upright from thin, nutrient-rich paleosols derived from floodplain deposits of siltstone and very fine-grained sandstone and were later entombed by an influx of sand on the floodplain. In order for the tree to be preserved *in situ*, the overlying sandstone would had have to been deposited rapidly. In a slow burial situation the trees would have fallen over, decayed at the surface and left little evidence of their existence. During the decay process the trunks of the trees would have been exposed to wind and it is likely that they would have broken off, leaving the entombed sections behind. When the base of a tree is buried quickly the organism dies and begins to decay in place (Rygel *et al.* 2004). A crevasse channel at 167 m is a good example of a mechanism that could have provided large deposits of sand to the floodplain. In fact, the splay's incision into the surrounding strata links it to the medium-grained sandy interval responsible for encasing the pith casts in Block B at 167 m.

The hummocky appearance on the top surfaces of the encasing sandstone beds incorporates bowl-shaped depressions centered on tree cast locations. These structures are interpreted as Vegetation Induced Sedimentary Structures (VISS). VISS are the result

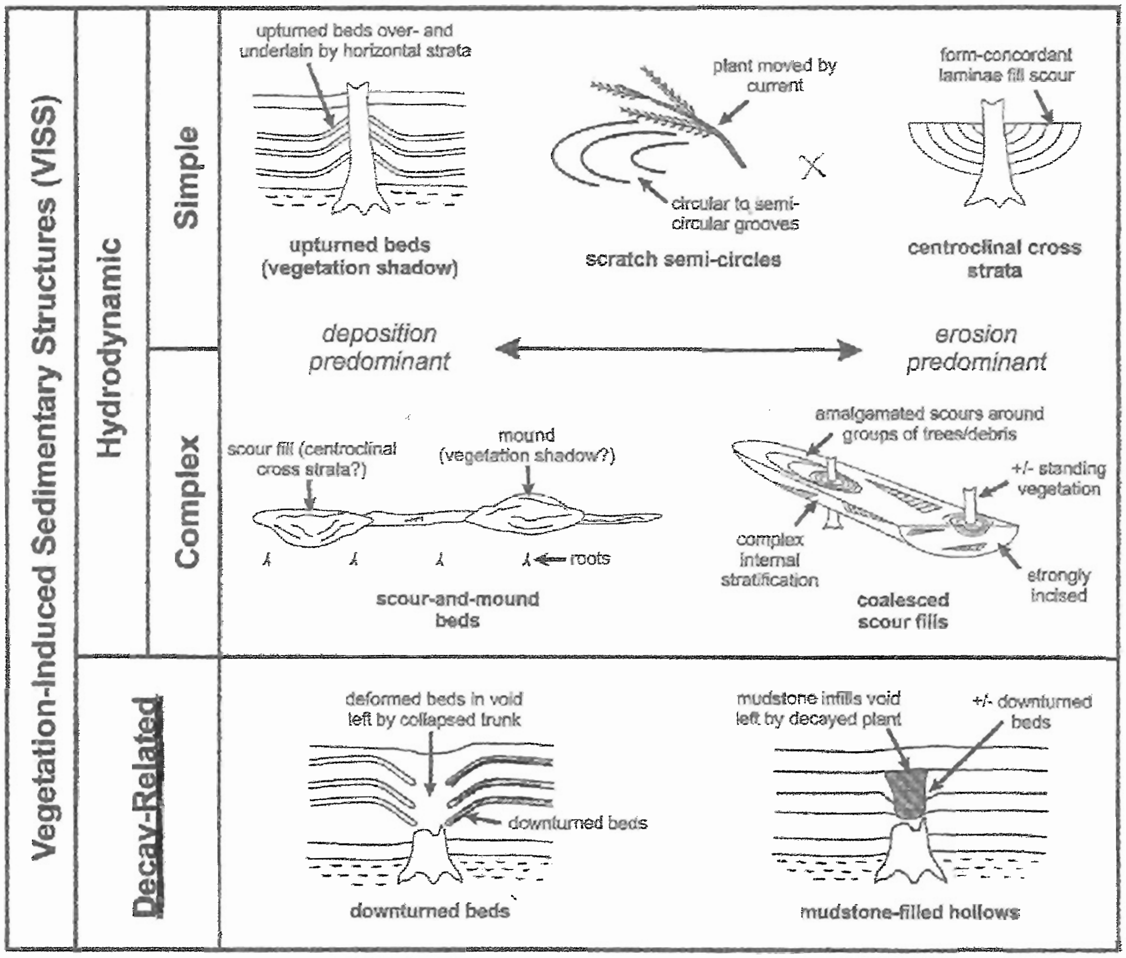


Figure 5.3 Diagram summarizing the different types of VISS associated with *in situ* plants. The VISS found in the Cheverie are both decay-related and hydrodynamic, including beds and centroclinal cross strata (Rygel *et al.* 2004).

of sediment accumulation around standing plants near or at the time of deposition (Rygel *et al.* 2004) (Figure 5.3). In particular, the bowl-shaped features are created when sediment flows drifted around the trunks of *in situ* trees, which acted to incise and deposit sediment around the circumference. The sediment is arranged by baffling flows of sediment within channels and overbank deposits (Zierholz *et al.* 2001). VISS are clearly seen in Facies B as part of the downward-dipping sandstone beds, between 164 and 170 m, infilling the area around the *in situ* trees.

5.4 Facies C Interpretation

The source of the clasts in the carbonate conglomerate is interpreted to be reworked nodules of caliche, similar to those observed down-section in Facies B. The occurrences of reworked caliche are analogous to Bell's (1929) description of "kunkur" and "cornstone" deposits in the upper portion of the Cheverie. The caliche conglomerate probably formed as a channel lag in a meandering river system by the redeposition of nodules that were eroded and then transported from up-stream. Deposits above the thick basal conglomerate are discontinuous, reflecting either a variation in the source or method of deposition of the clasts. Caliche conglomerate lags have also been found in the Belly River Formation in the foothills of western Canada (Jerzykiewicz 1992). In that case, the reworked caliche originated from a fluvial facies in the Lower Belly River that contained mature caliche paleosols.

The preservation of plant debris within Block B sets it apart from any other interval measured at the Cheverie Type section. The geometry of this facies and its position above a channel lag conglomerate make it distinguishable from that of a floodplain deposit (Selley 1994). The absence of a point-bar sand sequence distinguishes it from typical channel fills from Facies A. At 169 m there is a thick caliche conglomerate that marks the change between Facies B and Facies C. The change records a shift in the paleoenvironment that had facilitated the red bed succession. The lateral extent of both the organic grey beds and conglomerate between the fault-blocks suggests that this area became separated from the surrounding conditions of Facies B. This could have been accomplished by a powerful flooding event that led to a section of the channel being cutoff from the meandering system (Prothero and Schwab 2004), and being left as an oxbow lake. Once the channel was abandoned the larger grains settled out of suspension and vegetation and plant debris from the banks began to gradually fill the meander. At this point, the water depth may have been shallow enough to have wind-generated currents, creating wavy bedding (Hadlari et al. 2006). However, it was still calm enough to preserve plant material.

The transition from wavy to planar bedding represents a fall of water level in the abandoned channel. From 169.5 to 172.5 m in Block B there is a cycle of evaporation and drowning, where the planar beds become interbedded with the thin maroon mudstones. The repetition of the thin oxidized beds with thick reduced strata reflects seasonal conditions at the time of deposition. A semiarid climate would have evaporated any standing water in the channel during the dry season, creating the oxidizing conditions seen in the mudstone. At the same time the geometry of the system was not able to provide a significant opportunity for transportation and deposition of new coarse sediment, which resulted in the thin layering and fine grain size. The infill of water between the dry seasons could have come from a combination of flooding, meteoric water input and groundwater seepage from nearby channels.

Higher up in the Facies the abandoned channel matured into a back-swamp area, rich in coaly plant detritus (Figure 5.1). The transition was possible because the channel's surface geometry became a depression in the floodplain at its abandonment. Within the meander the overflow from the natural levees was confined with each major flooding event. Near the top of Facies C there is an accumulation of silt and mud that occurs within shortly spaced cycles. Perhaps this represents that an approaching balance between the abandoned channel fill and the floodplain. The channel filled with fine-grained particles as they settled out of suspension, which may have hosted an area of lush marsh vegetation that was later eroded by the overlying channel lag (Prothero and Schwab 2004).

5.5 Provenance

Grains consisting of quartz, orthoclase, muscovite, biotite, and tourmaline likely represent a granitoid source rock (Scholle 1979), while chlorite, calcite and epidote are likely to be alteration products. Granitoid rock fragments were also a major constituent in pebble conglomerates near the top of the section. The South Mountain Batholith most likely supplied the granitoid grains and fragments. The intrusion, which is late Devonian in age, is located southwest of figure 1.2 and outcrops for nearly 10,000 km^2 between Halifax and Yarmouth, Nova Scotia (Clarke and Muecke 1980). The composition varies between granodiorite, monzogranite and granite and is known to contain garnet (Clarke and Muecke 1980) (Saskia et al. 2009). Detrital garnet found in the pebble conglomerates may have also originated from Mn-rich transitional zones, which occur between the Goldenville and Halifax Groups (Scallion 2010).

Felted masses of fine-grained plagioclase crystals distinguish volcanic fragments from chert and clay, indicating a volcanic source terrain (Scholle 1979). The volcanic fragments are also susceptible to weathering and alteration (Scholle 1979) and in the sampled rocks the laths are partially replaced by calcite. The volcanic fragments probably originated from the lower White Rock Formation, which consists of rhyolitic tuff that is Silurian in age. The White Rock Formation can be found west of Gaspereau Lake (west of figure 1.2) (Ferguson 1983).

Pebble conglomerates at the top of the section contain siltstone, mudstone and polycrystalline quartz fragments. These sedimentary rock fragments are interpreted to be low grade Meguma lithologies or intraclasts of older Cheverie and Horton Bluff Formation clastics.

The sandstones located in Block A above 174 m are unlike any previously described in the Cheverie Formation. Petrological study has revealed these sands to be composed of 50% quartz, 30% calcite cement and 10% lithic fragments with minor orthoclase, mica, and detrital garnet. The large amount of calcite cement and lack of clay are what distinguish these sands from any others observed in the type section. The interval containing these coarse-grained sandstones contains an angular unconformity that is about 1 m down-section from the base of the Macumber Formation. The bivalve casts from this section could not be identified, but they remain unique to this area. These factors support the interpretation that these sands are a link between the Cheverie Formation's terrigeneous clastics and the pelmicrite of the Macumber Formation. Therefore I propose the topmost sands of the Cheverie type section should be distinguished as a unit called the *Leander calcareous sandstone member.*

5.6 Meandering Channel System

Oxidized floodplain sediments and maroon paleosols make-up a large portion of the strata at Cheverie. The deposits may have been part of an expansive seasonal plain that was arid to semi-arid during a large portion of the year with a paleoflow direction averaging northeast. The lack of organic particulates in Facies B suggests that the environment was conducive to decay, under aerobic conditions. Decay of larger organic matter was also occurring; pith casts are the only evidence remaining of *in situ* trees that grew on the floodplain deposits. Dewatering structures between siltstones and sandstones attest to periods having rapid sedimentation rates on the floodplain deposits and listric-style jointing in paleosols demonstrates cyclic pattern of hydration and dehydration. Channel lag, point-bar and overbank deposits of fluvial facies A-C are part of a meandering channel system summarized in Figure 5.4.

5.7 Regional Geometry and Deformation

Seismic Profile

On the seismic profiles (Figures 1.5 and 1.6), the division of the Horton Group into the Horton Bluff and Cheverie Formation allows us to view the sub-surface geometry of the strata as they extend towards the south, away from the type section. At the near-surface there are very few traceable reflectors representing Cheverie clastics. However, the reflecting surfaces at depth are shown to be either uninterrupted as in Line 003, or have coherent faulting within the larger package of clastic sediment, as in Line 002. The profile of the reflecting surfaces suggests that the Cheverie Formation both thins and gently dips towards the surface to the south. Waldron et al. (2010) interpreted the deformed surface lithologies and repetition of the Cheverie Formation (as shown by the

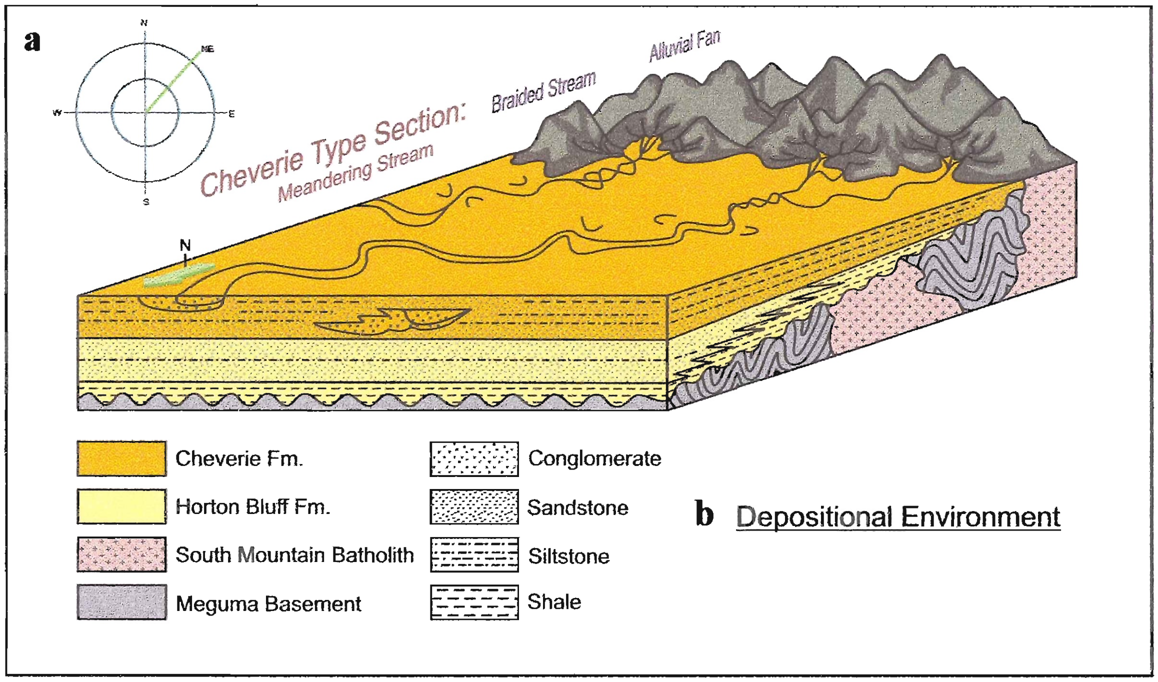


Figure 5.4
a.) Compass representation of the paleocurrent direction determined from field observations.
b.) Schematic block diagram representing the paleoenvironment of the Cheverie Formation from interpretations in this paper. The evidence supports a meandering fluvial system comprising of channel, floodplain and abandoned channel facies.

bore-hole data in the Cheverie #01 well) as being transported by the Kennetcook Thrust System. The underlying sub-horizontal packages are undisturbed Cheverie clastics. The margin of the Kennetcook Basin lies to the south, in the region where Moore and Ferguson (1986) recorded Cheverie in contact with Meguma Basement. In Line 003 the strong reflector by which the Cheverie was distinguished from the Horton Bluff may represent the base of the disconformity between the two formations towards the basin margin.

Shortening

The northeast movement of the fault blocks at the Cheverie type section record dextral strike-slip movement in the Cheverie Formation. This observation corresponds to Waldron et al.'s (2010) field observations and interpretation that shortening occurred in the Tournaisian along SW-NE faults following the deposition of the Horton Group. Similarly, the Macumber Formation in Block A has moved in conjunction with the underlying Cheverie clastics. This also corresponds to Waldron et al. (2010)'s interpretation of northeast transport, up-section in the Macumber fault-propagation fold. It is likely that the reactivation of the major NE-SW faults, which caused the E-W dextral shear responsible for the shortening as seen by the inversion structures interpreted by Waldron et al. (2010), occurred in the Viséan, after the deposition of the Macumber limestone.

CHAPTER 6 CONCLUSION

The Cheverie Formation type section contains approximately 176 m of gently dipping clastic sedimentary rocks which can be divided into three separate facies. Facies A consists of channel deposits characterized by crossbedded pebble conglomerates, caliche conglomerates and coarse grained sands. Facies B represents floodplain deposits dominated by maroon vertosls, siltstones, sandstones, and *in situ* caliche. Facies C contains organic rich silt and mudstone interpreted as abandoned channel deposits. The type section represents a meandering fluvial system under by arid to semi arid conditions. However the coarse nature of Facies A may also represent channel deposits that were discontinuously deposited within the semi-arid system. They can be interpreted as strata deposited under flashy, high flow strength conditions. Source rock candidates for granitoid, volcanic, sedimentary and low grade metamorphic rock fragments and grains are located south to southwest of the section. Below the Macumber Formation contact an angular unconformity distinguishes the base of the *Leander calcareous sandstone member*, which contains an interval of highly cemented quartz rich sandstones. Reactivation along dextral strike-slip faults resulted in basin shortening, creating fault propagation folds in the section

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MR013A

Cheverie Formation Depth: 0.65 m

Classification

Pebble conglomerate

Hand Sample

Very brittle, highly fractured pebbly conglomerate with abundant quartz clasts, light grey in colour with maroon regions in the matrix, clasts are subrounded

Thin Section

Textures and Structures: The sample is poorly sorted with subangular and subspherical clasts. The mean clast size is fine-grained gravel (pebble). The matrix grains are subrounded to subangular and subprismoidal. A large amount of secondary porosity and permeability associated with fractures. Quartz grains are cracked and show undulose extinction or subgrain texture. There are no apparent structures or lattice and shape preferred orientations within the thin section.

Composition:

Quartz	35%
Rock Fragments	45%
▪ Volcanics	22%
▪ Polycrystalline quartz	23%
Muscovite	4%
Fe-oxides	>3%
Zircons (x2)	>1%
Pore space	22%

Matrix: There is little to no clay content in the sample.

MR016A

Cheverie Formation Depth: 3.4 m

Classification

Medium-grained sandstone

Hand Sample

Porous, medium to coarse-grained sandstone, massive, grey-brown in colour, dark brown staining along pore spaces

Thin Section

Textures and Structures: The thin section contains moderately sorted medium-grained sand. The grains are subspherical to prismoidal and subrounded. Coarse-grained muscovite crystals are weakly kinked around surrounding quartz grains. The quartz grains show flat to undulose extinction. There is a large amount of secondary porosity and where diagenesis has created pore space organic material has coated the surrounding grain edges. However, there was little permeability observed in the thin section.

Composition:

Quartz	68%
Fe-oxides	4%
Organics	>3%
Muscovite	2%
Epidote	>1%
Tourmaline	>1%
Zircons (x3)	>1%
Pore space	22%

Matrix: There is little to no clay content in the sample. The matrix material has been almost completely removed, leaving the sandstone to be largely grain-supported, creating pore space

MR017C

Cheverie Formation | Depth: 14.3 m

Classification

Medium-grained sandstone

Hand Sample

Well sorted, medium-grained sandstone, light grey to off-white in colour, very massive, sparse fine-grained, dark grey crystals

Thin Section

Textures and Structures: The mean grain size of this very well sorted sandstone is medium-grained. The siltstone fragments are subprismoidal and subrounded, while the quartz grains are spherical to subspherical. Muscovite and biotite grains are strongly kinked around the quartz grains, which either display undulose extinction or subgrain development. There is a good amount of porosity in the sample, but little to no permeability.

Composition:

Quartz	75%
Clay	8%
Rock Fragments	>5%
▪ Siltstone	>5%
Muscovite/biotite	2%
Fe-oxide	2%
Zircon (x2)	>1%
Pore space	7%

Matrix: There is a small amount of clay between sand grains- the sandstone is mainly grain-supported. A large amount of secondary quartz has precipitated along the boundaries of quartz grains.

MR022B

Cheverie Formation Depth: 74.4 m

Classification

Fine-grained sandstone with calcite cement

Hand Sample

Thinly laminated fine-grained sandstone with small-scale cross-beds, showing climbing and wave ripples, buff maroon in colour with very few micas

Thin Section

Textures and Structures: The mean grain size is fine-grained sand with subrounded and subspherical to subprismoidal grains. The sample is well sorted. Elongate muscovite and chlorite grains are kinked around surrounding quartz grains. Quartz grains display flat to undulose extinction. Laminations in the thin section are defined by clay particles between areas dominated by calcite cement. Micas are more abundant in the clay regions. Fe-oxide staining is present along the grain boundaries adjacent to anhedral Fe-oxide grains. There are no preferred lattice or shape orientations associated with the grains in the cross-bedding. There is no porosity present in the thin section.

Composition:

Quartz	40%
Calcite cement	35%
Clay	15%
Fe-oxides	5%
Chlorite	2%
Muscovite	2%
Epidote	>1%

Cement: There is abundant polycrystalline calcite cement between grains that are largely cement supported in areas with low clay content.

MR022A

Cheverie Formation Depth: 75.6 m

Classification

Fine-grained sandstone

Hand Sample

Thinly laminated, fine-grained sandstone, dull maroon in colour, a few sparse micas reflect on the surface, hairline fractures run parallel to the bedding plane

Thin Section

Textures and Structures: The grains in the thin section are cross-bedded and show gradational bedding. Elongate muscovite grains are kinked around surrounding quartz grains. The mean grain size is fine-grained well sorted sand which are subangular to subrounded and subprismoidal. The quartz grains display undulose extinction. Fe-oxide in the sample is cubic to rectangular and occurs as fine crystals. There is low amount of porosity, with little to no permeability.

Composition:

Quartz	73%
Clay	15%
Fe-oxides	7%
Epidote	2%
Chlorite	>1%
Muscovite	>1%
Pore space	>2%

Matrix: The matrix contains clay particles. The clay gives the sandstone its maroon colour in the hand sample.

MR004A

Cheverie Formation — Depth: 166.8 m

Classification

Very fine-grained sandstone

Hand Sample

Very fine-grained maroon sandstone, in the outcrop it is from the base of a fossil tree layer, many small micas reflect on the surface, very massive rock with no visible fractures, some regions show a subtle fluid-like mingling between fine and very fine-grained material in clay.

Thin Section

Textures and Structures: The sample is a very fine to fine-grained, well sorted sandstone, with subrounded and subspherical to subprismoidal grains. Elongated muscovite grains are kinked around surrounding quartz grains. There is a low amount of porosity in the sample and little to no permeability. Overall, there is no preferred orientation in the sand grains, clay or cement.

Composition:

Quartz	45%
Clay	25%
Calcite cement	15%
Fe-oxides	9%
Muscovite	5%
Pore space	~1%

Matrix: The matrix is contains a large amount of clay. The proportions of clay fluctuate with the grain size so that more clay is present with very fine-grained sands. The clay gives the sandstone its maroon colour in the hand sample.

Cement: A small amount of fine-grained, anhedral calcite cement is intermingled with the matrix material.

MR006A

Cheverie Formation Depth: 169.1 m

Classification

Caliche pebble conglomerate

Hand Sample

Pebble conglomerate composed of reworked caliche nodules. Clast sizes range from 5 to 40 mm in diameter and have a mean size of 14 mm. Caliche clasts are well rounded and prismoidal. Exposed clasts have weathered to an orangey-brown colour, clasts on freshly cut surfaces are brownish-tan. The clasts are supported in a fine-grained maroon-coloured matrix. The outcrop exposures are indurated and generally less than 1 m in thickness.

Thin Section

Textures and Structures: The thin section shows circumclastic cracking. Quartz grains are corroded along their edges and float in the matrix material. Each clast has a different density of quartz inclusions, as well as a varying mean grain size. Most of the clasts have quartz inclusion trails that record the original orientation of the *in situ* nodule and in some cases, when the grain size is mixed, gradational bedding and cross-bedding can be identified. A few of the coarser grained clasts have gouged and settled into finer-grained clasts.

Composition:

Micrite/Mud	20%
Reworked Nodules	73%
▪ Fine	21%
▪ Medium	31%
▪ Coarse	5%
▪ Mixed	16%
Sparite	1%
Quartz	6%

Matrix: Contains a large percentage of micritic calcite and mud with minor sparite. The sample shows a floating texture. The matrix is filled with fine-grained anhedral quartz displaying undulose extinction.

MR011B

Cheverie Formation Depth: 170.9 m

Classification

Granule conglomerate with calcite cement

Hand Sample

Fine gravel to very fine gravel sandstone, light grey in colour, slightly vitreous

Thin Section

Textures and Structures: The grains and clasts are poorly sorted and do not display any structures or preferred orientations. The mean grain size is very fine gravel (pebble) with subrounded and subprismoidal grains and clasts. There is very little porosity and no visible permeability. Quartz grains exhibit flat to undulose extinction. Polycrystalline calcite contains small quartz inclusions and volcanic fragments contain small calcite intergrowths.

Composition:

Quartz	28%
Calcite Cement	25%
Rock Fragments	47%
▪ Siltstone	15%
▪ Polycrystalline quartz	12%
▪ Mudstone	10%
▪ Volcanics	6%
▪ Polycrystalline calcite	4%

Cement: Anhedral calcite cement creates a mosaic texture between grains.

MR011A

Cheverie Formation Depth: 171.4 m

Classification

Pebble conglomerate with calcite cement

Hand Sample

Coarse gravel to fine gravel clasts of siltstone, mudstone and carbonate, very poorly sorted, well rounded discoidal to roughly spherical, light grey in colour, matrix material is medium to very coarse-grained sand

Thin Section

Textures and Structures: The sample is very poorly sorted with subangular to subrounded quartz and feldspar crystals and well rounded rock fragments. Siltstone fragments contain small cubic Fe-oxide crystals. Plagioclase and muscovite from granite fragments are being replaced by calcite, leaving quartz inclusions and creating a pseudomorphic texture. Similarly, the internal lath structure of the volcanic fragments is being replaced by small radiating growths of calcite. Quartz grains exhibit flat to undulose extinction.

Composition:

Quartz	30%
Rock Fragments	44%
▪ Siltstone	20%
▪ Calcite/granite pseudomorphs	18%
▪ Mudstone	2%
▪ Polycrystalline quartz	2%
▪ Volcanic fragments	2%
Calcite Cement	19%
Orthoclase	4%
Muscovite	~1%

Matrix: The mean grain size of the matrix is very coarse sand and the conglomerate is overall clast supported

Cement: Anhedral calcite cement creates a mosaic texture, connecting matrix and clast material.

MR010A

Cheverie Formation | Depth: 173.45 m

Classification

Fine-grained sandstone

Hand Sample

Very fine-grained sandstone, dull grey in colour with some small reflective grains, mottled maroon areas, small fractured surfaces, very massive

Thin Section

Textures and Structures: There is fluid-like grain mixing of fine and medium sand in the thin section. The sample is poorly sorted with and mean grain size of fine sand. The grains are subrounded and sub subspherical. The quartz grains have flat to undulose extinction. Elongate muscovite grains are kinked around quartz grains. The Fe-oxide crystals in the sample are euhedral, sparse in medium-grained sand, but dense in the fine-grained sand and silt particles. Clinopyroxene occurs as medium-grained, well-rounded crystals.

Composition:

Quartz	50%
Clay	20%
Fe-oxide	8%
Calcite Cement	7%
Muscovite	5%
Silt	5%
Orthoclase	3%
Clinopyroxene	2%

Matrix: The sample is grain-supported with clay material.

Cement: A small portion of the intergranular space is filled with calcite cement.

MR012C

Cheverie Formation | Depth: 174.3 m

Classification

Granule conglomerate

Hand Sample

Granule conglomerate, light grey in colour, poorly sorted, quartz and feldspar crystals in a finer grained matrix, no apparent structures

Thin Section

Textures and Structures: The grains are poorly sorted, subspherical, with subangular grains and subrounded clasts. The grains range from medium to granule with a mean grain size of granule. Any matrix material has been replaced by calcite cement. There are some small-scale fractures in the thin section. There is low intergranular porosity and little to no permeability. Muscovite crystals are elongate and have been kinked around quartz grains. The quartz grains have undulose extinction and subgrains. There is no preferred orientation of grains or matrix material in the thin section.

Composition:

Quartz	45%
Calcite Cement	32%
Orthoclase	12%
Rock Fragments	8%
▪ Volcanics	5%
▪ Calcite/granite pseudomorphs	3%
Muscovite	2%
Hematite Cement	1%
Pore space	3%

Cement: Polygonal calcite cement has grown between the grains with minor hematite cement occurring around grain edges.

MR007A

Cheverie Formation | Depth: 174.6 m

Classification

Pebble Conglomerate

Hand Sample

Pebble conglomerate with calcareous clasts, poorly sorted, light grey in colour

Thin Section

Textures and Structures: The mean grain size in thin section is coarse gravel (pebble) with subangular to subrounded grains. Muscovite and plagioclase are being replaced by calcite in granite fragments forming pseudomorphs with quartz inclusions. Quartz grains exhibit flat to undulose extinction. A few detrital ooids were found in the thin section, showing radial calcite growth. There is some minor intergranular porosity, but no permeability. There is no preferred orientation of the clasts or matrix material.

Composition:

Rock Fragments	62%
▪ Calcite/Granite pseudomorphs	30%
▪ Polycrystalline quartz	17%
▪ Siltstone	15%
Orthoclase	15%
Clay	20%
Ooids	>2%
Pore space	~2%

Matrix: The matrix between the gains and fragments is composed of clay and calcite

MR012B

Cheverie Formation — Depth: 175.25 m

Classification

Coarse-grained sandstone with calcite cement

Hand Sample

Very coarse-grained sandstone, largely inequigranular, light grey in colour, fresh surface is vitreous with sparse dark minerals, the hand sample is very dense

Thin Section

Textures and Structures: Poorly sorted, subangular grains that are subprismoidal. There is a subtle gradational layering defining thick laminations. Grain sizes vary from fine to very coarse sand, with a mean grain size of coarse sand. Quartz grains have undulose extinction. Garnet crystals are angular with many small quartz inclusions. Volcanic rock fragments are subrounded, but are strongly cracked, broken and have radial calcite replacing the internal lath structure.

Composition:

Quartz	60%
Calcite Cement	25%
Rock Fragments	13%
▪ Volcanics	4%
▪ Polycrystalline calcite	4%
▪ Siltstone	3%
▪ Mudstone	2%
Garnet	>2%

Cement: Anhedral calcite cement creating a mosaic texture between grains

MR012A

Macumber Formation Depth: 175.3 m

Classification

Fossil-bearing pelmicrite

Hand Sample

Fine-grained homogeneous limestone, maroon in colour, thinly bedded at the outcrop scale

Thin Section

Textures and Structures: There are thinly laminated beds of peloids in a structureless micrite matrix with minor sparite. The peloids are roughly spherical to subspherical and are very well sorted and average to be medium-grained. The peloids have vague outlines and are at times difficult to distinguish between matrix material. A fine stylolitic structure is accentuated by an accumulation of black material along the thin section. There is also small, > 1mm, veins running perpendicular to the laminations.

Composition:

Peloids	70%
Micrite	20%
Sparite	10%
Fossils	> 1%

Fossils: Ostracods: shell structures that have formed of rod-shaped calcite crystals orientated perpendicular to the shell outline, showing a sweeping extinction pattern in cross-polarized light. The shells are thick walled with thick calcite cement in the internal cavities. There are recurved, hook-like terminations on each valve.