Classic Carboniferous Sections of the Minas and Cumberland Basins in Nova Scotia

With Special Reference to Organic Deposits

J. H. Calder[1], R. C. Boehner[1], D. E. Brown[2], M. R. Gibling[3], P. K. Mukhopadhyay[4], R. J. Ryan[1] and D. M. Skilliter[5]

[1]Nova Scotia Department of Natural Resources; [2] Canada-Nova Scotia Offshore Petroleum Board; [3]Dalhousie University; [4]Global Geoenergy Research Ltd.; [5]Boston College

The Society for Organic Petrology
Annual Meeting Field Trip, 29-30 July, 1998

NOVA SCOTIA
Natural Resources

Open File Report ME 1998-5

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'But the finest example in the world of a natural exposure in a continuous section ten miles long, occurs in the sea cliffs bordering a branch of the Bay of Fundy in Nova Scotia.'

Sir Charles Lyell, 1871

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* may not be visited due to time constraints imposed by the tide.

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Safety Measures for Coastal Sections

The coastal exposures of Nova Scotian geology offer spectacular views but also some very real hazards. Please read on.

TIDES: These geological sites witness the highest tides in the world. Consult tide tables or tide times published daily in most provincial newspapers before visiting them. If none are available, you can gauge the time of the high tide approximately with the phase of the moon: at full (and new) moon, the tide is high roughly at noon. *For most coastal sections, you should plan to depart two hours before high tide.* Plan your departure on the basis of how many hours after low tide the site became accessible. Low and high tides are separated by approximately 6½ hours, with the high tide time advancing (later) by about an hour each day.

INTERTIDAL AREAS: Avoid muddy areas, especially in the lower intertidal zone, where you can become stuck during a rising tide. Always be vigilant of the rising tide behind you.

FOOTING: Intertidal rocks can be exceedingly slippery, resulting in a swift and unforgiving fall. Avoid damp rocks and in particular those with green algal growth (*very* slippery).

CLIFFS: *Never climb the cliffs*: they are unstable and a fall can be fatal. *Stay back from the cliffs* as much as possible: rock falls occur without warning and can be fatal.

.... and wear a hard hat!

Acknowledgments

We would like to acknowledge the work of our various colleagues who are not authors of this guide, but who contributed to the ideas presented here through ongoing debate and exchange of thoughts. We are especially grateful to Doug MacDonald, who in two weeks performed the tasks of editing the text, overseeing the drafting of figures, and printing the field guide. Thanks to Barb MacDonald for desktop publishing under pressure. Robert Naylor kindly reviewed the field guide. Thanks to the Cartographic Section of the Nova Scotia Department of Natural Resources and to Tanya Costain for their work on the figures.

TSOP '98 Field Trip Itinerary

Wednesday, 29 July: low tide at Burntcoat Head 1200 hrs

08:30 (for 9:00)	Depart Prince George Hotel, Halifax
10:00	Arrive Falls Brook Quarry section, Horton Group: Bob Ryan
11:30	En route to Horton Bluffs; coffee stop at Tim Horton's, Windsor
12:30	Arrive Horton Bluffs section, Horton Group: Martin Gibling
13:30	Packed lunch at Horton Bluffs
13:45	En route to Cheverie
14:30	Arrive Cheverie section, Windsor Group: Bob Boehner
16:00	Depart for Amherst
18:00	Arrive Wandlyn Inn, Amherst. Supper, Wandlyn Inn, Amherst
20:30	Field Trip Overview: John Calder

Thursday, 30 July: low tide at Joggins 1300 hrs

08:30	Depart Amherst for Joggins
09:00	Arrive Joggins: Joggins section, Cumberland Group: John Calder, Martin Gibling and Deborah Skilliter
13:00	Picnic lunch, Joggins
13:30	Visit to the Joggins Fossil Centre
14:00	Depart for Parrsboro
14:30	Arrive at Fundy Geological Museum, Parrsboro
15:00	West Bay Formation at Ottawa House/East Bay: John Calder
16:00	One van to depart early for drop-off at Halifax International Airport (if needed) Cold lobster supper, Parrsboro
17:30	Depart for Halifax. Drop-off at Airport Hotel if required
20:00	Arrive Halifax

Introduction

The Maritimes Basin of Nova Scotia offers a nearly complete stratal record of the Carboniferous Period, spectacularly exposed along continually eroding coastal sections. On this field trip, we will visit some of these classic exposures (Fig. 1), with stops to examine each of the lithostratigraphic groups (Fig. 2), with the exception of the redbeds of the uppermost Pictou Group.

As we approach the end of the Twentieth Century, it is invigorating to see that these classic sections, long ago made famous by the likes of Sir William Dawson, Sir Charles Lyell, Sir William Logan, and Walter Bell, still can surprise and stimulate debate. It is safe to say that as this field guide is being written, geologists are re-evaluating long-standing ideas, 'facts' and models, with the fresh thinking that marked the work of our predecessors. One of these ideas involves reconsideration of the aquatic fossil record and its implications for our interpretations of the pre- and post-Viséan/Windsor basin fill. This fossil record has been long held, perhaps dogmatically, to be strictly continental and devoid of marine influence (see Calder, 1998 and recent research cited therein). Accompanying and perhaps spurring this open mindedness has come a resurgence of hydrocarbon exploration. At each of the field stops, coal-bearing strata and hydrocarbon source and reservoir rocks are prominent.

In this field guide, stop descriptions have been contributed by the various stop leaders, with a concerted attempt at minimal editing, except where necessary for the continuity of the guide and a modicum of consistency. In this way, the various points of view of individual geological colleagues hopefully remain. For any personal perspectives that may have crept in to your stories, the first author offers his apologies! Much of the introductory geology in the field guide has been borrowed liberally from the recent review of the Carboniferous evolution of Nova Scotia by Calder (1998).

Summary of the Carboniferous of Nova Scotia (after Calder, 1998)

During the Carboniferous Nova Scotia lay at the heart of paleo-equatorial Euramerica in a broadly intermontane paleo-equatorial setting, the Maritimes-West European province; to the west rose the orographic barrier imposed by the Appalachian Mountains and to the south and east, the Mauritanide-Hercynide belt. The geological affinity of Nova Scotia for Europe, reflected in elements of

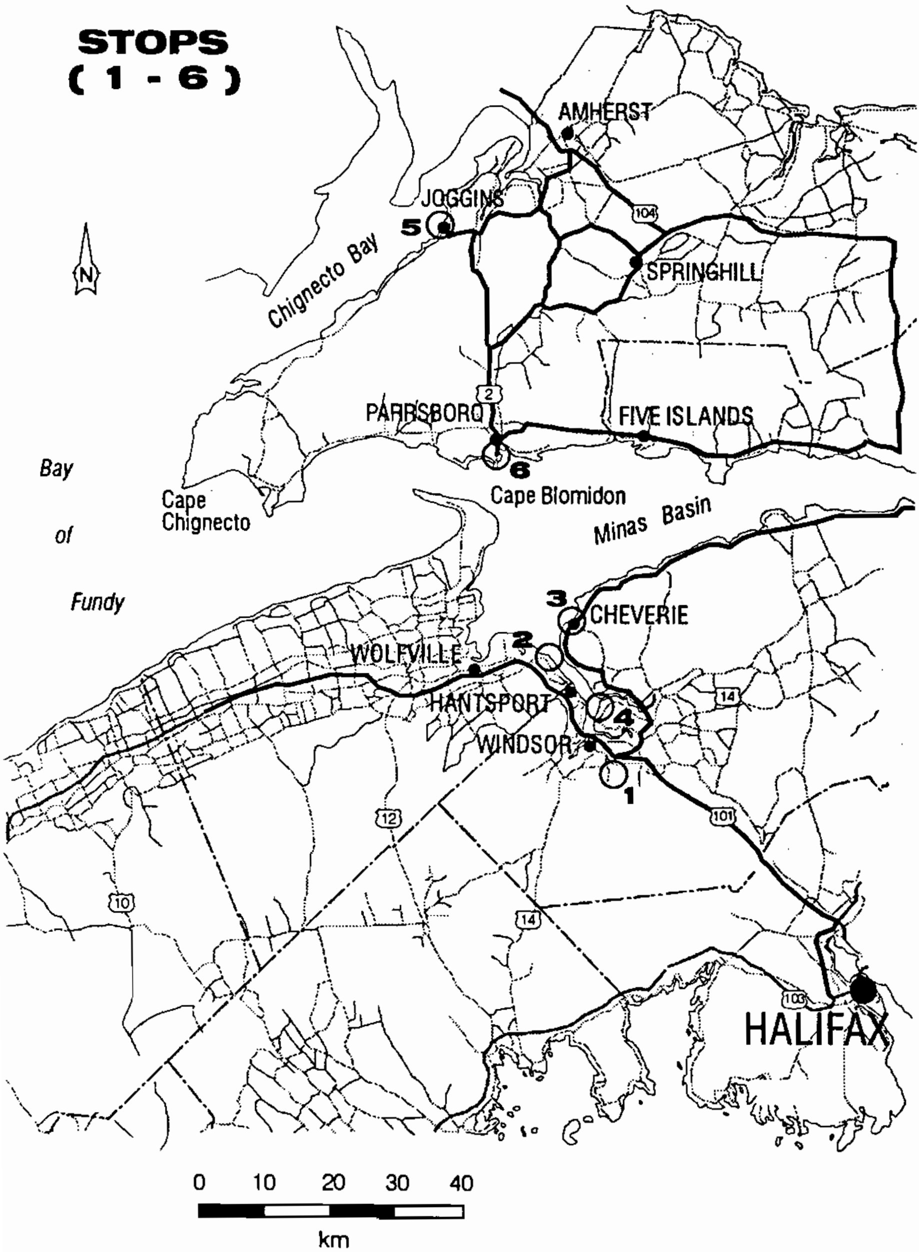


Figure 1. Location map showing the field trip sites.

the Carboniferous flora and fauna, was mirrored in the evolution of geological thought even before the epochal visits of Sir Charles Lyell.

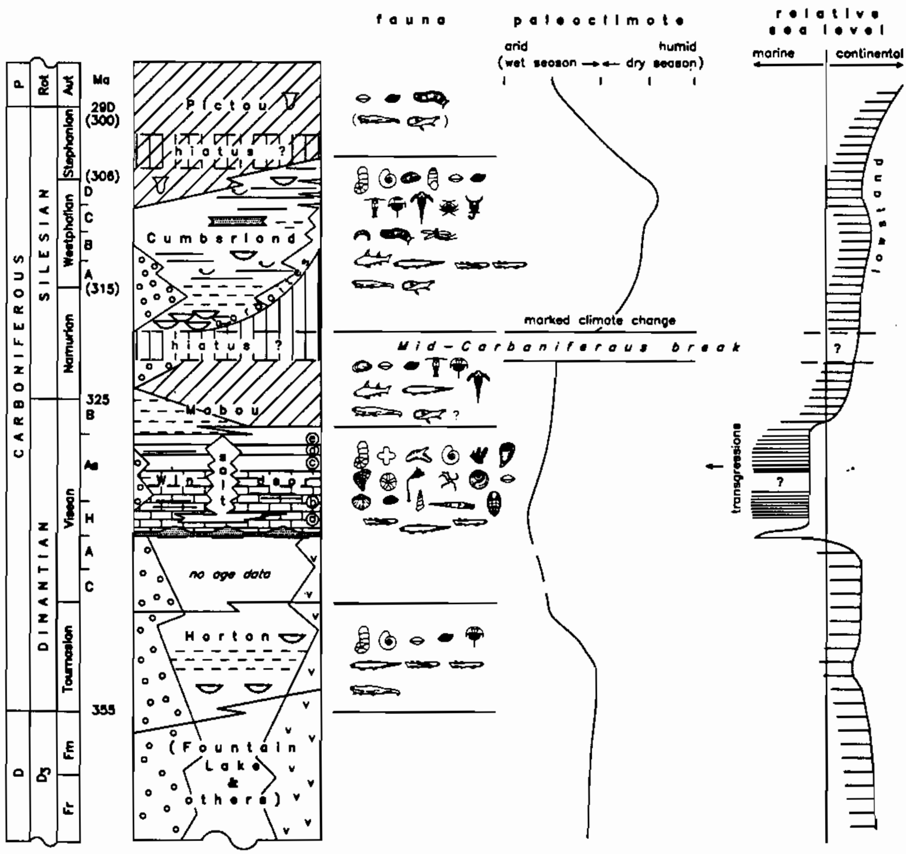


Figure 2. Stratigraphic column of the Carboniferous rocks of the Maritimes Basin in Nova Scotia (after Calder, 1998) with major faunal groups, interpreted paleoclimate and sea level changes. The stratigraphic position of field stops is indicated.

The Maritimes Basin of eastern Canada, born of the Acadian-Caledonian orogeny that witnessed the suture of Iapetus in the Devonian, and shaped thereafter by the inexorable closing of Gondwana and Laurasia, comprises a nearly complete stratal sequence as great as 12 km thick that spans the Middle Devonian through Lower Permian. Across the southern Maritimes Basin, in northern Nova Scotia, deep depocentres developed en echelon adjacent to a transform platelet boundary between terranes of Avalon and Gondwanan affinity. The subsequent history of the basins can be summarized as distension and rifting attended by bimodal volcanism waning through the Dinantian, with marked transpression in the Namurian and subsequent persistence of transcurrent movement linking Variscan deformation with Mauritainide-Appalachian convergence and Alleghenian thrusting. This Mid-Carboniferous event is pivotal in the Carboniferous evolution of Nova Scotia. Rapid subsidence adjacent to transcurrent faults in the early Westphalian was succeeded by thermal sag in the later Westphalian and ultimately by basin inversion and unroofing after the early Permian as equatorial Pangea finally assembled and subsequently rifted again in the Triassic.

The component Carboniferous basins have provided Nova Scotia with its most important source of mineral and energy resources for three centuries. Their combined basin fill sequence preserves an exceptional record of the Carboniferous terrestrial ecosystems of paleo-equatorial Euramerica, interrupted only in the mid-late Viséan by the widespread marine deposits of the hypersaline Windsor gulf. Stratal cycles in the marine Windsor, schizohaline Mabou, and coastal plain to piedmont coal measures 'cyclothems' record Nova Scotia's paleogeographic evolution and progressively waning marine influence. The semi-arid paleoclimate of the late Dinantian grew abruptly more seasonally humid after the Namurian and gradually recurred by the Early Permian, mimicing a general Euramerican trend. Generally more continental and seasonal conditions prevailed than in contemporary basins to the west of the Appalachians and, until the mid-Westphalian, to the east in Europe. Paleogeographic, paleoflow and faunal trends point to the existence of a Mid-Euramerican Sea between the Maritimes and Europe that persisted through the Carboniferous. The faunal record suggests that cryptic expressions of its most landward transgressions can be recognized within the predominantly continental strata of Nova Scotia. The recognition of marine influence has particular implications for interpreting and predicting the composition and stratigraphic occurrence of coal and hydrocarbon source rocks.

Geological Setting: The Maritimes Basin in Euramerica

The Carboniferous strata of Nova Scotia record most of the history of the larger, late Paleozoic Maritimes Basin (Williams, 1974) of New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland (Fig. 3). Late Paleozoic strata of the Maritimes Basin span the Middle Devonian (Dawson, 1862; McGregor, 1977; Forbes *et al.*, 1979) through Early Permian (Dawson, 1891 and earlier; Barss *et al.*,

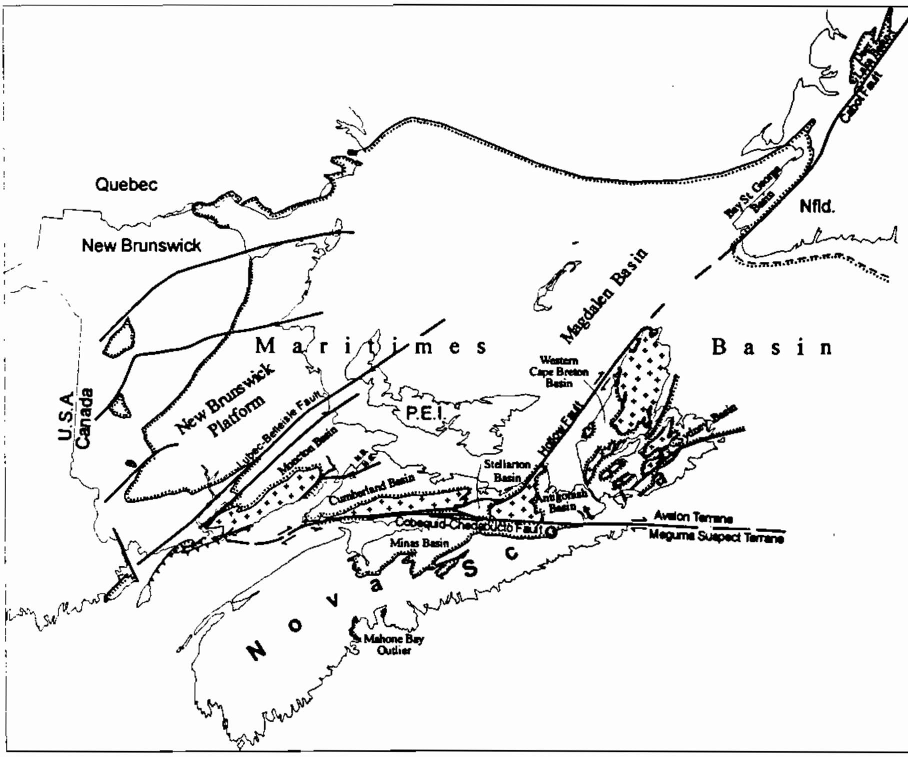


Figure 3. Map of the Maritimes Basin, showing current extent of late Paleozoic strata, basinal depocentres and major faults (after Calder, 1998).

1963) with remarkably few gaps. The Maritimes Basin is a complex of predominantly northeasterly trending intermontane basins, once variously interconnected and now, as then, defined by intervening massifs of the Avalon, Grenville and Meguma terranes. The basin was born of the Devonian (Emsian) Acadian orogeny (Poole, 1967), contemporary of the latest stage of the Caledonian orogeny, both of which record final closure of the Iapetus Ocean (McKerrow, 1988). The Carboniferous evolution of the Maritimes Basin bears witness to the nativity of Pangea as Gondwana and numerous platelets of suspect terrane collided with Laurasia and the Old Red Continent, manifested in the Hercynian and Alleghenian orogenies (Rast, 1988). Evolution of the Maritimes Basin during the late Devonian and Dinantian records extension (McCutcheon and Robinson, 1987; Bradley, 1982; Hamblin and Rust, 1989), most pronounced between the Lubec-Bellisle, Cobequid and Hollow faults, an area which has been termed the Maritimes Rift (Belt, 1969; van de Poll *et al.*, 1995). This was suceeded in the Silesian by transpression and transtension in a renewed orogenic phase (Plint and van de Poll, 1984; Nance, 1987; Waldron *et al.*, 1989; Yeo and Ruixiang, 1987) and broadly across the basin by thermal sag (Bradley, 1982) and ultimately in the Permo-Triassic, by inversion (Ryan and Zentilli, 1993).

The late Paleozoic to Mesozoic rocks in Atlantic Canada record a complex history of sedimentation, tectonics and volcanism in the northeast Appalachians. The strata within these successor basins reach a maximum thickness of 12 km in the central Gulf of St. Lawrence (Magdalen Basin). They are a complex molassic succession dominated by continental deposition. Sediments were derived both locally (especially in the Late Devonian and Early Carboniferous) and regionally (Late Carboniferous) from the Appalachian Orogen. These transient depocenters represent the waning stages of the Devonian Acadian orogeny and the subsequent uplift of the orogen following the mid-Devonian docking of the Avalon Composite Terrane (Avalonia) and the Meguma Terrane. The early Mesozoic records the initial rifting phase of the Proto-Atlantic Ocean and the late Mesozoic to Cenozoic its subsequent opening.

The Late Devonian to Early Viséan was characterized by crustal instability with initial molassic deposition of coarse- to fine-grained alluvial, fluvial, lacustrine and locally rift- related volcanic deposition in intermontane basins (Fountain Lake Group and Horton Group). Deposition occurred initially under dry (seasonal?) conditions (Late Devonian) then humid lateritic conditions. Extensive alluvial to fluvial-lacustrine deposition in the Tournaisian evolved through semi-arid dry conditions with local evaporitic lacustrine deposition and redbeds in the late Tournaisian to early Viséan (Horton Group).

Nova Scotia and the Maritimes Basin in the Carboniferous lay within paleo-equatorial Euramerica, drifting northward from a paleolatitude of South 12 degrees to cross the equator by the beginning of the Permian (Scotese and McKerrow, 1990). Generally considered a northern part of the Appalachian orogenic belt, the Maritimes Basin lay situated at the paleosoutheastern margin of the Appalachians in a palogeographic region distinct from the Appalachian Basin to the west (Fig. 4). The mountain range posed an orographic climate barrier, drainage divide and phytogeographic barrier to biotic exchange between these two areas. No such *land* barrier existed to the east, however, and Nova Scotia can be included with Britain and western Europe in a broadly intermontane paleogeographic region of tropical paleolatitude lying to the east of the

Appalachians, north of the Mauritanides, and west of the Urals, and traversed by the Acadian-Hercynide upland belt (Fig. 4). This region was called the Maritime-West European Province by Calder (1998), modified after Leeder (1987), analagous to the Equatorial Low Latitude-Acadia phytogeographic unit of Rowley *et al.* (1985). Even before the concept of continental drift, the close affinity of Nova Scotia for western Europe and Britain in particular has been long known (Dawson, 1888; Bell, 1929, 1944 among others).

Depocentres of the Maritimes Basin in Nova Scotia

The major basinal depocentres of the southern Maritimes Basin in Nova Scotia (Fig. 3); after Calder, 1998, modified from Gibling, 1995, from west to east, are: (1) Cumberland Basin, (2) Minas Basin (including Windsor-Shubenacadie, Musquodoboit-Mahone Bay and depocentres along the southern Cobequids), (3) Stellarton Gap and Stellarton Basin, (4) Antigonish Basin, (5) Western Cape Breton, at the margin of the submarine Gulf of St. Lawrence, (6) Central Cape Breton, including Glengarry, Loch Lomond, Salmon River, and (7) Sydney Basin. Each of these component basins in turn comprises smaller depocentres, in part reflecting the anastomosing fault configuration generated by the transcurrent fault systems of the Maritimes Basin. The accrued Carboniferous fill of these component basins may reach 12 km in thickness (Belt, 1968b). The reader is referred to Bell (1929, 1940, 1944; 1960), Belt (1965), Ryan *et al.* (1991), Williams *et al.* (1985) and to Gibling (1995) for comprehensive details of their stratigraphy. The component formations of the six main lithostratigraphic groups are given in Table 1. This field trip examines classic sections in the first two of these component depocentres, the Cumberland and Minas basins.

Late Paleozoic Stratigraphy of the Maritimes Basin in Nova Scotia

The first comprehensive account of the Carboniferous geology and mineral resources of Nova Scotia is that of Richard Brown (1829). Brown was employed by the London-based General Mining Association as manager of coal mining operations in the Sydney coalfield, Cape Breton County, from 1827 to 1864. An "experienced observer", as he was respectfully described by Sir Charles Lyell (1845, p. 206), Brown (1829) applied to the Carboniferous strata of Nova Scotia the then recently published stratigraphic nomenclature for Britain of Coneybeare and Phillips (1822). The early stratigraphic interpretation of Brown is striking in

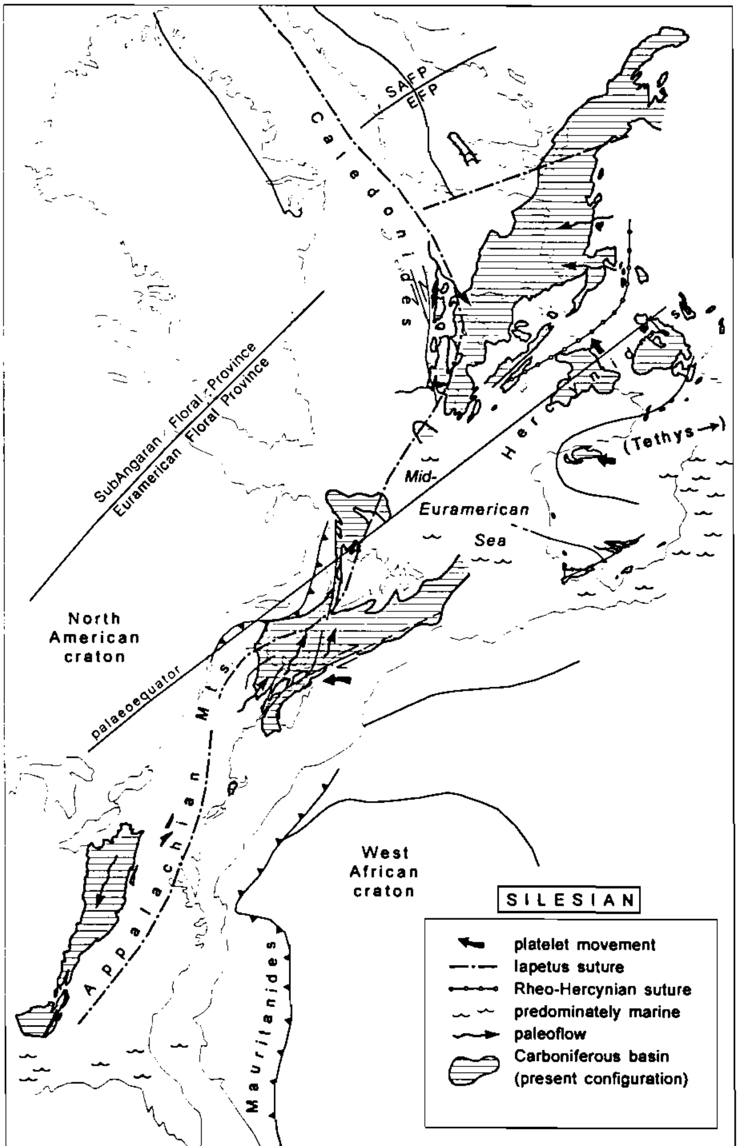


Figure 4. The Maritimes Basin in its paleogeographic context with the Appalachian Basin and Western European Basin, after Calder (1998). In this reconstruction, the existence of a Mid-Euramerican Sea was proposed by Calder (ibid).

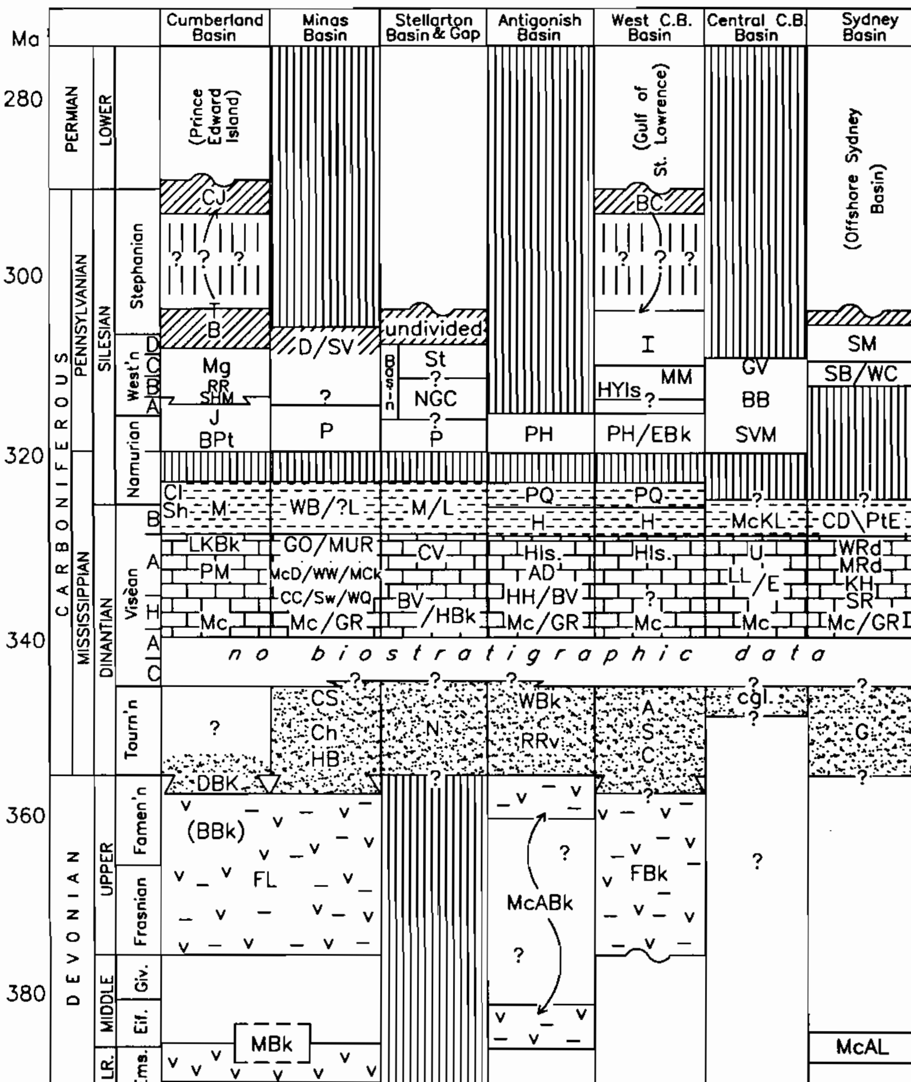
its similarity to current subdivisions (Table 1). Current stratigraphic nomenclature has been adopted largely from Dawson (1878), who drew upon the work in the coalfields of his contemporaries McOuat and Robb at the Geological Survey of Canada, and from the subsequently evolved nomenclature of Walter A. Bell (1929, 1944) and Edward Belt (1964).

Bell (1929, 1940, 1944) established series for the Carboniferous strata of Nova Scotia largely on the basis of the macroflora (Calder, 1998, appendix A) and bivalve fauna (Calder, ibid., appendix B), which he correlated with equivalent European stages. The series of Bell, which established the age relationship of coal-bearing strata within the disjunct Carboniferous basins, were subsequently adopted as the lithostratigraphic groups (Fig. 2 and Table 1) shown below.

The diachronous nature of lithostratigraphic units in the Maritimes Basin was illustrated by the application of miospore biostratigraphy (Belt, 1964; Hacquebard *et al.*, 1960; Barss *et al.*, 1963). Problems inherent with the adoption of a lithostratigraphy born of biostratigraphy have dogged virtually all subsequent stratigraphers. This inherent stratigraphic problem has been accomodated in part by the growing practice of assigning diachronous coal measures within the disjunct coal basins to the Cumberland Group and succeeding redbeds to the Pictou Group, as proposed by Ryan *et al.* (1991).

Because the biostratigraphy of the Carboniferous of the Maritimes Basin is rooted in the terrestrial fossil record, except during the mid to late Viséan (Fig. 2), the effects of provincialism and paleogeography can be particularly problematic in achieving precise correlations with stage boundaries based on marine fauna elsewhere in Euramerica. The scarcity of recognized tonsteins (Lyons *et al.*, 1994) further stymies the use of absolute radiometric dates, which otherwise could be employed to assist in the resolution of chronostratigraphy.

Table 1. Lithostratigraphic formations of late Paleozoic fill in the Maritimes Basin, Nova Scotia (after Calder, 1998).



FORMATIONS

Pictou Group:
B – Balfron
BC – Broad Cove
CJ – Cape John
T – Tatamagouche

Cumberland Group:
BB – Big Barren
BPt – Boss Point
D – Deloney
EBk – Emery Brook
GV – Glengarry Valley
HYIs – Henry Island
I – Inverness
J – Joggins
Mg – Malagash
MM – Mabou Mines
NGC – New Glasgow Conglomerate
P – Parrsboro*
PH – Port Hood
RR – Ragged Reef
SHM – Springhill Mines
St – Stellarton
SV – Scotch Village
SVM – Silver Mine

Mabou Group:
CD – Cape Dauphin
CI – Claremont*
H – Hastings
L – Londonderry
M – Middleborough
McKL – McKeigan Lake
PQ – Pomquet
PtE – Point Edward
Sh – Shepody
WB – West Bay

Windsor Group:
AD – Addington
BV – Bridgeville
CC – Carroll's Corner
CV – Churchville
E – Enon
GO – Green Oaks
GR – Gays River
HBk – Holmes Brook
HH – Hartshorn
HIs – Hood Island
KH – Kempt Head
LKBk – Lime Kiln Brook
LL – Loch Lomond
Mc – Macumber
MCk – Miller Creek
McD – MacDonald Road
MUR – Murphy Road
MRd – Meadows Road
PM – Pugwash Mine
Sw – Stewiacke
SR – Sydney River
U – Uist
WQ – White Quarry
WRd – Woodbine Road
WW – Wentworth

Horton Group:
A – Ainslie
C – Creignish
Ch – Cheverie
CS – Coldstream
DBk – Diamond Brook
F – Falls
G – Grantmire
HB – Horton Bluff
S – Strathlorne
WBk – Wilkie Brook

Fountain Lake et al.
BBk – Byers Brook
FBk – Fisset Brook
FL – Fountain Lake
MBk – Murphy Brook
McABk – McArras Brook
McAL – McAdam Lake

Organic Deposits

Coal Deposits

With the exception of a few restricted beds in the Middle Devonian McAdam Lake Formation and Lower Carboniferous Horton Group, coal-bearing strata are assigned to the Pennsylvanian Cumberland Group (Fig. 2). Coal deposits (Fig. 5) of (?late Namurian-) Westphalian A-C age developed as areally restricted rheotrophic mires, nourished through the dry season by supplemental groundwater flow (Calder, 1994), were generated at piedmont margins (Springhill coalfield: Calder, 1994), in distributary (Joggins coalfield: Calder, ibid.) and lacustrine (Stellarton Basin: Calder, 1979; Hacquebard and Donaldson, 1969; Naylor *et al.*, 1989; Waldron, 1996) settings during regional transpression and transtension. The coal-bearing strata of the Stellarton Basin in particular include sapropelic ('oil shale') deposits (Smith and Naylor, 1992). Areally extensive mires

Lithostratigraphic formations of late Paleozoic fill in the Maritimes Basin, Nova Scotia (after Calder, 1998).		
Horton Group	late Famennian-Tournaisian	alluvial deposits and lacustrine to nearshore marine grey beds; basin margin conglomerate (up to 3000 m)
Windsor Group	mid to late Viséan	schizohaline marine evaporites (limestone, anhydrite, gypsum, halite and potash) and redbeds (ca. 1000 m?)
Mabou (Canso) Group	late Viséan - Namurian A	nearshore marine to lacustrine grey and red beds (up to 3000 m)
Cumberland Group	(?Namurian C -) Westphalian A - Stephanian	alluvial and lacustrine coal measures (up to 4000 m)
Pictou Group	Westphalian D - early Permian	continental alluvial redbeds (1650 to 3000 m)

developed in the Westphalian D-Cantabrian on upper coastal plains (Hacquebard and Donaldson, 1969; Gibling and Bird, 1994) during thermal sag. The resulting coal deposits constitute the main economic seams of Nova Scotia, mined in collieries of the Sydney Basin. These coal beds, in the past assigned either to the Morien or Pictou groups, may have attained a mesotrophic status if only through the increased, hence insular, area of the peatlands (Marchioni *et al.*, 1994; Calder *et al.*, 1996).

Kinematic research into coal bed methane generation indicates that gas desorption in coal beds of less than R_o 0.9 may be impeded by micropore blockage by earlier-generated oil, but enhanced above that maturity by cracking of the oil (Mukhopadhyay *et al.*, 1993). In all basins, rank increases within the bituminous range with depth of burial (Hacquebard and Donaldson, 1970). Near the juncture

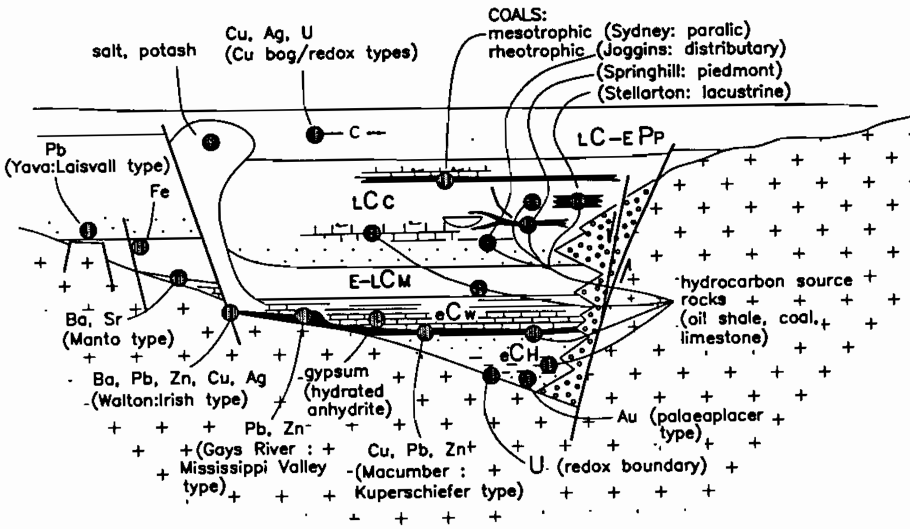


Figure 5. Schematic disposition of coal, hydrocarbon source rocks, and mineral resources in the lithostratigraphic groups of the Maritimes Basin (after Calder, 1998).

of the Hollow and Cobequid faults in the eastern Debert-Kemptown coalfield, rank attains a high of semi-anthracite.

Hydrocarbons

Hydrocarbon source rocks in of the Maritimes Basin in Nova Scotia (Fig. 5) include sapropelic shales of the Horton Group, widespread organic-rich carbonate laminites of the Windsor Group, and sapropelic shales, sapropelic and humic coals, and basin-wide, organic-rich bivalve-bearing limestones and shales, all of the Cumberland Group.

With few exceptions (see Utting and Hamblin, 1991), the strata of the Maritimes Basin at surface lie everywhere within the oil or gas windows, with an R_o at surface ranging from 0.4 where supressed by liquid hydrocarbons (Mukhophadyay *et al.*, 1991) to >2 (Hacquebard and Donaldson, 1970; Ryan and Boehner, 1994). Oil seeps occur presently (Bell, 1958; Short, 1986), even though the apatite fission track record indicates that the oil window had been attained early in the basin history, prior to 250 Ma (Grist *et al.*, 1995). New models of hydrocarbon generation in Nova Scotia should incorporate the different thermal and structural histories of Horton, Windsor and Mabou strata before the Mid-Carboniferous event and Cumberland and Pictou strata thereafter, and should consider possible cryptic marine transgressions within groups traditionally described as "non-marine" (Calder, 1998).

Although the organic-rich shales of the Horton Group traditionally have been considered to hold the greatest potential as a hydrocarbon source (Bell, 1958), current research is focusing elsewhere. The potential of organic-rich carbonates of the Windsor Group has been largely overlooked, and perhaps even more so, the thick and areally extensive black shales of the Mabou Group and organic-rich limestones of the coal measures.

Horton Group Sections (Stops 1 & 2)

General Stratigraphy of the Horton Group

Bell (1929) defined the Horton Series and divided it into a lower Horton Bluff Formation and an upper Cheverie Formation. The type area is near Hantsport (Fig. 6), including the Horton Bluff section (Stop 2). Bell (1960) subsequently defined the strata as the Horton Group (Fig. 2), and divided the Horton Bluff Formation into four informal units: basal member, lower and upper parts of the middle member, and the upper member. Martel (1990) and Martel and Gibling (1996) presented detailed coastal and stream sections and formally named four members (Fig. 7) that correspond closely with those of Bell.

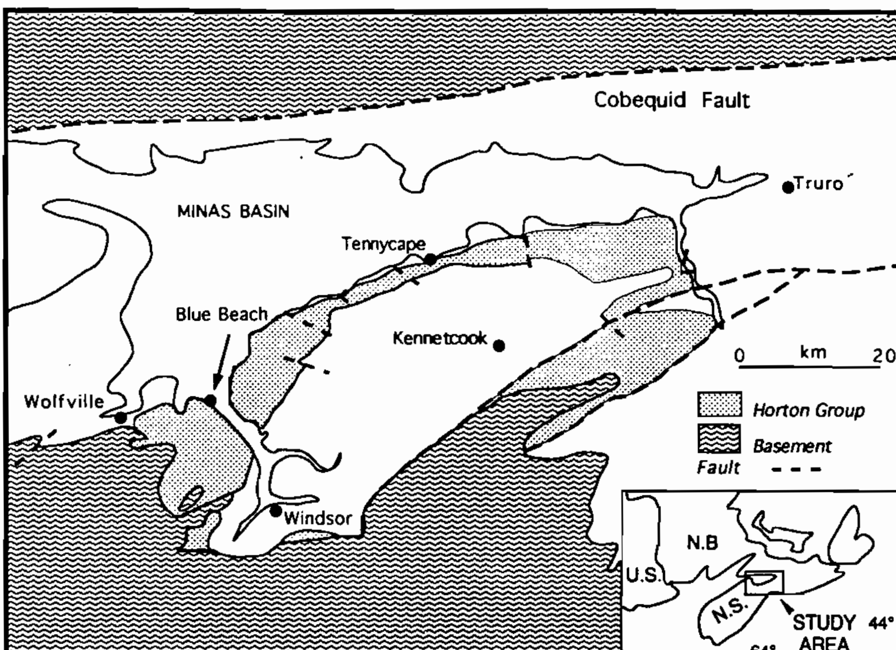


Figure 6. Simplified geological map to show distribution of the Horton Group in the Windsor Sub-basin and location of the Blue Beach section. Basement south of the Cobequid Fault is composed of undifferentiated Meguma Group and granitic rocks. The Horton Group includes the Horton Bluff and Cheverie formations. Blank areas onshore indicate younger Carboniferous and Mesozoic rocks (from Martel and Gibling, 1994).

The formation is at least 525 m thick in the type area (Stop 2), where it rests unconformably on metasedimentary rocks of the Meguma Group and granitic rocks of the South Mountain Batholith. It thins southwestward to continental alluvial redbeds (1650 to 3000 m) ~350 m in the Upper Falmouth area and Falls Brook Quarry (Stop 1), pinching out completely in the Five Mile Plains area. A Horton Bluff section 1015 m thick was penetrated in the 1975 Soquip Noel #1 well at Kennetcook (Fig. 6), and lithological sections and seismic data indicate that the Horton Group thickens substantially northward towards the Cobequid Fault (Martel and Gibling, 1996). The Horton Bluff and Cheverie formations are dated, using palynomorphs, as Upper Devonian to Tournaisian (see summaries in Utting *et al.*, 1989; Martel *et al.*, 1993; Martel and Gibling, 1996).

The Falls Brook Quarry near Three Mile Plains (Stop No. 1)

Stop leader: Robert J. Ryan, Nova Scotia Department of Natural Resources

Location and Access

The Falls Brook section is located approximately 1.7 km due south of Three Mile Plains (Fig. 1 and 8a). From the Highway 14 turnoff on the 101 Highway proceed south for 0.9 km to the junction with Highway 1. Proceed 3.4 km west on Hwy 1 to the turnoff for the Windsor Back Road, and from this junction proceed along the Windsor Back Road toward Martock approximately 1.4 km (past the T junction in the road) to a small gated lane (Windsor Water Supply) that heads almost due south. The quarries are just east of this road 1 km south of the Windsor Back Road.

Geological Units Exposed

The Falls Brook Quarry section (Fig. 8b), described previously by von Bitter and Moore (1992), is unique in exposing over a short distance all of the lithotypes that characterize the Horton Group of the Maritimes Basin. The progressive onlap of Horton Group strata onto a Cambro-Ordovician basement high in this area has resulted in deposition of a sequence wherein the lithology of the entire Horton Group is represented. The result is that the lower units are thin when compared to their basinal equivalents exposed, for example, at Horton Bluffs (Stop No. 2). Diamond-drilling in the area confirms the nature of the facies and unit correlations. Units above the middle Horton Bluff are consistent in thickness but the lower and middle Horton Bluff members vary considerably with paleotopography.

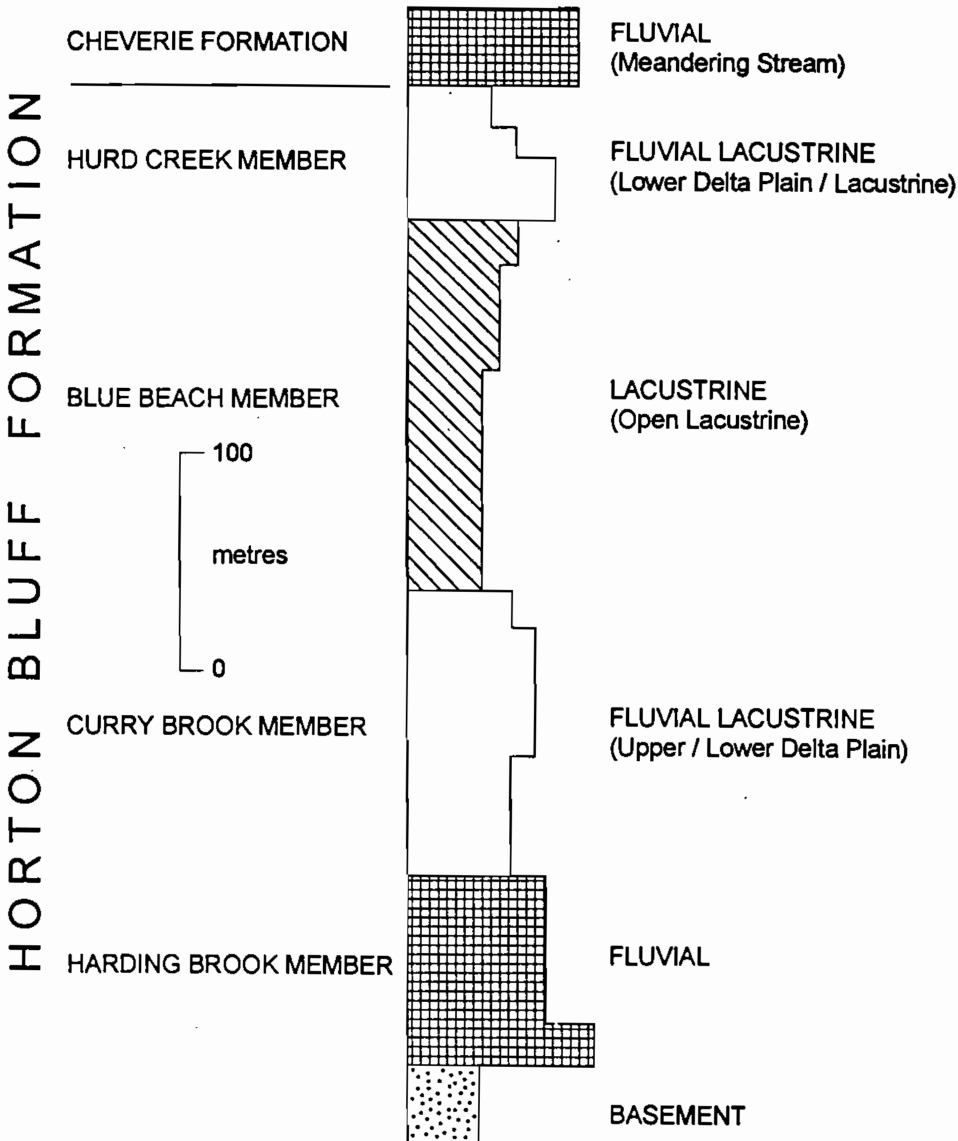


Figure 7. Simplified stratigraphic column for the Horton Group in the type area near Hantsport, with paleo-environmental interpretations. Modified from Martel and Gibling (1996).

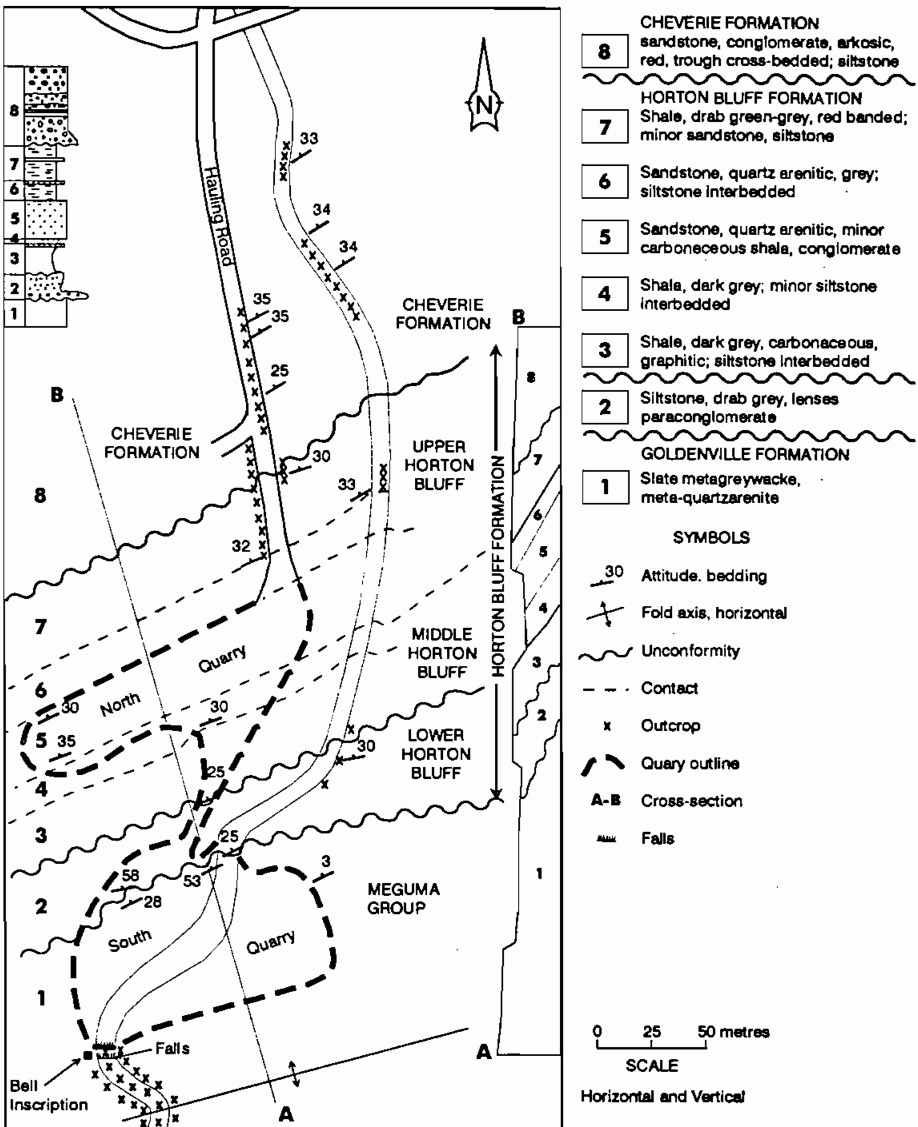


Figure 8a. Location map for the Falls Brook Quarry (Stop 1).

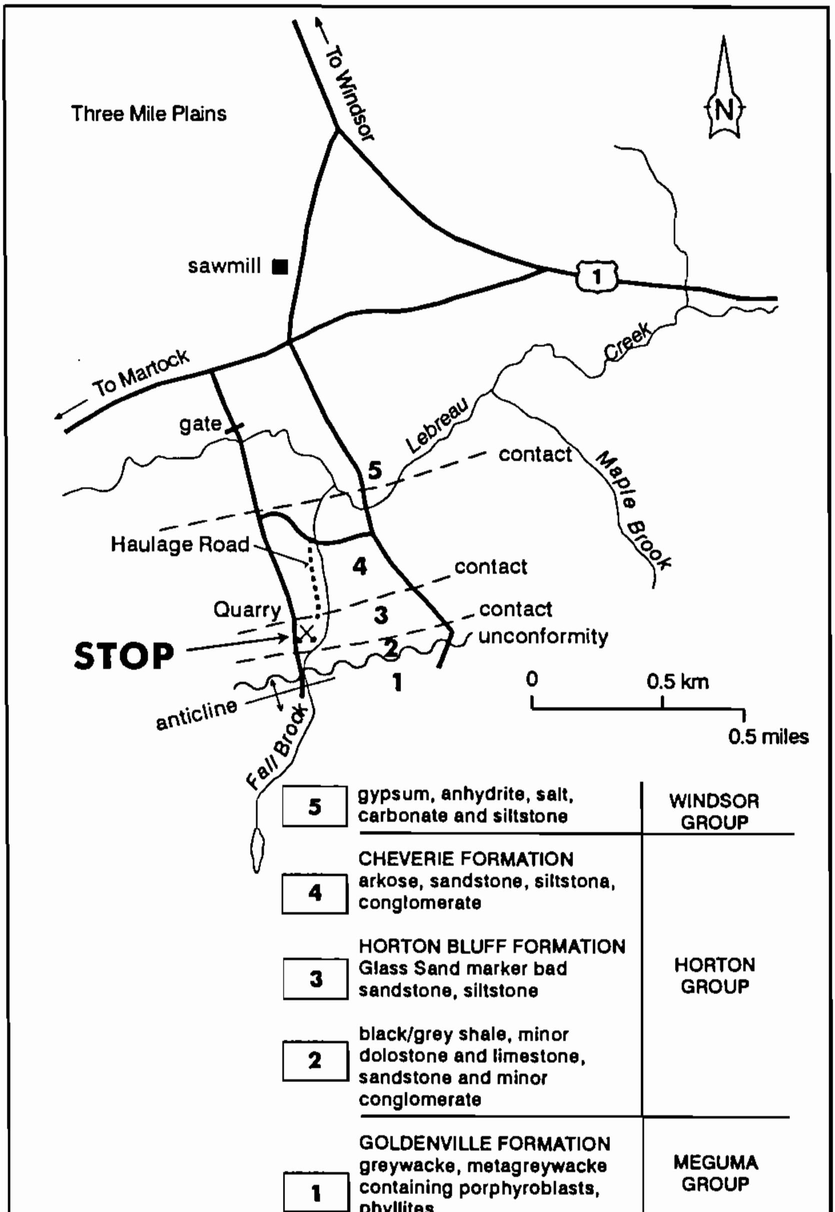


Figure 8b. Site map for the Falls Brook Quarry (Stop 1), modified after von Bitter and Moore (1992).

None who have worked in the Carboniferous strata of Nova Scotia escape without a deep appreciation for the stratigraphic and paleobotanical work of Walter A. Bell of the Geological Survey of Canada. His memoirs, summarizing his work in the Carboniferous basins of Nova Scotia during the period 1912-1966, stand as keystone reference works.

Inscibed in quartzite of the Goldenville Formation at the top of the Falls, on the west (left, facing downstream) side, are the words:

BELL

Aug. 27, 1913

Starting at the south end of the South Quarry and working up-section from the vicinity of the Falls, the following units are exposed (Fig. 4). The basal exposure is the Goldenville Formation (Steves Road Unit), a thick metamorphosed succession of metagreywackes, meta-quartzarenites and slates of Cambro-Ordovician age. These strata are overlapped unconformably by a compressed section of the lower (Harding Brook), middle (Blue Beach) and upper (Hurd Creek) members of the Horton Bluff Formation (Mississippian: Tournaisian). Our interpretation of the stratigraphy differs from that of Von Bitter and Moore (1992), who considered the Meguma and Horton groups to be in fault contact. The Horton Bluff Formation is a succession of interbedded quartzarenites, subarkoses, siltstones, and shales with variable thicknesses of interbedded coaly shales and pebble conglomerates. The Horton Bluff Formation is in turn overlain unconformably by arkosic conglomerates and sandstones with subordinant interbedded fine-grained siltstones and shales which constitute the Cheverie Formation of the Horton Group. To the north of the quarry, the gypsum cliffs of the overlying White Quarry Formation of the marine Windsor Group (Viséan) can be seen.

Meguma Group: Goldenville Formation

The Goldenville Formation of the Meguma Group (Unit 1, Fig. 8) was the principal rock quarried from the South Quarry (Fig. 8) and at this locality are predominantly metasandstones, metasiltstones and thin slates cut by a few thin quartz veins. There are well preserved primary sedimentary structures in these beds even though they have been metamorphosed to greenschist facies and folded. The Meguma Group strata are approximately 9 km thick and are interpreted to have been deposited in submarine delta fans by turbidity currents. The Meguma Group strata at this locality have been folded into a broad anticline with the fold axis striking east-west approximately 200 m south of the quarry (Fig. 8). Meguma Group rocks are the primary hosts of gold deposits in Nova Scotia with the gold usually occurring within bedding-parallel quartz veins near anticlinal hinges. It is interesting to note that this locality is the site of an abandoned gold mine that recovered gold from the basal quartz pebble conglomerate of the Horton Group. The quartz in the conglomerate was probably locally derived from gold-bearing quartz veins associated with the adjacent anticline. Although these rocks are Cambro-Ordovician in age and metamorphosed, it is often difficult to distinguish them from some of the overlying Mississippian terrestrial strata of the Horton Group. The most reliable methods are to look for the spotted nature (small metamorphic minerals) of the silty horizons in Meguma Group rocks and the presence of plant fossils in the Horton Group strata.

Horton Group: Horton Bluff Formation

Lower Member of the Horton Bluff Formation

The lower, Harding Brook/?Curry Brook Member of the Horton Bluff Formation (Unit 2, Fig. 8) at this locality comprises a succession of interbedded quartz pebble-rich polymictic paraconglomerate, coarse-grained subarkose, and grey fine-grained carbon-rich siltstones and thin shales. The sequence is sand dominated with the conglomerates inter-cross-stratified with the sandstones. The organic-rich shales contain type 2 to 3 kerogen with R_o of 0.7-0.8% and are a potential petroleum source rock, although not as impressive as the upper units of the Horton Bluff Formation. This is only a thin wedge of the member; however, the rock types present are characteristic of the thicker basinward facies of this unit. The strata are interpreted to have been deposited as locally derived alluvial fans as well as low sinuosity streams along the basin margin. Lacustrine influence in the unit is more evident toward the top of the sequence. The conglomerates at the base of the unit have been mined for paleoplacer gold in the past. Any gold you find is yours to keep!

Middle Member of the Horton Bluff Formation

The middle, Blue Beach Member of the Horton Bluff Formation (Units 3 and 4, Fig. 8) is made up predominantly of black to grey shale, coaly shale, siltstone and nodular carbonate beds. There are a few thin sandstone beds but they usually do not exceed 1.2 m in thickness. An exposure of organic-rich, coaly shale within this unit is of type 3 kerogen and is within the oil window, with R_o of 0.7-0.8%. This unit is thin at this locality but can exceed 300 m in thickness elsewhere in the Maritimes Basin. The unit fills in the paleotopography inherited from the basement structure and the unit thickens considerably in areas underlain by basement synclines (inferred from diamond-drilling in the area). Top of formation maps in the area show a marked flattening of topography at the top of the Middle Horton Bluff member when compared to the lower unit. These rocks are the stratigraphic equivalents of the black albertite-bearing shales of the Albert Formation of the Horton Group in southern New Brunswick. Albert Formation rocks in the Stoney Creek area of New Brunswick are the source and reservoir rocks for that small but long-producing oil and gas field. Concretions are common within these beds and are interpreted as paleosol horizons. The unit is fossiliferous with abundant plant debris, ostracods, and fish scales present in the shale. Plant stems of the early lycopsid *Lepidodendropsis* are present in some of the coarser interbeds. The middle member of the Horton Bluff Formation is interpreted to represent lacustrine deposition in a large shallow inland lake that covered much of the Maritimes Basin during the time of deposition. The presence of soil horizons and the abundance of plant detritus are interpreted as evidence that there were periodic regressions of the shoreline in this lake environment. Local sandstone interbeds with distributary channel configurations indicate that there were lacustrine deltas developed along the shores of the lake, and these may have also contributed to the terrestrial plant detritus found in the shales and siltstones. This thick lacustrine shale unit can be correlated throughout the entire Atlantic region of Canada.

Upper Member of the Horton Bluff Formation

The upper, Hurd Creek Member of the Horton Bluff Formation can be divided into two units: the lower, Glass Sand (Units 5and 6, Fig. 8) and the upper, Multi-Coloured Shale beds (Unit 7, Fig. 8).

Glass Sand Unit

The Glass Sand is an easily distinguishable unit in the upper member of the Horton Bluff Formation. The unit is characterized by thick quartz-rich sandstones, which at some localities are pure enough to be used for the manufacture of glass (past production of Depression-era glass, now a collectible Nova Scotian antique, gave rise to the name). The unit is dominated (90% or more) by quartzarenites ranging from quartz-pebble conglomerates to fine-grained quartz sandstones. The Glass Sand unit varies in thickness from 25 to 35 m. The sandstones are generally fining-upward cycles approximately 50 cm in thickness. There is a paucity of large-scale cross stratification and an absence of lateral accretion beds. Minor kaolinite, lithic fragments, traces of pyrite, and ubiquitous (although not volumetrically significant) plant detritus are the only components of the rock other than quartz. The unit is very consistent and can be traced in subsurface and outcrop for more than 30 km along strike with no visible variation in lithotypes present. The fining- upward cycles usually culminate with fine-grained medium-grey siltstone with abundant fossil debris. Fossils include both plants and aquatic fauna (ostracods and fish scales). Paleocurrent determinations from the unit are very consistent, indicating deposition in low sinuosity streams. The intervening grey lacustrine fine-grained beds, the unimodal paleocurrent trends, the absence of large-scale cross stratification, and the lateral consistency of the beds suggest that they were deposited in a beach or low gradient delta fan environment along the lake margin in the waning stages of deposition of this large inland lake or embaymant. The consistent quartz-rich nature of the unit may be a reflection of a monomineralic source area, the Goldenvlle Formation, rather than a mineralogically mature environment caused by long transport.

Multi-Coloured Shale Unit

This unit can be distinguished by the fine-grained nature and variegated coloration of the beds. The unit varies in colour from maroon red, grey, grey-green to light yellow. The colours are more easily distinguished in drill core from the area, but some of the colour variations can be observed in outcrop at the quarry. The rock types present are multicoloured silty shale and siltstone interbedded with grey shale. There are a few thin sandstone interbeds. The abundance and thickness of the grey shales and the abundance of plant debris decrease up section. At the base of the unit the grey shales still have a significant TOC content; however, upper beds generally have less than 0.5% TOC. The thickness of the unit rarely exceeds 20 m, although locally it may be very thin, probably as a result of erosion along the overlying unconformity with the Cheverie Formation.

Horton Group: Cheverie Formation

The Cheverie Formation of the Horton Group (Unit 8, Fig. 8) is composed primarily of a thick succession of arkosic pebble conglomerate and coarse-grained sandstone. The multilateral, multistoried sandstone bodies are interbedded with thin siltstone and shale that are usually red-brown. In the central parts of the basin the upper part of the formation is siltstone dominated; however, thick sandstone interbeds are common. The sandstone units are trough cross-stratified and there are usually several stacked channels within each sandstone bed. The sandstones form large sheet-like blankets which extend for many kilometres. This unit is essentially a "granite wash" and the arkosic nature of the beds indicates a major shift in the source area (bedrock sediment supply) in the Horton Group. The arkosic strata are clearly derived from the Devono-Carboniferous granitoid rocks of the South Mountain Batholith. The inference can be made that there was a major uplift and denudation event just prior to the onset of deposition of the Cheverie Formation in the middle to upper Tournaisian. The unconformity between the Horton Bluff Formation and the Cheverie Formation represents a significant change in the composition of the detrital material entering the basin and a shift to deposition in a large alluvial fan braidplain environment. Although grey fine-grained beds occur within the formation, they are rare. The usual non-red siltstones and shales are green in colour. The abundance of plant debris and TOC is significantly lower in the Cheverie Formation compared to the underlying Horton Bluff Formation. Although there is a paucity of suitable source rocks in the Cheverie Formation, permeabilities and porosities in the sandstone units indicate that the arkosic sandstones have excellent potential as reservoir rocks.

Horton Bluffs Coastal Section (Stop 2)

Stop leader: Martin R. Gibling, Dalhousie University

Location and Access

The Horton Group crops out widely in the Windsor Subbasin where the Blue Beach section at Horton Bluff (Fig. 1) provides what is probably the most continuous exposure of the dark shales in Atlantic Canada. The Blue Beach section is approached by driving north on Highway 101 and taking Exit 9 to Avonport. Shortly after leaving the highway, turn left at a T-junction and drive north roughly parallel to the main highway. Turn right toward Oak Island Road at the next T-junction, in the small village of Avonport, and proceed past the school (on your right) and up the hill, bearing right on Bluff Road. Continue downhill and cross the railroad track *once* **Note: If you have crossed the railway tracks twice, you have proceeded too far.** You are now very close to the shore of the Avon River on your left. One hundred metres beyond the tracks, turn left on a grassy lane that terminates immediately at the beach and provides access to the Blue Beach North section (Access N: Fig. 9). Park there or along the nearby road. Turn right on the beach and proceed south to the lowermost bed of the section. The Blue Beach North section extends from the access point for about 1 km to the high cliffs below the lighthouse, where it is separated from the Blue Beach South section by a fault. (For alternative access to the Blue Beach South section, continue south along the Hantsport road, and turn left on a dirt road that takes you downhill to the beach (Access S: Fig. 9). Parking is available just beyond the railroad bridge).

The Fundy tides reach their maximum range (~17 m) along this coast, and it is possible for the unwary adventurer to be cut off. Make sure that you know the times of low and high tide before examining the section. A small, rough path ascends the cliff in the cove just south of the lighthouse, and can be used in an emergency. However, it is steep and slippery, and is not recommended for normal use. The cliffs are loose, and should be approached with care.

The Blue Beach and Hurd Creek Members are exposed in the Blue Beach South section, but only the Hurd Creek Member is seen in the Blue Beach North section (Fig. 9), the locality of this field stop. A detailed bed-by-bed column of the northern section is shown in Figure 10.

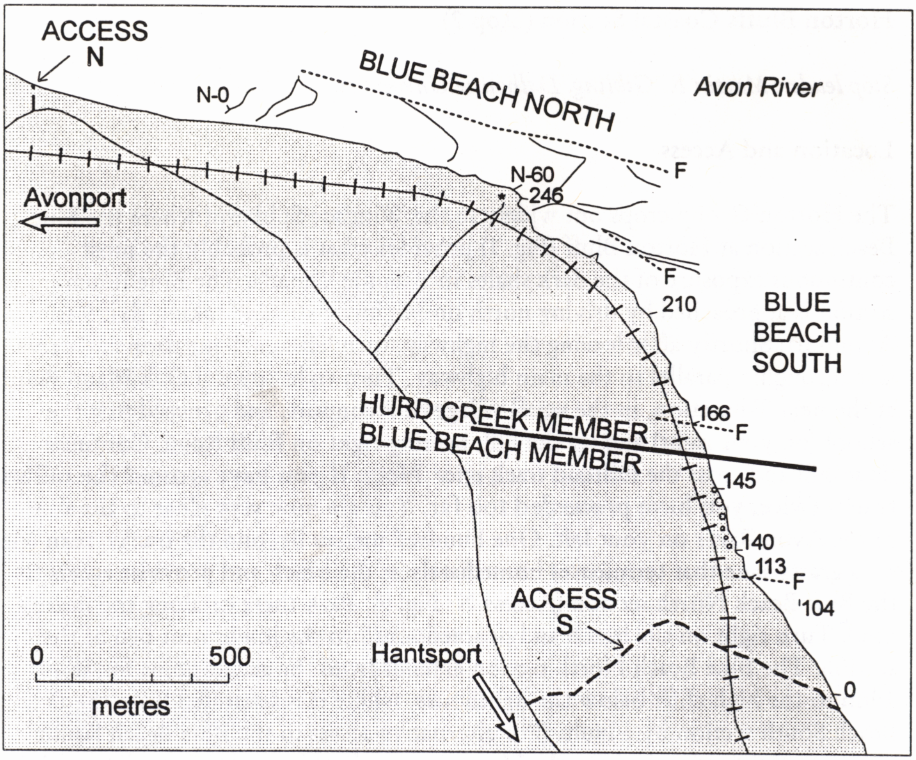


Figure 9. Location map of Blue Beach, showing Blue Beach North (N) and South (S) sections. Numbers correspond to metres above the base of each section. Crosses indicate railroad track; F indicates faults; asterisk indicates lighthouse. Modified from Martel (1990, Fig. 5.2).

Cycles and Depositional Setting

The most prominent aspect of the cliff section is the well developed cyclicity (Hesse and Reading, 1978; Martel and Gibling, 1991). A detailed log for five cycles is shown in Figure 11, with a general interpretation in Figure 12. The cycles are typically ~6 m thick and shoal upward, with three components: a basal grey shale; a medial sandstone and shale; and an upper green mudstone with dolomite sheets and nodules.

The basal shale is medium to dark grey, and has an abrupt, planar contact with the underlying cycle, locally overlain by a single-grain layer of coarse quartz, fish

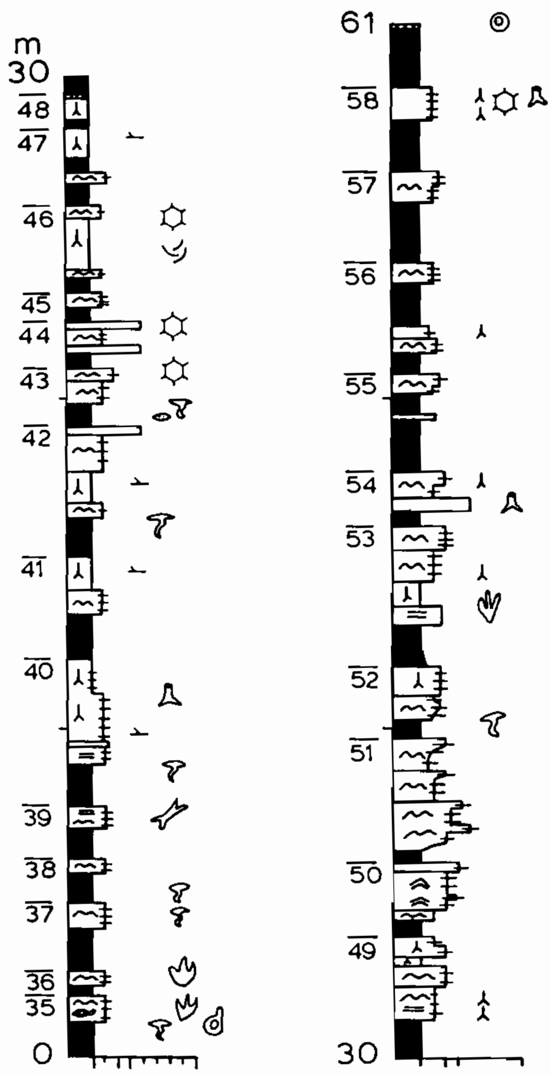


Figure 10. Stratigraphic log for the Hurd Creek Member in the Blue Beach North section (see Fig. 3). The section totals 61 m, with the highest bed located in cliffs below the lighthouse, where the strata are cut by a fault. The oolitic limestone at the top of the section is also found at the top of the Blue Beach section, and the cycles (35-59) are numbered to correlate with the more complete Blue Beach South section. From Martel (1990, Fig. 6.3).

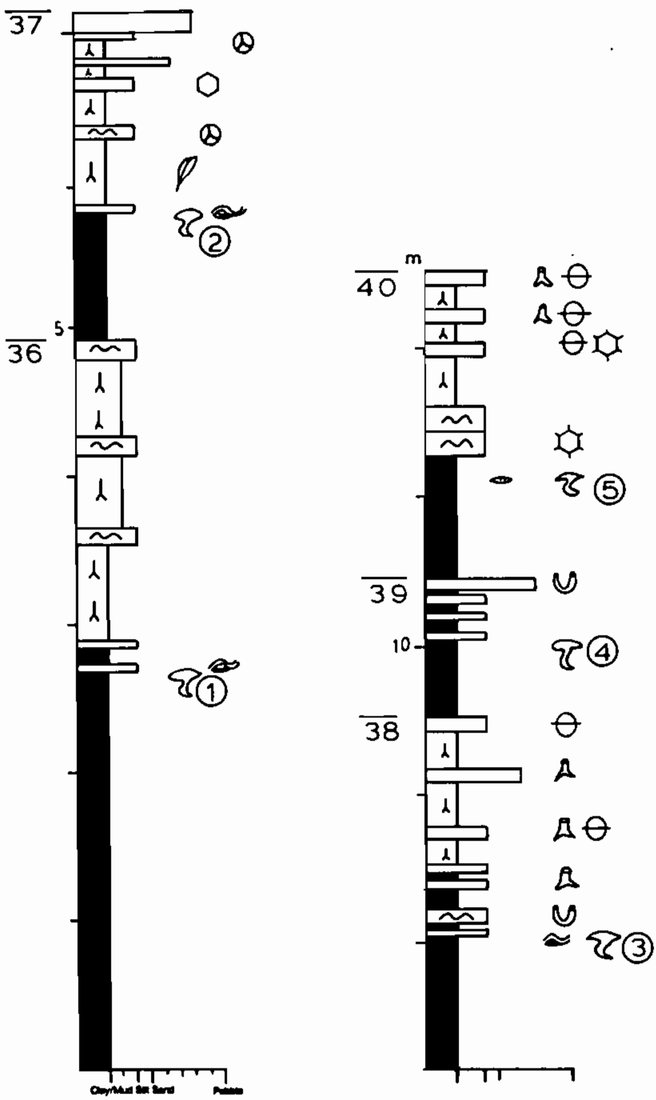


Figure 11. Details of cycles 36-40 in Blue Beach North section, to show the distribution of five major zones of clastic dykes. Note that the dykes extend downward from the lowermost sandstones in the cycles. From Martel and Gibling (1993).

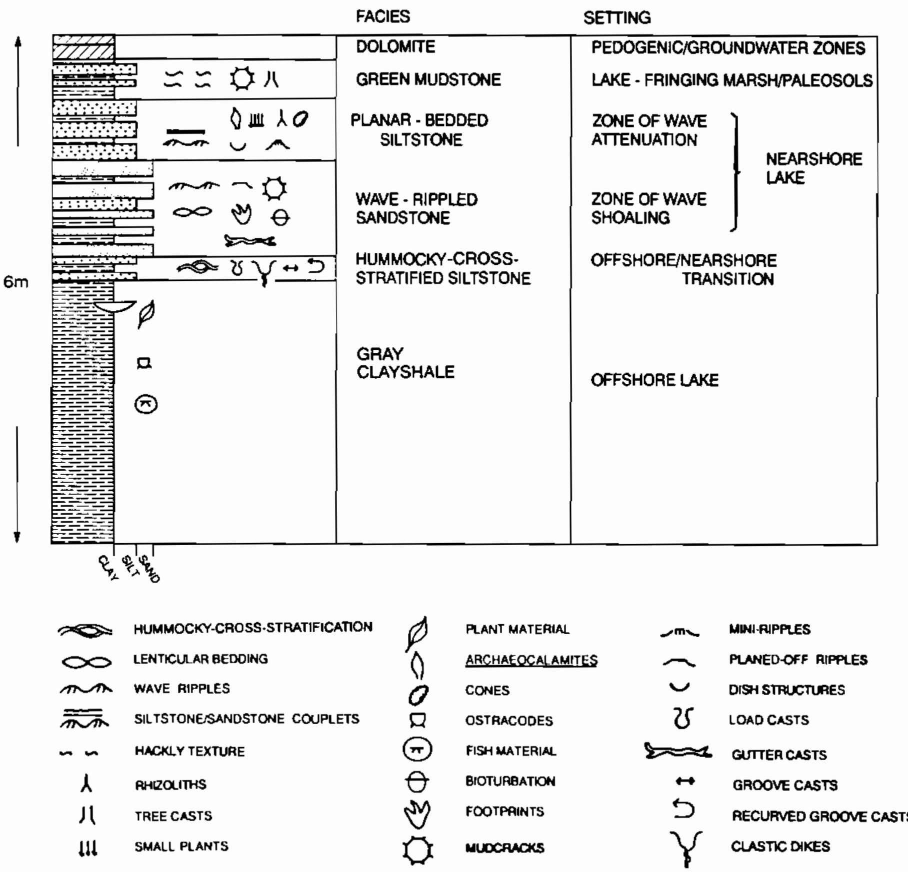


Figure 12. Idealized Horton Bluff Formation cycle (Blue Beach and Hurd Creek members), with description, hydrologic interpretation, and environments of deposition. Entire cycle is typically ~ 6 m thick. From Martel and Gibling (1994).

debris, and reworked paleosol fragments. The shales contain fossils of paleoniscid fish, ostracodes, conchostracans, fish, amphibians and plants (Bell, 1960; Bless and Jordan, 1971; Carroll *et al.*, 1972). Trace fossils (*Planolites*) are uncommon, and the shales are mostly platy weathering, indicative of only limited bioturbation. Dolomitic septarian nodules are prominent in places. The shales are interpreted as an offshore facies, deposited under quiet and variably aerobic to anaerobic conditions.

The shales are overlain, usually abruptly, by interbedded sandstone, siltstone and clayshale, which form bedsets that project from the cliff face. The lowermost beds contain regularly spaced sandstone lenses that are isolated within clayshale. Where seen in three dimensions, these lenses are up to 40 cm thick and 3 m wide, and most are linear and up to 6 m long. They contain low-angle truncation surfaces and antiformal sediment accumulations that are typical of hummocky cross-stratification (HCS), and many are capped by wave-rippled sandstones. The lenses and associated sandstones have excellent suites of sedimentary structures that include gutter casts, prod marks, and well developed groove casts on their lower surfaces. Some groove casts are recurved, with parabolic shapes, indicating that they and other grooves were formed under oscillatory waves with an associated unidirectional flow component (combined flow, possibly due to longshore drift)(Martel and Gibling, 1994). Planar beds with horizontal and graded laminae are also present. A variety of features indicate shallow and locally subaerial conditions: rhizoliths, mudcracks, rain prints, ladder and planed-off ripples, double-crested ripples, scratch circles (formed when the leaves of rooted vegetation are rotated by the wind), and tetrapod trackways. The trace fossils *Isopodichnus, Pelecypodichnus, ?Margaritichnus, Palaeophycus* and *Planolites* ares present on some basal bed surfaces. Vertical casts and associated rhizoliths of *Archaeocalamites* are also present. The sandy, medial part of the cycles is intepreted as a wave-dominated nearshore facies. The HCS lenses with basal sole structures and capping wave ripples represent individual storm events. The upper beds were deposited under very shallow water and were periodically subaerially exposed.

The upper parts of the cycles comprise poorly stratified, rooted green mudstone with thin sandstones. Vertical trees include probable *Lepidodendropsis* (Bell, 1960) and *Archaeocalamites.* Dolomite is present as sheets and nodules, with sucrosic texture in thin section. The facies is interpreted as a poorly drained paleosol, with pedogenic (nodular) and groundwater-generated (sheet) carbonates. The tough, well-cemented sandy beds are a distinctive feature of the wave-cut platform, and show prominent circular hollows and surrounding ridges — concretionary growths formed around the former positions of trees that are no longer preserved.

The Horton Bluff Formation has generally been interpreted as lacustrine, based on its sedimentological features and the apparent absence of marine biota. However, Tibert (1996) re-examined the ostracodes from the Blue Beach and Hurd Creek Members (originally reported by Bell, 1929, 1960). He identified the genera *Copelandella, Shemonaella, Chamishaella, Cavellina, Carbonita, Bairdia,* *Geisina* and *Youngiella,* and noted that several species are well documented in coeval marine assemblages elsewhere in the world. Additionally, Tibert identified agglutinated foraminifera (*Trochammina* sp.) and glaucony (confirmed by microprobe analysis) in the formation. Tibert's work implies a marine connection during Horton Bluff deposition, although the source ocean remains uncertain. Calder (1998) hypothesized that this and other marine connections in th Carboniferous of Nova Scotia derived from he called a Mid-Euramerican Sea that waxed and waned from a deep basin between the Maritimes Basin east of Newfoundland and the Westren European Basin, west of Ireland.

Clastic Dykes and Collapse Structures

Clastic dykes and collapse structures both are spectacular features of the cycles. They are virtually confined to the base of HCS lenses that overlie thick clayshales, and are especially well represented in five consecutive cycles in 13 m of the Blue Beach North section (Fig. 10). The dykes project from the base of the lenses (Fig. 13), and their quasi-regular spacing in cliff sections is a function of the regular distribution of the HCS mounds. They range from 1 cm wide and 5 cm deep to 40 cm wide and 40 cm deep (measured vertically), narrowing downwards, and some are at least 5 m long below the linear mounds. Most dykes show ptygmatic folding due to the higher degree of compaction experienced by the surrounding muds. From the total unfolded length of the (presently folded) dykes, the maximum original penetration depth is estimated at 110 cm. Seventeen measurements of unfolded dyke length to present thickness of shale penetrated by the dyke average 2.3, which is a measure of the compaction ratio of the shale. Dykes in a single cycle are aligned sub-parallel to one another and mean dyke orientation is similar from one cycle to the next. Dyke orientation is also parallel to wave-ripple crest orientation both in the same cycle and regionally, as well as to the orientation of linear HCS accumulations.

Hesse and Reading (1978) suggested that the dykes and overlying sediment lenses were generated by upward transposition of liquified sediment from underlying feeder beds as a result of earthquake shocks, with sediment extrusion at the sediment surface to form the mounds (essentially sand volcanoes). However, the recognition that the mounds are wave-formed structures, as well as good evidence for downward movement of sediment into the dykes, suggests a different origin (Martel and Gibling, 1993). The dykes were probably initiated in shallow water during or shortly after the storms that laid down the HCS-bearing lenses. The lenses loaded down into surficial, fluid muds, and the dykes were injected

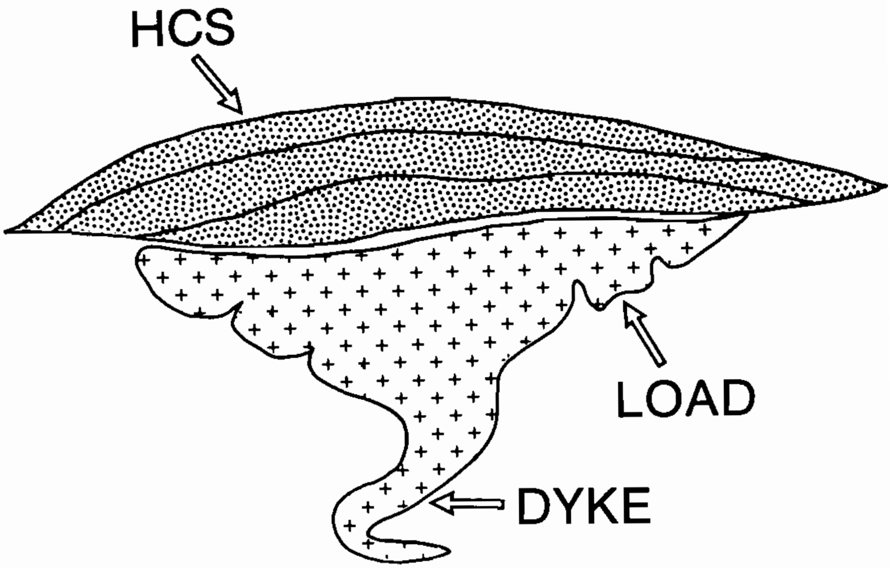


Figure 13. Simplified diagram to show sedimentological setting of clastic dykes. The dykes are composed of sandstone and narrow downward below large, hummocky cross-stratified (HCS) mounds. Contortions in the sandstone dykes reflect the higher degree of compaction of the surrounding shale. Modified from Martel (1990, Fig. 7.4).

downward where underlying, more compacted muds failed in a brittle manner. Cyclic wave loading and microseisms may have promoted sediment failure. Although the prior orientation of HCS lenses would seem to have been a primary control on dyke orientation, the fracture direction probably also reflects a tensional stress controlled by a gentle, basinward slope.

Five bowl-shaped features, 2-15 m in diameter, are striking features on the wave-cut platform of the Blue Beach North section. They show slight to intense deformation of the sediment fill, with evidence of downward motion along planar slip surfaces, and many have an underlying, linear clastic dyke (Fig. 14). They were interpreted by Hesse and Reading (1978) as collapse structures, associated with sediment extrusion of liquified (and possibly gas-rich) sediment. However, the evidence points to subsidence without extrusion. Similar collapse depressions have been described from interdistributary bays of the Mississippi Delta (Coleman and Prior, 1980).

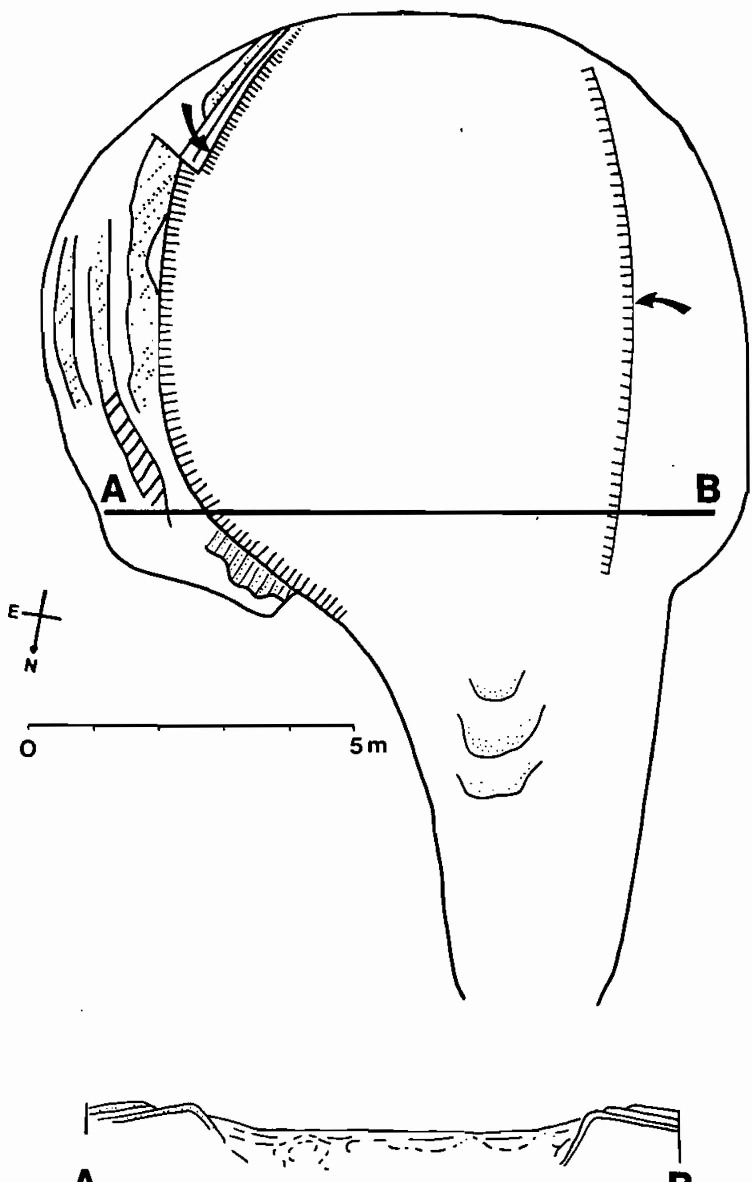


Figure 14. Schematic drawing of collapse structure on the foreshore of the Blue Beach North section. Sediment appears to have collapsed into the central area along slip planes (arrowes). Modified from Hesse and Reading (1978).

Tectonic Setting and Sequence Stratigraphy

The Horton Group is well exposed along the southern shore of the Minas Basin but is not exposed on the northern shore (Fig. 6) apart from small outcrops of coeval formations in the Cobequid Hills to the north. This uneven outcrop distribution limits detailed tectono-stratigraphic interpretation. The northward thickening of the Blue Beach and Hurd Creek Members from Blue Beach northwards to Tennycape (Fig. 6), as well as the northward thickening across the Minas Basin apparent in seismic, suggests that the Horton Bluff Formation occupies a half-graben with a master fault near the present line of the Cobequid Fault. Following this interpretation, the outcrop belt that includes Horton Bluff developed on the hanging-wall margin of the basin. In accord with this interpretation are paleoflow patterns in other members of the Horton Group, which suggest that the coastal plain prograded northward above the basal unconformity with the Meguma Group. At both Blue Beach and Tennycape, cycles thin upwards and are progressively dominated by subaerial facies and biota (Martel and Gibling, 1991; Tibert, 1996), with a decreased proportion of the offshore shale facies. This implies a progressively decreasing rate of tectonic subsidence, following a major subsidence and transgressive event early in Blue Beach times that can be identified in Horton outcrop belts across Atlantic Canada.

Horton half-graben fills are present onshore and offshore elsewhere in Atlantic Canada (e.g. Hamblin and Rust, 1989), and reflect a regional phase of extension following the mid-Devonian Acadian Orogeny. The Horton Group in the Minas Basin is the lowermost Paleozoic unit to overstep the boundary of the Meguma and Avalon terranes, brought together during the Orogeny. Age dates from the South Mountain Batholith near Wolfville (~370 Ma) suggest that the Meguma Terrane underwent rapid exhumation prior to Horton subsidence and accumulation (~355 Ma for the basal strata in this area).

The stacked shoaling up cycles (Fig. 11) can be described in sequence stratigraphic terms as parasequences, separated by flooding surfaces. The upward trend to more subaerial conditions implies that they are part of a prograding parasequence set. Exxon sequence boundaries are not apparent in the section. One possible explanation for the 'parasequence world' of Horton Bluff is that the basin subsided episodically along the northern boundary fault, causing repeated transgression in coastal zones in the Blue Beach area, with subsequent progradation to form shoaling-up cycles. Under conditions of rapid subsidence, base-level falls were probably insufficient to cause major incision and generate sequence boundaries.

Several major faults are evident in the Blue Beach section, and strata farther east at Walton are intensively deformed, and locally overturned. The timing and significance of the deformation is not well understood, but it may reflect a major mid-Carboniferous tectonic event that is well documented elsewhere in mainland Nova Scotia, especially adjacent to the Cobequid Fault.

Hydrocarbon Potential of Organic Material

Black, organic-rich shales are present in the Horton Group at many localities across Atlantic Canada, and the Horton Group historically has been considered the most prospective upper Paleozoic unit for hydrocarbon generation (Bell, 1958). Hydrocarbons of the Stoney Creek oil and gas field in the Moncton Subbasin have been linked to Horton shales. Smith and Naylor (1990) summarised available information and obtained new analyses for the Horton Bluff shales at Blue Beach and in drill core at Upper Falmouth to the south; to these we add new data obtained for this study. The Blue Beach shales contain <1 to 3.5% TOC but are thermally over mature, with Tmax values of 436-460°C and hydrocarbon yields of <5 l/t on distillation. The shales at Falmouth are of substantially better grade. They contain 2.7-31.6% TOC, with hydrocarbon yields of up to 28.3 l/t. Tmax values were 433-439°C. Rather low hydrogen indices (81-180) suggest a humic, rather than an algal, source for the organic matter. Kerogen type 2 and types 2 to 3 are represented. As noted above, vascular plant material is common at the Blue Beach section.

The maturity profile of Horton Group source rocks indicates that they have been rendered over mature by fluid migration adjacent the Cobequid Fault where R_o values exceed 1.5%. At distances 2 to 3 km away from the fault, however, they fall within the oil window (Mukhopadhyay, 1991).

Horton-Windsor Group Contact at Cheverie (Stop No. 3)

Stop leader: Robert C. Boehner, Nova Scotia Department of Natural Resources

Location and Access

From Exit 5A ramp on Highway 101, turn left. Below the overpass, take a second left on the gypsum mine road, passing Fundy Gypsum on the right. Turn left on Highway 214, then left on Highway 236, crossing the bridge over the St. Croix River. At the stop sign, turn right towards Union Corner. Proceed left on Highway 215 (Glooscap Trail) for 2.8 km. On the left, the Kennetcook Limestone of the Windsor Group is exposed. At Cheverie (Fig. 1), turn left on Ross Road and continue to the shore. [Please respect the wishes of the landowners with respect to parking your vehicle.]

Background

The Maritimes Basin complex (Fig. 3) was breached in the Viséan by a major evaporitic marine incursion of the sub-sealevel landscape. Deposits of this marine incursion are assigned to the Windsor Group (Fig. 2). The Windsor Group evaporitic basin system continued to infill and expand, arguably with relatively little coincident tectonic activity. The middle to late Viséan was a time of regionally extensive, restricted marine to evaporitic marine and continental redbed deposition. Numerous minor and major cycles were accumulated in shallow shelf to interconnected intermontane basins. Deposition occurred under hot semi-arid to arid stressed environmental conditions.

The structural geology of the Kennetcook Basin is complex (Boehner, 1991) and is compatible with restraining-convergence tectonics on subsidiary faults related to dextral east-west strike slip motion on the Cobequid Chedabucto Fault System (e.g. Kennetcook Thrust Fault). Superposition of the Triassic rift basin in a later extensional environment has further complicated the interpretation of the structural history. Well documented thrusting has been previously restricted to small scale thrust faults near the western extremity of the basin (e.g. Cheverie). A complex gravity slide/decollement has been identified by Moore and Ferguson (1986) in the Windsor area. The relationship of this structure with the highly deformed Horton Group and the Kennetcook Thrust on the northern side of the basin remain to be determined. It is not clear if there is a genetic relationship with similar complex structure near Kennetcook and along the north part of the

Shubenacadie Basin. The transpressive-thrusting model is compatible with gravity slide tectonics. The Windsor Group evaporites and especially the lower salt section, are a preferred locus for ductile deformation and decollement in the Carboniferous Basin fill (e.g. Boehner, 1992). Giles and Lynch (1994) have recognized a regional detachment within the Windsor Group in east-central Nova Scotia.

Late Paleozoic to early Mesozoic basins in Nova Scotia, especially in the north-central part of the province, have complicated and interesting stratigraphy, sedimentology, structure and very significant mineral and energy resource potential. The Cheverie Stop (Fig. 15) is located in the northwestern part of the Kennetcook (Windsor) structural basin. The Musquodoboit, Shubenacadie and Kennetcook (Windsor) structural basins are the main components of this area, referred to as the Minas Sub-basin of Bell (1958) which includes the Carboniferous outcrop area on the north central part of the Meguma Platform. The area occurs along the extreme northern boundary of the Meguma Zone and, consequently, the geology of the Carboniferous basin fill is complicated by the proximity to the Cobequid-Chedabucto Fault System and superimposed Mesozoic rift basin occuring in the area of the Bay of Fundy and Minas Basin (Fig. 1).

This tectonically complicated setting is important in the localization and deformation of significant mineral deposits (Boehner and Ryan, 1989; Fig. 5) including base metals, silver and barite (e.g. Walton, past producer), manganese, siderite, gypsum and anhydrite (e.g. Wentworth and Miller Creek Operations of Fundy Gypsum Company Limited and the Domtar Gypsum, Maynard Quarry near McKay Section), sulphur, salt and limestone (e.g. Miller Creek Quarry). In addition, interest in hydrocarbon exploration (including exploration well-drilling) began in the early part of the century near Cheverie and Falmouth (Windsor). Interest continued to recent times, including several programs operated from the mid 1940s to the early 1980s with several wells drilled the Kennetcook area. Most of this hydrocarbon exploration focused on plays in the Horton Group and the lowermost part of the Windsor Group. The rocks in this interval are noted for hydrocarbon shows and occurrences (e.g. Cheverie, Walton Barite Mine, Soquip *et al.* Noel No. 1); however, commercial discovery and development have yet to occur.

Previous geological mapping in the area includes: Boyle (1972), Crosby (1962), Weeks (1948), Ferguson (1983) and Moore and Ferguson (1986). The founding work on the detailed stratigraphy and biostratigraphy of the Windsor and Horton groups in this region, their type areas, was produced by Bell (1929 and 1958).

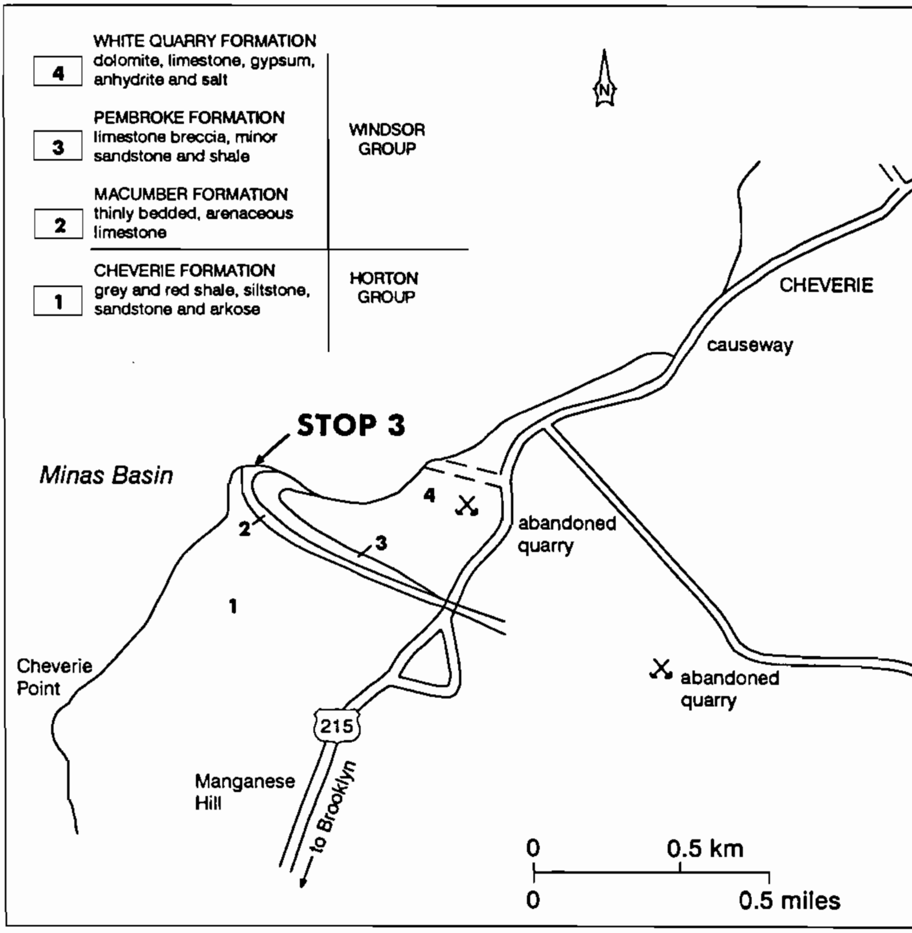


Figure 15. Site and geology map of Cheverie (Stop 3), after Ferguson (1983).

Cheverie Stop

The Cheverie Stop (Figs. 1 & 15) is located on the eastern shore of the Avon River estuary near the transition to the Minas Basin. It is very easy to access via paved roads (Routes 14 and 215) north from Windsor and Brooklyn. Cheverie Point is accessed by a short road northwest off Route 215 at a location 750 m south of the New Cheverie Road intersection in the community of Cheverie. Most maps identify White Head as a shoreline feature. This is located at the northeastern end of the Cheverie Stop.

The Cheverie Stop area is part of the Bay of Fundy tidal system, with tidal range approaching 15 m. This coincidence of extreme tidal action, erosion and geological structure has resulted in an excellent locality to view the upper part of the Horton Group and the contact with the overlying Windsor Group in the shoreline cliffs and wave cut platforms. Although this is a relatively benign shore section, due care must be exercised to avoid unnecessary exposure to rock falls along the high cliffs, and especially in traversing the intertidal zone to avoid soft mud areas. The tide level must always be considered to avoid getting cut off at points (see Safety Considerations for Coastal Sections).

The Cheverie Stop provides a small window into the complex and interesting late Paleozoic basin geology near the Cobequid-Chedabucto Fault System and coincident Mezozoic rift. The general geology, sedimentology and stratigraphy of the Horton Group has been outlined in previous field stop descriptions. Outcrop sections of the Horton Group, Horton Bluff Formation and Cheverie Formation are present at the Cheverie section; however, only the uppermost portion of the Cheverie Formation will be examined. The lower units of the Windsor Group, especially the Macumber Formation (the basal carbonate), Pembroke breccia, and the White Quarry Formation (basal anhydrite), are well represented and easily accessable at low tide.

Macumber Formation

The Macumber Formation lectostratotype and type area is identified in the Cheverie area based on units b and c of Section 1 described by Bell (1929). The name was introduced by Weeks (1948) and this basal carbonate unit of the Windsor Group probably has the most voluminous research literature of any formation of the group (e.g. Schenk *et al.*, 1994, and references therein).

The Macumber Formation comprises buff to light grey-brown to dark grey pelletal limestone to dolostone, variably argillaceous and arenaceous. Well developed laminations are characteristic. The Macumber Formation in the Maritimes Basin varies widely in thickness in the region from 1 to 18 m. At Cheverie it is quite thin (only a few metres) due in part to the presence of thick Pembroke breccia. Although it is relatively thin, it is a key correlation unit because of the wide distribution as the basal Windsor Group carbonate in Atlantic Canada. The Macumber Formation, also known as the A_1 or Ribbon limestone, or Ship Cove Formation and other names, overlies concordantly, conformably? to unconformably older Carboniferous rocks including Horton Group or older

Devonian to Carboniferous rocks. In the Cheverie section it overlies a thin, distinctive, locally developed quartzose sandstone with abundant *Schizodous* bivalves on the upper surface (included in the Windsor Group by Bell). Locally and regionally it is conformably overlain by, and often transitional with a thick anhydrite sequence informally referred to as the basal anhydrite (local name White Quarry or Carrolls Corner Formation).

Macumber-Basal Anhydrite Contact - Paleokarst and Pembroke Breccia

In some present-day outcrop areas the contact between the Macumber Formation and the overlying basal anhydrite is marked by the presence of a complex carbonate breccia (a few to tens of metres thick), referred to as the Pembroke breccia. This contact is a common location for karst-related solution features, including solution trenches that may extend down dip for 100 m or more and be filled with Carboniferous or Cretaceous sediments and/or Quaternary to recent material. Multiple generations of paleo-karst features are evident. In general, undisturbed (stucturally or by karst processes) contacts are rarely exposed and such is the case at Cheverie.

White Quarry or Carrolls Corner Formation (basal anhydrite)

The basal anhydrite of the Windsor Group is dominated by thick, massive, nodular to poorly stratified anhydrite with minor thin (locally petroliferous) carbonate, halitic or mudstone interbeds. It is approximately 80-90% anhydrite and typically is variably hydrated to gypsum in near-surface environments where karst features are well developed. The thickness varies from 100-300 m and the unit is regionally distributed throughout Atlantic Canada. It is especially well developed in the Cheverie region and exceptionally well exposed and accessible at the Cheverie section. It conformably and transitionally overlies the Macumber Formation. The basal anhydrite unit is commonly overlain by a very thick salt sequence, which for obvious reasons does not occur as outcrops.

The basal anhydrite is well exposed in the area of White Head in the Cheverie Section and is not complicated by extensive hydration. Rapid erosion is a factor in allowing the occurence of the anhydrite in outcrop. Irregular cliffs and superb wave-cut platform outcrops of the gently dipping beds expose the various textures and inter-relationships of the anhydrite and carbonate/mudrock. The carbonate/mudrock interbeds are exceptionally petroliferous which probably attracted interest in hydrocarbon exploration (including exploration well drilling) in the early part of the century near Cheverie. These anhydrite/carbonate relationships include discrete and distinctive interbeds and lamination through interstitial nodular progressions to massive mosaic anhydrite textures. These transitions can be observed along strike as well as vertical facies changes over a few centimetres (bed boundaries) to tens of metres from relatively pure carbonate/mudrock to nodular mosaic anhydrite.

Two variants of tectonic breccia in the anhydrite section are also well exposed at Cheverie. The south exposure of mud and gypsum occurs near the abandoned gypsum quarry and adjacent to a concealed interval in the inferred contact area with the Pembroke brecia and Macumber Formation. The northerly exposure of gypsum and mudrock near White Head is more clearly a fault contact with Horton Bluff Formation mudrocks.

Pembroke Breccia

Breccia rocks of the Macumber Formation are a problematic and important geological unit in the Kennetcook Basin and are similar to those described by Boehner and Giles (1993). Weeks (1948) introduced the term 'Pembroke Formation'; however, the term was later abandoned and the term 'Pembroke breccia' is applied to a variety of carbonate breccia spatially associated with the Macumber Formation. The Pembroke breccia at the Cheverie section is exceptionally well developed and accessible in outcrop along a strike length of several hundred metres in low shoreline cliffs and wave-cut platforms in the intertidal zone.

The age, origin and development history of these breccias has generally not been well defined. Lavoie *et al.* (1995) have made substantial advances in documenting the character and genesis of these complex rocks. Their work identifed three breccia types at various localities in the province, including Cheverie: (1) syn-sedimentary, (2) tectonic or karst- related, or (3) multigeneration. Understanding their relationship in space and time to metallic mineralization and potentially hydrocarbon reservoirs near the base of the Windsor Group will be important in establishing mineral and energy exploration models. Two factors are very significant. The carbonate breccia is dominated by, and most likely derived from, laminated and recrystallized carbonate typical of the Macumber Formation and carbonate interbeds within the White Quarry Formation (basal anhydrite). The breccia forms a substantial thickness of host rock for mineralization, and may be tens of metres thicker than the Macumber Formation. The breccias appear to have a spatial association with the dissolved and eroded solution trench typically formed at the contact between the Macumber and White Quarry formations. The breccia is also often associated with faults, but in many areas disappears rapidly downdip beneath the basal anhydrite. Alternative hypothesis for formation include: synsedimentary breccia, growth fault origin, and karst or residual accumulation in paleo-solution trench features with or without faults.

Hydrocarbon Occurrences

Organic-rich and carbonate interbeds in the White Quarry Formation (basal anhydrite) exposed near Cheverie reek of hydrocarbons. They yield type 2 to 3 kerogen, within the oil window, with R_o of 0.8-0.9%. Production index (PI) values, however, suggest early hydrocarbon generation. The Macumber limestone has favourable potential as a hydrocarbon source, lying within the oil window with R_o of 0.9%, type 2 kerogen, and TOC in the 1-2% range. Windsor Group source rocks everywhere fall within the oil window, with the exception of areas immediately adjacent the Cobequid Fault (Mukhopadhyay, 1991).

Recent natural gas exploration interest in the Alton area in the Shubenacadie Basin could expand into the geologically similar Kennetcook Basin. Minor liquid oil and natural gas occurences have been documented in the Kennetcook Basin (e.g. Walton Mine). Potential traps and source rocks similar to the Alton occurrence could exist in the west-central parts of the Kennetcook Basin. The only seismic surveys available were run in the eastern part of the basin where the Soquip *et al.* Noel No. 1 well was drilled (Boehner, 1991). Unfortunately, the base of the Windsor Group was intersected at a very shallow depth without a significantly thick salt seal. Interesting occurrences of natural gas were reported in the upper part of this well (near base of Windsor Group).

Upper Windsor Limestone - Avondale Section (Stop 4)

Stop leader: David E. Brown, Canada-Nova Scotia Offshore Petroleum Board, Halifax, N.S.

Location and Access

The exposure is accessable, with their permission, via a farm track on the property of Mr. and Mrs. William D. Siler, Avondale, which passes to the left of their farmhouse. The road passes through an apple orchard beyond which it is best negotiated on foot or by four wheel drive vehicle. At the shore, turn to the right and proceed to the first outcrop.

Introduction

The easily accessible limestone succession exposed here on the south bank of the Avon River (Fig. 16) is an excellent example of the thin, but laterally continuous carbonate sheets representative of the Upper Windsor Group. However, this 10 m thick exposure is unique in containing a well preserved calcrete paleosol horizon developed at the top of the sequence, significant oil staining within the same interval, several other excellent potential reservoir zones, and a black lacustrine shale (possible source rock) in the clastic strata immediately below the carbonates.

The Avondale sequence was first described by Bell (1929) in his seminal work on the Windsor Group, though he incorrectly assigned it to the underlying Avon Limestone. Crowell (1967) recognized that these rocks were equivalent to one of Bell's unnamed units, and so subdivided the subzone into the Avon (D-1) and Meander River (D-2) limestones, with the Avondale exposure designated as the reference section for the unit. Waring (1967) and Moore (1967) also studied this section and agreed with Crowell's interpretation that the limestones represented a transgressive unit with capping breccias the result of evaporite dissolution. This writer's work (Brown, 1979) described in detail the sedimentary environments of the carbonate sheet's lithozones and determined that it represented a pair of incomplete, asymmetrical transgressive and regressive cycles (Fig. 17). Most important was the recognition of the well developed but complex calcrete soil horizon capping the sequence, and a detailed description of its various textures which provided an understanding of its evolution, and paleoclimatic and paleogeographic significance. Later revision of Windsor Group stratigraphy in the central Nova Scotia subbasins by Giles and Boehner (1979) grouped the Meander

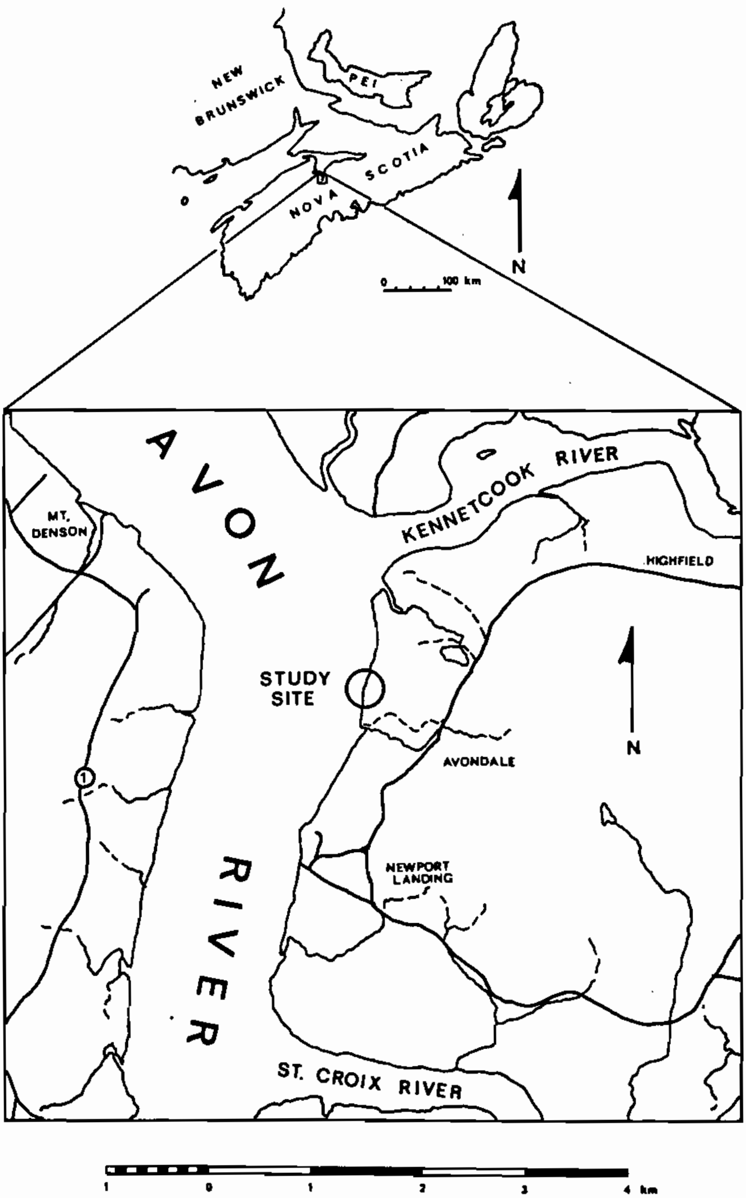


Figure 16. Location map of the Meander River Limestone Member, Murphy Road Formation, at Avondale, Nova Scotia.

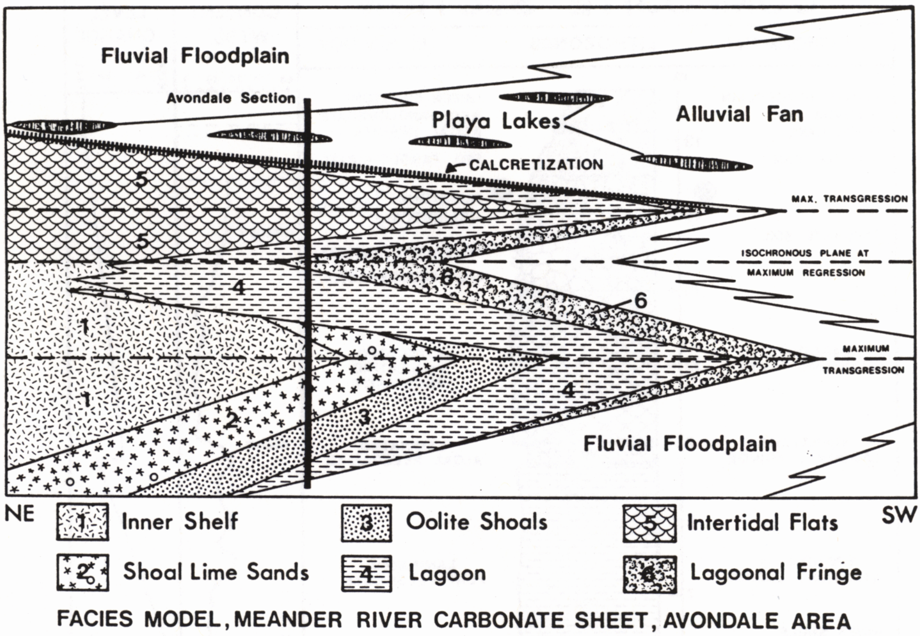


Figure 17. Facies model of the Meander River limestone (from Brown, 1979). A discussion of the development of facies and their relationships is presented in the text.

River and other related Upper Windsor limestones (C, D and E subzones) into a single large depositional cycle and in the Minas subbasin Giles (1981) assigned them to the Murphy Road Formation.

Description of the Succession

As noted above, the Meander River sequence represents a textbook example of a shallow marine transgressive carbonate succession (Fig. 18). The sequence transgressed a basically featureless clastic fluvial plain, similar to those which separate each of the Upper Windsor limestones. These clastics are tens of metres thick and are composed of red calcareous fluvial sandstones, siltstones and mudstones. Minor lacustrine intervals can be recognized and exposed at Avondale is a 10-50 cm thick black shale (with fine-grained sand laminations at the base) overlain by a thin buff-coloured unconsolidated siltstone to fine-grained sandstone with oscillation ripples. Overlying this are about 2 m of green fluvial/lacustrine deposits becoming limonitic at the base of the carbonates.

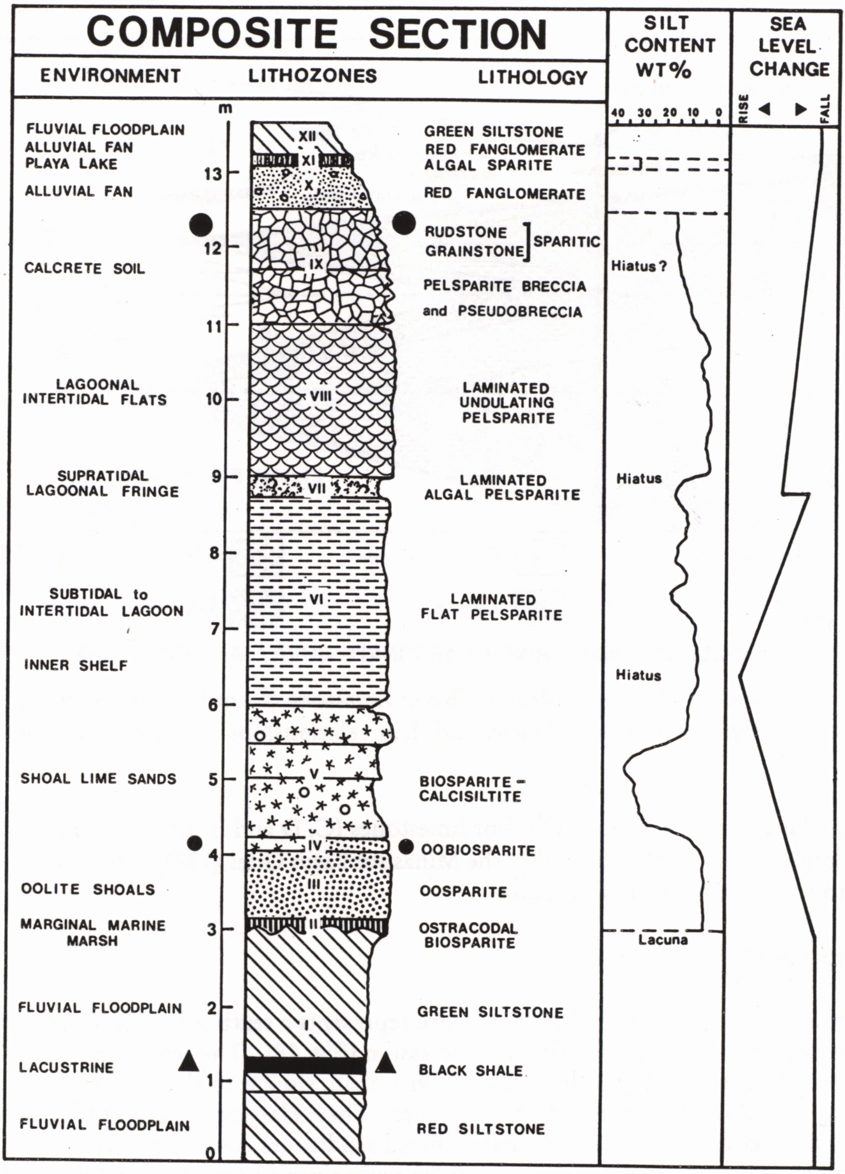


Figure 18. Composite stratigraphic section of the Meander River Limestone Member as exposed at Avondale. Possible source rock is indicated by triangles. Relative oil staining is indicated by the black dots. A detailed description of each facies is given in the text (slightly modified after Brown, 1979).

The contact between the clastics and overlying carbonates displays little relief and is essentially flat-lying. A thin (10-20 cm) transgressive ostracodal and oolitic grainstone marks the initiation of carbonate deposition and likely represents a coastal marsh setting. This lithology grades rapidly into an extremely well sorted brown ooid grainstone about 1.1 m in total thickness. This open marine (tidal?) shoal sequence is vaguely laminated with low angle cross-stratification, and reveals evidence of both early syndepositional and later calcite spar cementation, although significant intergrain porosity is visible in hand specimens. The 20 cm thick transition to the overlying open marine lime sands is composed of a dark grey to black, shaley fetid ooid to bioclastic grainstone. The ooids here are noteworthy due to their colour and large size when compared to the underlying strata. The light grey, poorly consolidated marine lime sands to silts (about 1.8 m thick) are rich in bioclastic debris (crinoids, echinoids, brachiopods, pelycepods and dascycladacean algae fragments) and are heavily bioturbated. Toward the top of the interval the rocks shows more distinct rippled bedding and progressively less evidence of bioturbation and fauna in life positions, inferring deeper water conditions.

Overlying the shoal lime sands are about 2.7 m of platy, laminated grey to brown pelleted micritic limestones with rare fossils. A deep water, inner shelf environment is interpreted for this unit. Individual beds increase in thickness upward and are separated by thin, soft, shaley yet highly fossiliferous light grey lime siltstones. Interestingly, towards the top of the unit the micrites, black algal laminations with associated laminoid fenestrae, calcite-lined open voids, small 0.8 mm gypsum crystals, and a mottled texture become increasingly common. These features reveal evidence of a much more shallow water environment, possibly a lagoonal setting. Although no physical evidence is observed, it is believed that a rapid regression took place such that the lagoonal strata were superimposed conformably upon the deeper water, inner shelf micrites. Indeed, the top of this unit is marked by a thin (35 cm) leached, limonitic brown limestone displaying abundant algal mats, gas and gypsum blisters, and buckle cracks, all indicative of a subaerially-exposed surface, here interpreted as a supratidal lagoonal fringe environment.

Immediately overlying the supratidal setting are 2 m of brown, pelleted, highly burrowed micritic rocks very similar in appearance to the deeper water lithologies. However, this lithology is characterized by repetitious (cyclic?) 5-10 cm thick undulatory beds (interference ripples) separated by thin (2-5 mm thick) black calcareous shales. Prism cracks are observed on planar surfaces and small 0.8 mm gypsum crystals are common. A lagoonal intertidal flat environment is interpreted for these rocks. Again, like the previous facies, fossils are rare and calcite-lined open voids become increasing common.

Superimposed upon the tidal facies is a 1.6 m thick, mature calcrete paleosol horizon. The outstanding exposure of this early post-depositional lithozone reveals the full progression of subaerial diagenesis on the underlying micritic sediments, from slightly mottled, cracked and pitted textures at the base, intermediate solution and collapse breccias and pseudobreccias, to an upper silt-rich saccharoidal calcite spar grainstone (heavily oil-stained). Classic paleosol features recognized in this lithozone include solution pipes, roots and root traces, solution vugs, dissolution and collapse breccias, slump features, buckle cracks, meniscus cementation, laminated beds, coated clasts, limonite staining, siltstone intraclasts, and laminated 'saucer' pebbles.

Capping the entire carbonate sequence are intraclast-rich sandstones and siltstones, interpreted to represent distal debris flow and sheetflood deposits sourced from nearby basin margin alluvial fans overlain by clastic fluvial strata. About half a metre above the top of the paleosol is a very thin (6 cm) flat-pebble algal-laminated micrite which are believed remnants of playa lake deposition.

Hydrocarbon Systems and Features

There is only a limited understanding of the hydrocarbon system(s) for the Windsor Group, and indeed, the entire Carboniferous succession in Atlantic Canada. Numerous oil shows, as well as possible source and reservoir rocks have been identified and encountered both on and offshore. However, over the past century exploration activity has been sporadic and with the exception of the Stoney Creek oil and gas field in New Brunswick, discovered in the early 1900s, there have been no significant discoveries nor sustained commercial production of hydrocarbons from the rocks of this age in the region.

Based on the above example, most of the hydrocarbon potential was (and to a certain degree is still) believed to exist in various fluvial-lacustrine facies of the basal Horton Group (Tournaisian). Oil and gas shows and staining have also been encountered in overlying Windsor Group (Viséan) carbonates and evaporites, though mostly in Lower Windsor rocks. Interestingly, Bell's (1958) speculations on the potential of the Lower Windsor pointed to possible significant biohermal reservoirs being developed in the Sydney Basin (i.e. Gays River-type carbonate banks). These would make attractive reservoirs as they are known to occur on structural highs, are variably dolomitized (enhanced porosity and permeability), and could be sourced from basinal evaporites and shales, and also sealed by the former (Giles *et al.*, 1979; Boehner *et al.*, 1989). However, migration pathways within the evaporites to such build-ups could be problematic and would appear to require the assistance of later faulting and fracturing.

Bell (1958) suggested that although fair to good potential source rock facies were to be found in the Horton and Lower Windsor strata, the better reservoir zones existed in the biohermal limestone beds of the Upper Windsor. Within the Upper Windsor, several biohermal-biostromal reef mounds have been documented (Boehner, 1988; Boehner *et al.*, 1989). Potential reservoirs in the Upper Windsor would have better potential to receive upward-migrating hydrocarbons generated from deeper, more mature basinal Lower Windsor source rocks. Again, suitable migration pathways are required. Seals in this interval are also problematic as they are composed mostly of variably-grained fluvial clastics of the Canso Group.

At the Upper Windsor Avondale section, several potential reservoir facies are represented, and they, or their lateral equivalents, may be encountered throughout the basin (Fig. 18). The basal limestone has observable interoolitic porosity visible to the naked eye, though to date, no porosity/permeability analyses have been conducted to quantify these rock attributes. When freshly broken, these rocks occasionally give off a weakly petroliferous odor indicating possible passage of hydrocarbons at one time. However, at the unit's top is a 10 cm interval of poorly sorted, dark grey to black shaley oolitic bed, which although it has no visible porosity, gives off a strong petroliferous odor on fresh samples.

A more important, and perhaps overlooked reservoir facies, is the calcrete paleosol developed at the top of the carbonate succession. Indeed, a number of hydrocarbon shows encountered in petroleum wells and drillholes were from intervals described as "breccias" of various types, though their stratigraphic position is not known or poorly understood (see examples in McMahon *et al.*, 1986). Due to subaerial exposure and diagenesis, excellent vuggy and intercrystalline porosity has developed in otherwise tight tidal and lagoonal micritic mudstones. To date, the unit's porosity and permeability have yet to be properly quantified. Whereas here reservoir development is facies-dependent within the oolitic grainstones, the development of the calcrete is not and depending on the time and extent of exposure, regression or basin drawdown may be superimposed on any of the Meander River facies. This has significant exploration implications. Although the proclivity and effects of calcretization are greater toward the basin margins (Crowell, 1967), it is possible that minor basinal warping and faulting within the basin centre, perhaps related to movement of deeper Lower Windsor evaporites, could expose the carbonates to subaerial diagenesis.

In addition to creating an excellent reservoir facies, any later structural activity could tap into and/or juxtapose source and reservoir facies, thus facilitating either vertical or lateral migration of hydrocarbons generated from older or time-equivalent strata. Indeed, the recognition of a major thrust fault in the adjacent Kennetcook basin to the east of the Windsor Subbasin (Boehner, 1990) and similar faults in other subbasins (Smith and Collins, 1985) would provide the necessary conduits for the large scale migration of hydrocarbons and mineralizing fluids. Evidence for this mechanism has been observed at the Walton barite deposit adjacent to the Kennetcook Trust (Boehner, ibid.) where petroleum was pervasive at the deposit in the form of liquids, staining, and fluid inclusions (Boyle, 1972).

Such a scenario could explain the presence of the well developed and pervasive oil staining present in the calcrete's uppermost sucrosic spar grainstone (Fig. 18). Freshly broken samples from this black, 30 cm thick zone give off an intense petroliferous odor, and display an orange fluorescence oil staining suggestive of a mature oil which might be biodegraded. Intriguingly, the stained interval has a very sharp basal contact which is horizontal with original bedding. This infers that liquid hydrocarbons were likely generated very early and must have migrated from a distal source up-dip toward the basin margins perhaps driven by tectonic activity in the source area prior to any tectonism and formation of traps in this area. If correct, then reservoirs within this and other Upper Windsor limestone members in the Minas Subbasin may have received liquid hydrocarbons and, where nor breached by erosion or penetrated by later faults remain preserved as untapped accumulations.

Although it appears to have been overlooked, there may be potential for source rocks existing in Upper Windsor Group rocks. About 2 m below the carbonate at Avondale strata is a variably thick (10-50 cm) black lacustrine shale overlain by a thin buff-coloured unconsolidated siltstone to fine-grained sandstone with oscillation ripples (Fig. 18). An incomplete analysis of this rock has recently been completed though more detailed work is required. Fluorescence observation on unpolished whole rock suggests the presence of oil-prone mixed algal and terrestrial organic matter of kerogen Type 2-3 or 2 and that the sample is within the oil window (the calculated vitrinite reflectance would be between 0.8 to 1.1% R_o (Mukhopadhyay, personal communication, 1998). Although modest at this site, it is speculated that this interval, and related ones, likely thicken basinward and have potential to become volumetrically significant and under the right conditions to generate appreciable quantities of hydrocarbons.

The Joggins Carboniferous Section (Stop No. 5)

Location and Access

To reach Joggins (Fig. 1) by road, leave Route 302 at Maccan, turning west (right if travelling south from Amherst via Nappan) on Route 242. Proceed 20 km, crossing bridges spanning the Maccan River and the River Hebert, continuing through the village of River Hebert to Joggins. Proceed along the main street, turning right toward Lower Cove; park at the bridge crossing Little River and proceed to the left (southward) along the shore. Alternatively, follow the signs from Main Street leading to the designated parking area and descend the steps at Bell's Brook.

Background

The Joggins Section is arguably the world's best exposed section of Carboniferous coal measures. The "classic" section from Lower Cove south to MacCarrens Creek (Fig. 19) comprises cliffs 20 m high that run for 3 km, bordered by a wave-cut platform about 500 m wide that is completely exposed at low tide. Since the first visit to this coastal section by Sir Charles Lyell in 1842, Joggins has been one of the most celebrated geological sites in the world. The fossil record from whence its claim to fame largely derives, we owe largely to the half century labour of love by Nova Scotian Sir William Dawson. In recognition of its pre-eminent place in the history of geology, the community of Joggins and surrounding area currently are developing a submission to the United Nations for the designation of the fossil cliffs as a World Heritage Site.

In spite of its fame, advances in our understanding of the Joggins section have been painfully elusive since the pioneering, and to date most exhaustive, research of the section by Sir William Dawson in the Nineteenth Century [summarized in his highly recommended, seminal work *Acadian Geology* (editions of 1855, 1868, 1878 and 1891)]. A revised sedimentological description of the section by Davies, Gibling, Calder and others provides an important new framework for research of the fossil record and its paleo-ecology. Recent paleontological research of the fossil lycopsid forests by Andrew Scott (Royal Holloway, University of London) and Calder in concert with the sedimentology of Gibling and Davies, and an appraisal of the marine affinities of the aquatic realm by Skilliter and Calder, are two lines of current research that offer promise in increasing our ourstanding of this most marvellous but enigmatic of Carboniferous sections.

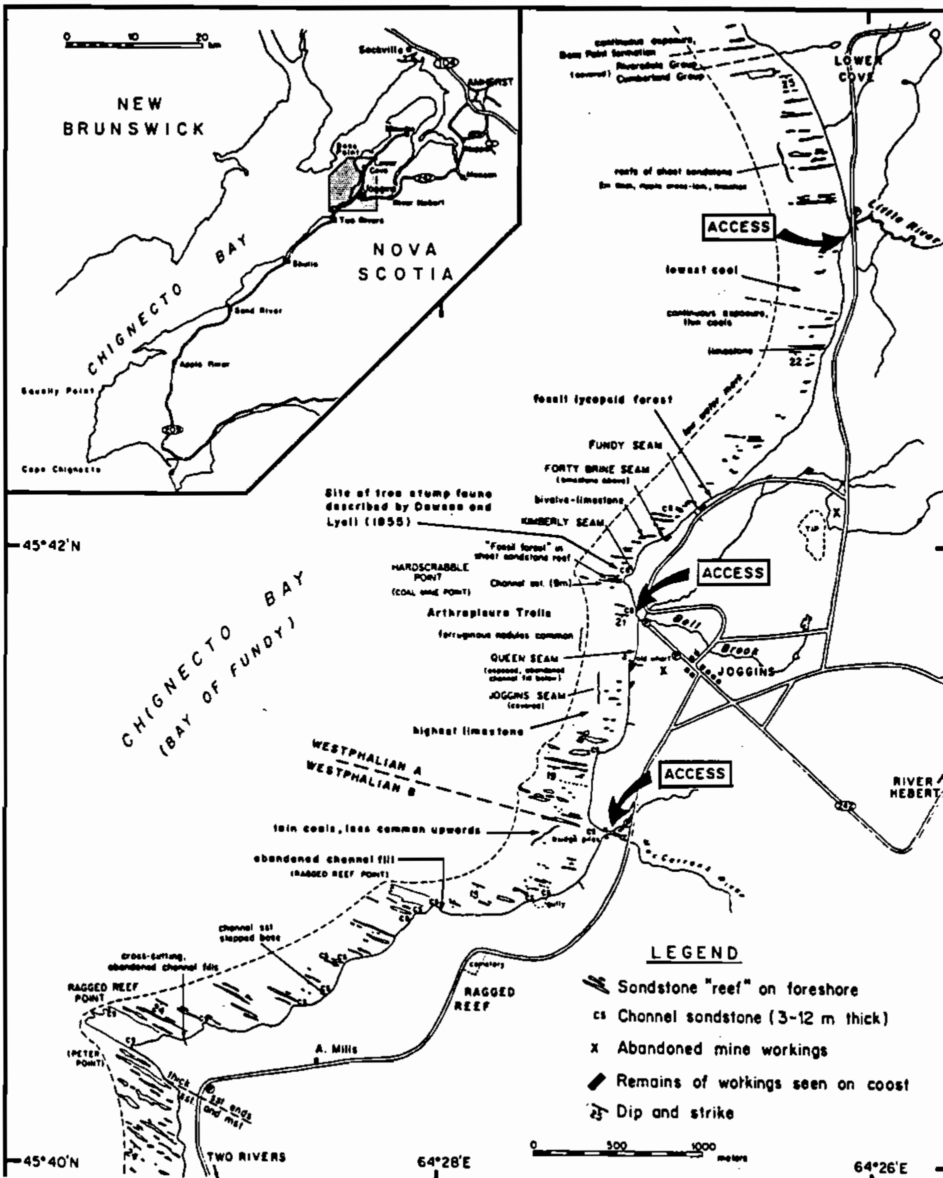


Figure 19. Site map for the Joggins fossil cliffs (Stop 5), modified after Gibling, 1997.

Recent Work

Many papers have been published about the Joggins section, although surprisingly few in this century. The works of Dawson are the most prolific and important. Logan (1845) presented a bed-by-bed section that includes cm-scale measurements of the coal beds, which he numbered, and has remained the cornerstone of stratigraphic study ever since. More recent sedimentological studies of parts of the section were carried out by Duff and Walton (1972) and Rust *et al.* (1984). Selected paleosols were studied by Smith (1992). A detailed analysis of floral occurrences and associated tetrapod remains was carried out by Scott and Calder from 1993-96, and several papers are completed or in preparation. A study of trace fossils and foraminifera was published by Archer *et al.* (1996), and studies of fossil charcoal and sedimenological response to wildfire were carried out by Falcon-Lang (Royal Holloway) in 1996 and 1997.

In the summers of 1996 and 1997, a comprehensive remeasurement of the section from Lower Cove to Bell's Brook was completed by Sarah Davies (University of Edinburgh), Gibling and Calder. The overlying strata exposed between Bell's Brook and McCarron's Creek were measured by Teniere and Tonelli (Dalhousie) in 1997. This is the first time that the entire 2 km thick "classic" section has been systematically measured since the 1840s. This measured section now provides a comprehensive stratigraphic and sedimentological framework for the section, especially for the remarkable fossil occurrences (Fig. 20).

Stratigraphy

The classic Joggins section lies within the Cumberland Basin (Fig. 3). It comprises the Joggins and Springhill Mines formations (Westphalian A to early B) of the Cumberland Group (Rayn *et al.*, 1992), exposed between Lower Cove and McCarron's Creek in a near-continuous section nearly 2 km thick. Underlying these strata are 400 m of less completely exposed Joggins Formation strata in Lower Cove, and an additional ~1500 m of continuous exposure around Boss Point of the Mabou Group and overlying Boss Point Formation (late Viséan to Namurian or Westphalian A). An additional 650 m of strata of the Springhill Mines Formation, differentiated from the Joggins Formation by its absence of fossiliferous limestones, is exposed from McCarron's Creek to the Ragged Reef. These strata develop inland to include 4 m thick piedmont coals of the Springhill Coalfield (Calder, 1993; 1994). South of Ragged Reef, the cliffs continue for many kilometres along Chignecto Bay with a near-continuous strike section. Thus, the

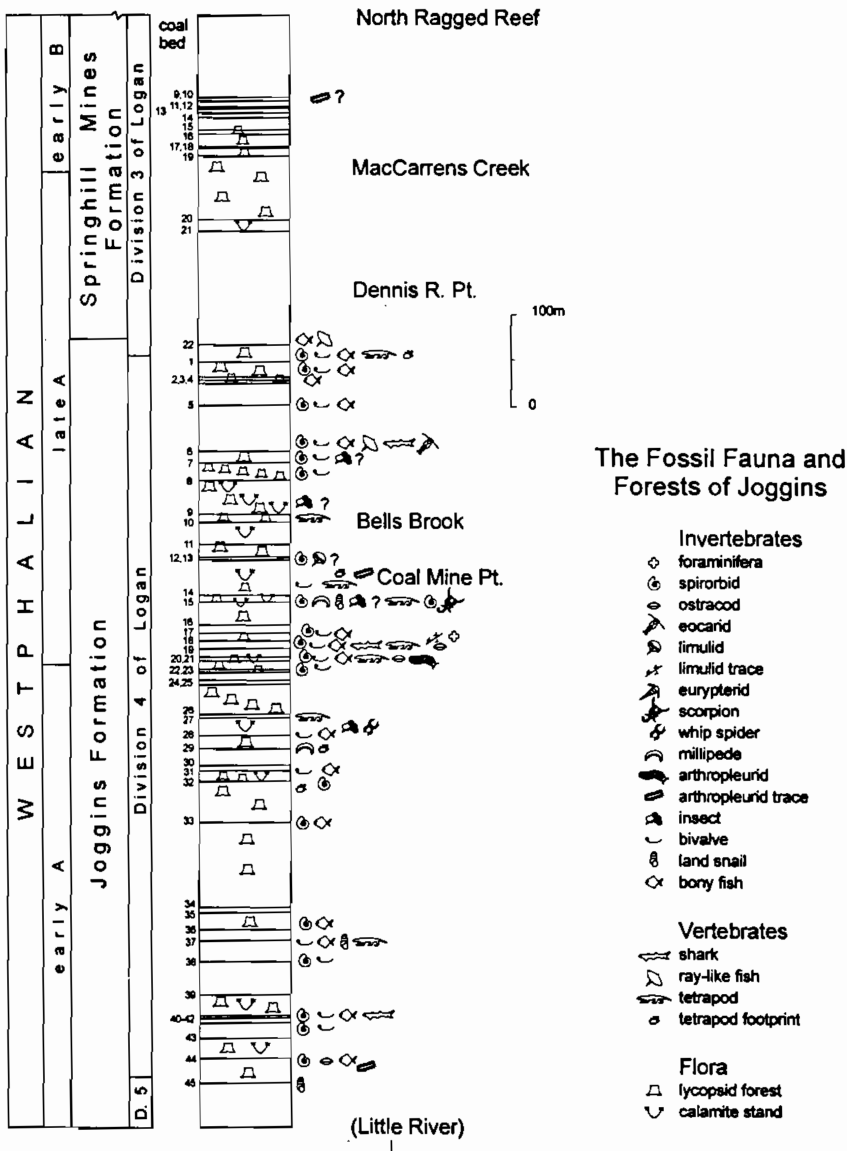


Figure 20. Simplified stratigraphic column of the classic Joggins section showing horizons of coal beds enumerated by Logan (1845), erect lepidodendrid trees, and calamite stands and faunal occurrences (from Calder, in prep.).

Joggins section forms part of a near-continuous, mid-Carboniferous section >4 km thick. The remarkably thick section reflects the rapid subsidence of the fault-bounded Cumberland Basin under a transtensional to transpressional regime near a micro-plate and terrane boundary; basinal subsidence at this time was linked to the Alleghanian Orogeny and the final stage of assembly of Pangea.

The Fossil Record

The fossil record of Joggins and its paleo-ecology has been the subject of research by Calder over the past few years and a comprehensive summary is forthcoming (Calder, submitted). The complete flora and fauna are included in the appendices of Calder (1998). The fossil fauna of Joggins can be grouped into two categories each for the terrestrial and aquatic realms: invertebrates and vertebrates. The terrestrial record by far has received the greatest attention, with comparatively little work on the aquatic invertebrates and even less on the vertebrates (fishes).

The aquatic record derives exclusively from the limestone and 'clam coal' beds that overlie certain of the seams, in particular the Forty Brine (Coal 20) and overlying 'clam coal' (Coal 19) (Stop 5.3) and the Joggins Seam (Coal 7). Their paleo-ecological significance with respect to marine incursions, hence, has remained largely unevaluated; however, not all aquatic fauna are unequivocally freshwater. Taxa of dubious affinity include agglutinated foraminifera, spirorbids, bivalves, limulids, eocarid crustaceans, elasmobranch sharks and coelacanths (Calder, 1998).

Many of these fossils can be found in fallen material on the beach, and some of the best material is on display in the Fossil Centre at Joggins. Joggins is a protected site under the Special Places Act of the Province of Nova Scotia and excavation of fossil material from the cliffs is prohibited. Common fossils found in beach stones, however, are collectible. That said, virtually all of the important paleo-tological discoveries over the years have been made from material fallen from the cliffs, so be on the lookout! Should you find a vertebrate or other unusual fossil, please bring it to the attention of the trip leader, Nova Scotia Museum (902-424-6451), Fundy Geological Museum (902-254-3814), or Joggins Fossil Centre staff.

Sedimentology

The cliff and platform exposures allow an unrivalled 3D perspective of the strata, which can be grouped into several facies types:

Alluvial redbed facies (Stop 5.1) include narrow (width: depth ~ 10:1) channel bodies, typically a few metres thick with numerous abandoned hollow fills internally, isolated within red floodplain strata (immature, humid paleosols). Thin sheet sandstones represent crevasse splays and levees. Where they have been studied higher in the section, these deposits have been interpreted as anastomosing river deposits.

Alluvial grey facies (Stop 5.4) larger channel bodies are well exposed where they form resistant headlands. They are up to 10 m thick, contain scroll bar deposits (exhumed on the wave-cut platforms) and lateral accretion surfaces, indicative of meandering rivers. Some channel bodies have erect trees exposed on their margins (as in many modern rivers).

Bay-fill and poorly drained floodplain facies (Stop 5.2) comprise stacked, progradational coarsening-up units. They represent the fills of shallow standing water bodies, and are commonly associated with distributary channel bodies. Abundant rooted and transported vegetation is present, including the many erect trunks, and coals up to 2 m thick are present. Some fills are capped by ganisters (silica-cemented paleosols) or by hydromorphic paleosols.

Shallow nearshore facies (Stop 5.3) are largely wave-dominated shales and sandstones, with hummocky cross-stratification (HCS) and wave ripples. Large-scale (50-100 m across) domal forms can be observed in the cliff and wave-cut platform exposures. They include stacked HCS units and delicate exposure features (planed-off ripples, backwash drainage structures), and are interpreted as the deposits of nearshore bars. Dark, organic-rich limestones up to 1 m thick contain an abundant shelled fauna. Brackish marine (?estuarine) conditions are indicated by the trace fossil suite, foraminifera, and recent Sr isotope data on fish fragments (see Calder, 1998).

Coal Beds and Hydrocarbon Source Rocks

The coal beds of this famous section have received suprisingly little study, and the bulk of what has been done is largely unpublished as yet. Coal beds of the Joggins Formation typically are thin (less than 1 m) although they can form seams interstratified with clastic partings that comprise zones exceeding 2 m, as for example, the Fundy Seam and overlying Coal 28. Typically the coals are bright, clarain-rich and pyritic; calcareous permineralization of lycopsid periderm occurs locally within the coal beds. Discrete breaks (plies) in a bed invaribly occur on fusain horizons. R_o at surface ranges from 0.67 to 0.70% and may be suppressed to lower values by liquid hydrocarbon expulsion (Mukhopadhyay *et al.*, 1991).

The coal beds typically are dominated by the arboreous lycopsids including *Lepidodendron*, with the miospore *Lycospora pellucida*, produced by *Lepidophloios*, particularly abundant within the Forty Brine and Queen seams (Dolby, 1998). Conspicuously rare are miospores of *Sigillaria*, whose compression fossil is commonly found associated with fossil forests in the section. This may reflect its weak output of miospores or its ecological prefrence for ecotonal clastic-rich substrates.

Analysis of the hydrocarbon-generating potential of basin wide organic-rich limestones and 'clam coal' beds from the Joggins section reveals that they contain 1.41 to 13.10% TOC. The Joggins Formation source rocks are thermally immature to slightly mature, with Tmax values of 414-434°C and R_o of 0.6%. Hydrogen indices in the range of 316-978 suggest derivation from algal and vascular plant sources, with kerogen types 1, 2 and 2 to 3 represented. These data are consistent with widespread flooding events, possibly from a marine source, of lowland plant communities.

Sequence Stratigraphy

The Joggins section is a coastal to alluvial succession, and should be a good candidate for recognition of high-resolution Exxon sequences, sequence boundaries and systems tracts. However, our detailed analysis has failed to identify sequence boundaries in the section, despite the very complete exposure. Paleosols are apparently immature throughout, and channel bodies are meandering or anastomosing in style, in accord with the associated floodplain facies. There are no indications of major basinward shifts of facies (for example, proximal braidplain sandstones) that might indicate major lowstand events or be candidates for valley fills. Instead, the section is dominated by a hierarchy of flooding surfaces, and these define parasequences that are stacked in progradational and retrogradational sets. The flooding surfaces are marked by bivalve-ostracode limestones, coals and carbonaceous shales, grey mudstones in predominantly red successions, and ostracode (freshwater) limestones in some redbeds. The parasequence sets form large-scale cycles (~50-200 m thick) that reflect major transgressive - regressive events. The cycles typically show a gradual passage from shallow subtidal through lagoonal to alluvial facies as the coastal plain prograded, followed by a return through lagoonal to subtidal facies. The cycles vary from near-symmetric to strongly asymmetric in their facies organization. The sharp-based nature of most subtidal sandstone sheets suggests that many progradational events were associated with base-level fall (forced regression), although the falling levels were apparently insufficient to cause incision and valley formation at this locality.

It is probable that rapid subsidence in the Cumberland Basin, with an abundant sediment supply, allowed sedimentation to be virtually continuous. Under these conditions, major hiatuses that would be represented by valley fills or mature paleosols would not be generated. Such a style of basinal filling through a thick succession is unusual, and forms an interesting contrast to the better known Exxon model.

Alluvial Redbeds of the Lower Joggins Formation (Stop No. 5.1)

Stop leader: Martin R. Gibling, Dalhousie University

The lower strata of the Joggins Formation provide an opportunity to examine the alluvial redbed facies. Channel bodies typcally occupy narrow incisions, manifested as isolated bodies in the intertidal zone in contrast to the more laterally continuous sheets of the grey beds higher in the section. Internal bed geometry of the sandstone bodies is characterized by successive cross-cutting hollow fills evocative of intermittent flashy flow.

These strata contrast in their sedimentary style with those associated with coal beds and with fossil forests higher in the section, indicating that they were deposited under different, presumably more seasonal conditions.

Fundy Seam Fossil Forests (Stop No. 5.2)

Stop lader: John H. Calder, Nova Scotia Department of Natural Resources

At this locality, spanning the 37 m thick interval (Fig. 21) from Coal 32 of Logan (1845) to Coal 29 (the Fundy Seam), occurs one of the finest examples of the fossil lepidodendrid forests for which the Joggins cliffs are noted. The forests are coincidental with the first 'thick' coal bed of the Joggins Formation, Coal 32, atop a thick succession of redbeds. This interval serves to illustrate the sedimentologic association of the lepidodendrid-calamitean forests that recurs throughout the section.

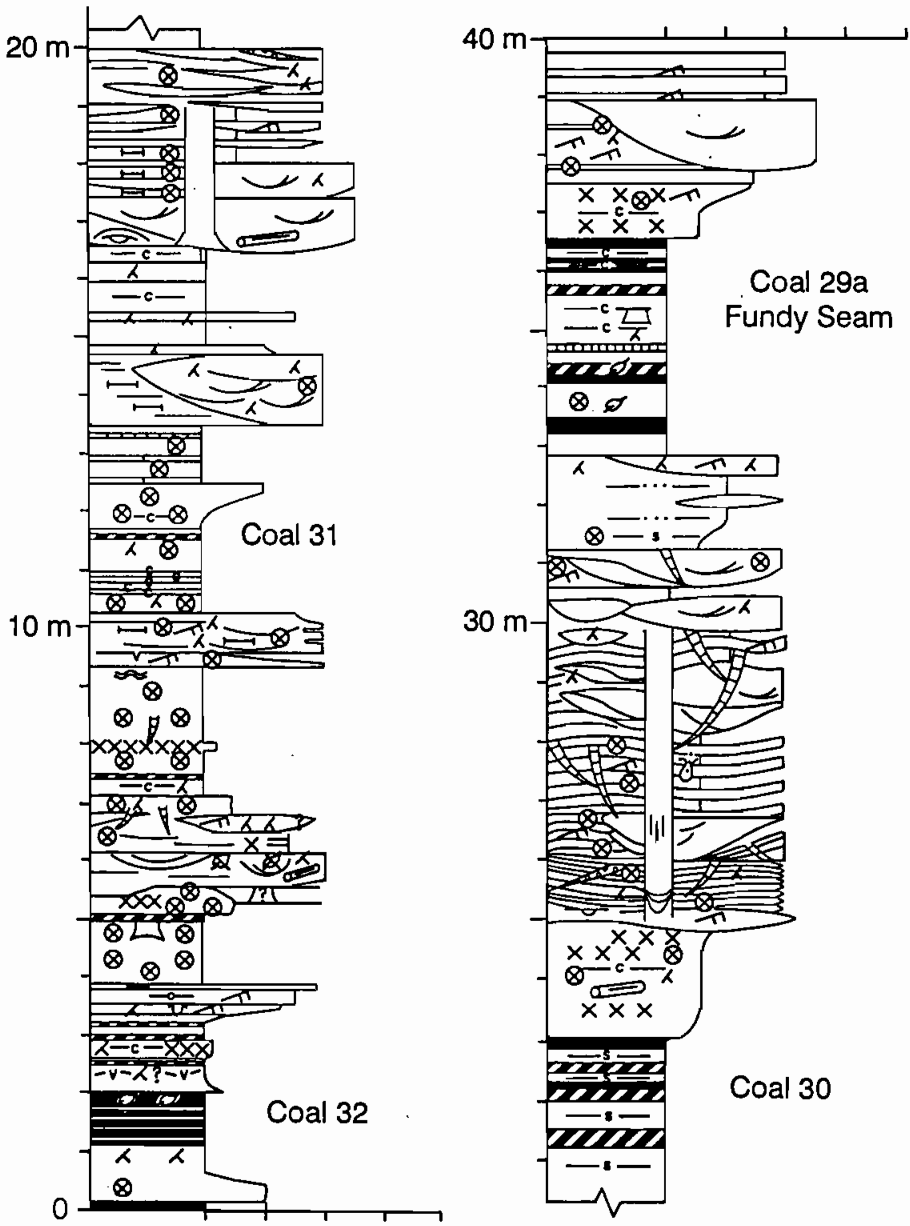


Figure 21. Sedimentological profile of the fossil forests in the interval between Coals 32 and 29 (Fundy Seam).

EErect Lcopsid and Clamite Tees, and Teir Efects on Sedimentation

The section contains 49 recorded horizons containing erect trees (Fig. 20), and new finds are constantly being made as the cliffs recede and the thin sediment cover on the wave-cut platform shifts. The most spectacular preserved trees are up to 3 m tall and nearly 1 m in diameter near the base, but many are also visible truncated shortly above the base of the trunk. (Fallen logs up to 13 m long have been found in former coal mines in the area). Virtually all lepidodendrid trees (lycopsids bearing the rootstock *Stigmaria*) are rooted in coal beds, however thin. The trees are easily visible in the cliff faces, and numerous occurrences with tens of trunks in a single layer can be examined in resistant sandstone 'reefs' that run across the wave-cut platform.

How the trees were entombed before they decayed has always been a vexing question. Our sedimentological studies show that the tallest trees were entombed in 'bayfills' of shallow, standing-water bodies as a result of floods that brought in large amounts of sand from adjacent distributary channels. The correlation of entombing heterolithic sandtone beds with channel fills can be demonstrated by walking out the layers across the wave-cut platform at this locality. The hetreolithic sandstones that entomed the lepidodendrid forests invariably are characterised by the ubiquitous presence of erect calamites (Fig. 21) that appear to have persisted by adventitious propagation. The taphonomy of the calamites and sedimentology of the enclosing sedments indicate that the heterolithic beds were emplaced at intervals, presumably from successive, closely spaced flood events. Some erect lepiodenrids trees are partially charcoalified, indicating that wildfires periodically razed the forests. Research by Howard Falcon-Lang and Andrew Scott (Royal Holloway) suggests that wildfires may have contributed to the high sediment flux from a devegetated hinterland, aiding rapid entombment. Most erect trees are sediment-filled, although a few are permineralized, including rare specimens of possible medullosan (seed fern) affinity.

An unusual feature of the section is the abundance of scour hollows around trees, with centroclinal cross-stratified sandstone filling the hollows (Fig. 21). Also noted are vegetation shadows, infilled hollows where trees were uprooted, and (rarely) scratch circles. So pervasive has been the effect of vegetation on sedimentation that many crevasse-splay sandstones are dominated by scour-and- mound features around the preserved vegetation. This effect has rarely been documented in the ancient record and, if unrecognised, might be attributed to mounded bedforms such as HCS or antidune deposits.

As with all fossil lepidodendrid forests, the identification of the trees even to the generic level is a challenge due to their decortication and disruption of diagnostic leaf scars on the basal trunks by secondary growth. Although virtually all Joggins standing trees have been ascribed to the lycopsid genus *Sigillaria* by Dawson and by subsequent workers, it is likely that other genera are represented. In this interval, *Sigillaria* dominate the compression flora of prostrate tree trunks, but also represented are *Lepidophloios*, *Lepidodendron* and possibly even *Bothrodendron*. Elsewhere in the section, halonial, branch-scarred trunks of *Paralycopodites* are encountered as compression fossils.

Note that pit props and rails protrude from three beds, testimony both to the long history of coal mining and to the forces of coastal erosion in the Bay of Fundy.

Forty Brine Seam Section (Stop No. 5.3)

Stop leader: Deborah M. Skilliter, Boston College

The Forty Brine section (Fig. 22) is the subject of a graduate thesis by DMS at Boston College (Skilliter, in prep.). The stratal interval described below is the subject of investigation for evidence of marine influence within this classic continental sequence. The study interval can be divided into two main sedimentological units: (1) terrestrial channel sandstone bodies at the base and top of the section, which bound (2) an interval consisting of thin coal seams, limestones, 'clam coal', claystone, siltstone, thin, tabular sandstone bodies, and the 'trace-fossil bed'.

Terrestrial Channel Sandstones

Sandstone units, interpreted by DMS as terrestrial channel sandstones based on field relationships, are observed at the base and top of the study section. The basal terrestrial unit consists of 1.88 m of medium-grained, cross-stratified, grey sandstone. The basal contact of the sandstone is erosive and channel margins scoured into underlying units are preserved. The channel sandstone is thickly bedded with intermittent thin beds. The sandstone contains plant roots, pyrite nodules, and siderite nodules and bands. There is a partial, *in situ*, upright lycopsid measuring 55 cm in height and 37 cm in diameter at the base of the sandstone unit. Plant roots (*Stigmaria ficoides*) radiate from the base of the tree. The sandstone is overlain by approximately 1 m of light grey, friable claystone,

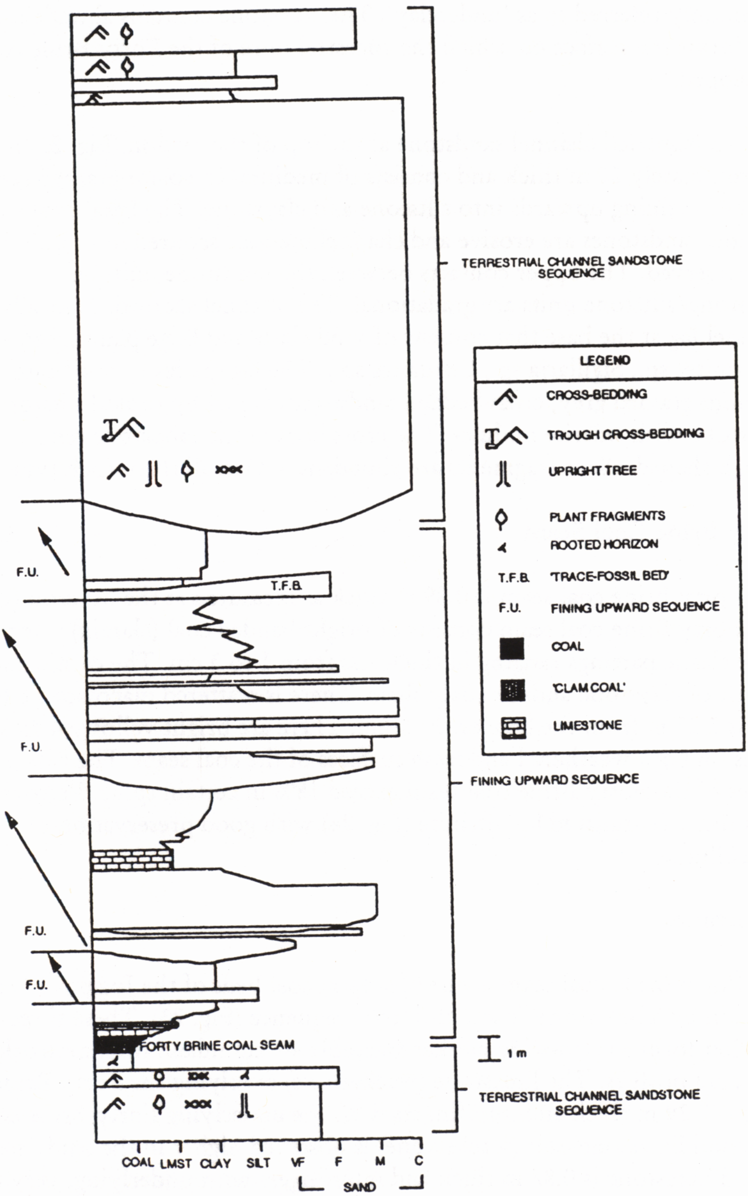


Figure 22. Sedimentological profile of the Forty Brine interval, from Skilliter (in prep.).

commonly referred to as 'underclay'. The claystone contains abundant plant roots and forms the surface on which the ancestral mire of the Forty Brine coal seam developed.

The multistoried channel sandstone at the top of the section (Fig. 22) is approximately 20 m thick and consists of medium- to coarse-grained grey sandstone fining upwards into siltstone and claystone. The basal contacts of the channel sandstones are erosive and channel margins scoured into underlying units are preserved. The upper contacts between the sandstone units and claystone/siltstone units are gradational. The channel sandstones locally contain channel lag at the base that consists of mud clasts and large plant fragments (Calamites sp., Sigillaria sp., Cordaites sp.). The lag grades upward into medium-grained grey, cross-bedded sandstone capped by rooted siltstone and claystone with siderite nodules. The cross-beds in the sandstone tend to be trough-shaped. Plant fragments are abundant within all three rock types.

Forty Brine Coal Seam

The Forty Brine coal seam is 0.89 m thick as measured at the outcrop (Fig. 23) . The Forty Brine coal seam consists of bright banded coal (clarain) punctuated by three clastic partings ranging in thickness from 1 to 3 cm. The clastic partings consist of claystone and/or coaly shale. There is scattered macroscopic fusain debris 0.25 m from the base of the seam. There are bright yellow surficial sulphur stains on both weathered and fresh surfaces of the coal seam. The total sulphur values of the Forty Brine coal seam exceed 18% in certain splits. Petrographically, the seam is dominated by vitrinite (Fig. 24) with good preservation of gelocollinite.

Limestones

The Forty Brine coal seam is one of several coal beds of the Joggins Formation overlain by a limestone/'clam coal' roof sequence (Fig. 23). These three units together form a basin-wide marker traceable 40 km inland in mine workings and drill core profiles. The limestone (wackestone) overlying the Forty Brine coal seam is 0.29 m thick and interfingers with the underlying Forty Brine coal seam. A second limestone unit (wackestone) is observed higher in the study section. The second limestone is 0.87 m thick and interfingers with underlying, very thin bands of 'clam coal' and clarain. Both limestone units are carbonaceous and, when freshly broken, emit a bituminous odor. Both limestones contain similar faunal

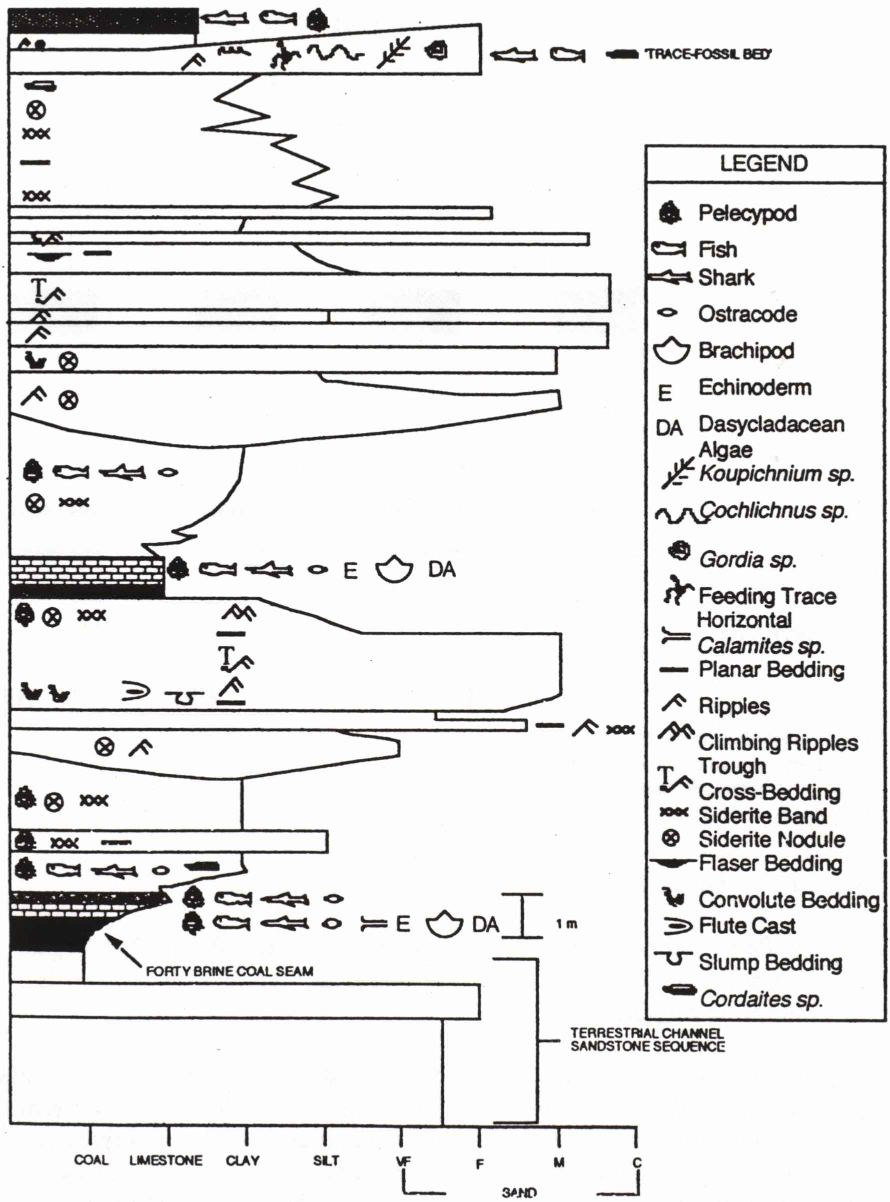


Figure 23. Detailed sedimentological profile of the Forty Brine seam (Coal 20 of Logan, 1845), limestone roof and overlying 'clam coal' (Coal 19), from Skilliter (in prep.).

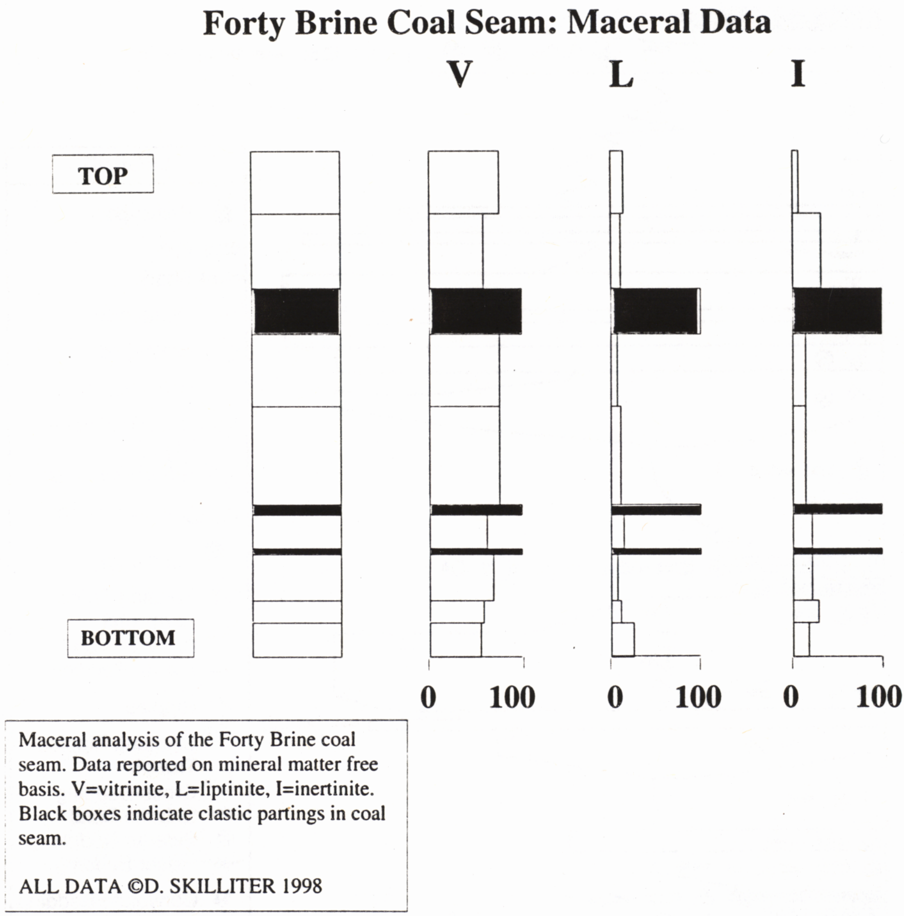


Figure 24. Petrographic profile of the Forty Brine coal seam (Coal 20 of Logan, 1845), illustrating the dominance of the vitrinite group typical of Joggins coals (from Skilliter, in prep.).

assemblages consisting of ostracodes, foraminifera, abundant pelecypods (*Naidaites longus, Naidaites carbonarius, Curvirimula sp.*), rare brachipods, rare echinoderm fragments, fish scales and bones, shark teeth (*Xenacanthus sp., Ctenacanthus sp.*), polychaete worms (*Spirorbis carbonarius*), Dasycladacean algae (marine green algae), three different types of coprolites of unknown but presumably piscine affinity, small vertebrate bone fragments (fish, amphibians, reptiles), and rare plant fragments.

'Clam Coal'

'Clam coal' is evocative, local vernacular for a repetitive, fissile, bituminous-rich black shale unit. Within the study interval, there are three discrete beds of 'clam coal'. At the base of the section, the 'clam coal' interfingers with and overlies the lower limestone unit. The 'clam coal' in this part of the section is 14 cm thick and the lateral thickness and extent is fairly uniform. 'Clam coal' is overlain gradationally by grey claystone. The second unit of 'clam coal' occurs mid-section where it underlies the second limestone unit. Here, the 'clam coal' is complexly interfingered at the base with 3 cm of bright coal. The 'clam coal' is 2 cm thick and thins laterally. The third occurence of 'clam coal' in the study section lies 30 cm above the 'trace-fossil bed' near the top of the fining-upward sequence. In this location, the 'clam coal' interfingers at the base with two bands of bright coal. The 'clam coal' is 41 cm thick and the lateral thickness and extent are fairly uniform. 'Clam coal' at this location is overlain by 3 cm of very soft, friable light grey clay. Outside of the study interval, 'clam coal' is observed at several locations (both above and below the study interval) in the Joggins section.

The 'clam coal' (Fig. 23) contains abundant disarticulated pelecypod shells (*Naiadites carbonarius*, *Naiadites longus*, *Curvirimula sp.*) which define the fissility of the unit. Pelecypod valves in the 'clam coal' are preserved with the convex edge of the valve facing down toward the sediment interface. No pelecypods were observed preserved in a living position. The faunal assemblage in the 'clam coal' is dominated by pelecypods. There are a high number of pelecypods, but a rather low diversity (genera appear to be restricted to two: *Naidaites* and *Curvirimula*). The individuals of both genera do not vary much in size. The average length from umbo to beak is approximately 1.5 to 2 cm. As well as pelecypod shells, the 'clam coal' contains brachiopod shells and spines, ostracodes, foraminifera, fish scales and bones, shark teeth (*Xenacanthus sp.*, *Ctenacanthus sp.*), polychaete worms (*Spirorbis carbonarius*), malacostracans (*Pygocephalus dubius*), coprolites, and small vertebrate bones (amphibians and reptiles). The faunal assemblage observed within the 'clam coal' very closely resembles that observed in the limestone, the main difference being the dominance of pelecypods in the 'clam coal'.

Claystone

There are several occurences of claystone with the study interval. The claystone units are grey, thinly-laminated, and fissile. Where the claystone overlies 'clam coal', siltstone, and/or sandstone the basal contacts are gradational. Where the claystone overlies limestone, the basal contacts are fairly distinct. Upper contacts with most units are gradational. The thickness of the claystone units ranges from a few centimetres to 3.70 m. The claystones contain siderite nodules and bands. These units contain a similar faunal assemblage as the 'clam coals' (pelecypods, ostracodes, fish scales and bones, etc.) and are notable for the absence of plant macrofossils. One particular unit of claystone, approximately 3 m above the top of the Forty Brine coal seam, exhibits extremely fine laminations which appear to approximate tidal rhythmites.

Siltstone

There are several occurences of siltstone within study section. Where the siltstone units overlie sandstone bodies, the basal contacts are gradational. Where the siltstone units overlie claystone bodies, the basal contacts are sharp. Upper contacts are gradational. The siltstones within the study section range in thickness from a few centimetres to 3.40 m. Generally, the siltstones are grey, thinly-laminated and contain siderite bands and rare siderite nodules. Isolated mud flasers in partly preserved ripple troughs are observed in a siltstone bed near the top of the fining-upward sequence (~4.5 m below the 'trace-fossil bed'). Thin, sandy streaks, lenses, or beds (lenticular beds) are also preserved in select siltstone beds. Small-scale ripple cross-laminations (current ripples) are common in the siltstone units. Faunal remains within the siltstone units are sparse; occasional pelecypod (Naidaites sp.) shells are observed. No plant macrofossils were observed within the siltstone units.

Tabular Sandstone

Several occurrences of thin sandstone bodies are observed in the study section. Morphologically, the sandstone bodies are thin and tabular. The lateral extent of the tabular sandstone bodies is uniform. The basal contacts of all of the thin, tabular sandstones observed within the fining-upward sequence are erosive. The upper contacts are gradational. The sandstone bodies range in thickness from 0.09 to 2.0 m, are grey, and range from very fine- to medium-grained. Common sedimentary structures within the tabular sandstone bodies include basal plane beds, ripple cross-laminations, planar laminations, siderite nodules and discontinuous siderite bands. The sandstones appear to be depauperate in faunal and floral remains.

One particular tabular sandstone body, approximately 3.0 m from the base of the study section, contains convolute beds, load casts, flute casts, parting lineations, and planar laminations at the base of the bed. These features are subsequently overlain by ripple cross-laminations, dune-scale trough cross-beds, ripple cross-laminations, and parting lineations. The flow regime in this particular sandstone body is decelerating (upper to lower flow regime).

'Trace Fossil Bed'

The 'trace-fossil bed' was first identified by Donald Reid of the Joggins Fossil Centre and studied by Archer *et al.* (1995). The 'trace-fossil bed' lies approximately 20 m above the top of the Forty Brine coal seam (Fig. 22) and consists of a series of centimetre-scale, fine-grained grey sandstone beds. The overall unit ranges in thickness from 0.54 m in the cliff to 2.00 m on the shore.

The base of the 'trace-fossil bed' is a disconformity. Planar beds with parting lineations, indicative of upper flow regime, are preserved near the base and top of the 'trace-fossil bed'. Three varieties of ripples are preserved within the 'trace-fossil bed', the most common being uni-directional current ripples. Symmetrical wave ripples with rounded crests are observed near the top of 'trace-fossil bed'. Interference ripples (also known as ladder-back ripples) are observed on several bedding surfaces. The interference ripples preserve two sets of ripples at almost 90 degrees to one another, indicating a change in palaeoflow direction. Interference ripples form as the result of two co-existing, but differently orientated trains of waves. The interference ripples in the 'trace-fossil bed' have an abundance of exquisitely preserved trace fossils.

Arthropod trackways observed in the 'trace-fossil bed' include the ichnogenera *Kouphichnus* and *Protichnites*. Other trace fossils observed in the 'trace-fossil bed' include the ichnogenera *Cochlichnus*, *Gordia*, *Haplotichnus*, *Plangtichnus*, *Taenidium* and *Treptichnus*. Using modern traces as a comparison, the *Koupichnium sp.* traces are believed to be have been made by horseshoe crabs (limulids).

Archer *et al.* (1995) sampled siltstone/claystone beds immediately above and below the 'trace-fossil bed' for the presence of foraminifera and thecamoebians. Their results yielded agglutinated foraminiferal assemblages dominated by the genera *Trochammina*, *Ammobaculites*, and *Ammotium*. The samples did not yield any thecamoebians, which are fresh-water protozoans.

Coal Mine Point: Lyell and Dawson's Tetrapod Forest (Stop 5.4)

Stop leader: John H. Calder, Nova Scotia Department of Natural Resources
At this stop in 1852, Dawson and Lyell discovered, either through serendipity (Dawson, 1868) or a careful search strategy (Lyell and Dawson, 1853), the remarkable occurrence of tetrapods and land snails within the casts of erect lepidodendrid trees. Dawson continued the search alone thereafter, aided by the co-operative manager of the Joggins coal mines, who contributed explosives to the cause. In all, over one hundred specimens comprising at least eleven tetrapod and five terrestrial invertebrate taxa have been discovered in the trees (Carroll *et al.*, 1972; appendix 'B' of Calder, 1998), the great majority by Sir William (Dawson, 1878, 1894). Perhaps the most famous of these, *Hylonomus lyelli* (Dawson, 1860), for well over a century was the earliest known reptile.

The strange circumstance of the tree stump fauna long has been favoured to have come about as the result of pitfall into the partially buried, hollow stumps (Dawson, 1878; Carroll, 1972). However, the overwhelming occurrence of reptilian material close to the bases of trunks suggests the possibility that the reptiles were using the hollow trees as dens. This is also supported by the presence of several species in some trees, replete with coprolites, and by the fragmental nature of the bone material. Charcoalified trees and fragments within virtually all tetrapod-bearing tree casts (some probably from the burnt interiors of the trunks) raise the possibility that wildfires contributed to killing of trees and den creation, and possibly to the demise of denning reptiles.

In 1998, yet another important specimen was discovered lower in the section, this by Mr. Brian Hebert, of Lower Cove. Like those discovered by Lyell and Dawson, the disarticulated skeleton(s) occurs near the base of the tree, amidst the hallmark charcoal.

The coal bed in which the fossil forest of Lyell and Dawson is rooted (Coal 15, correlated with a split of the Kimberley Seam to the east) is one of the several investigated by Hower *et al.* (in press). Like most at Joggins, the coal is both bright and pyritic, and typically dominated microscopically by vitrinite. Compressions of prostrate lycopsids are rife within the coal, resembling *Sigillaria* as described by Dawson, but more probably derived from other decorticated lycopsids. The miospore palynology of the bed is dominated by *Lycospora pellucida* and *L. pusilla* suggesting dominance of the mire vegetation by the arboreous lycopsids *Lepidophloios* and *Lepidodendron*. Megaspores of the deciduous branched lycopsid *Paralycopodites* also were recorded from the coal bed. Geochemical analyses indicate its origins as a highly minerotrophic peat, with late enrichment in calcophile elements, including lead and zinc (Hower *et al.*, in press).

Overlying the fossil forest and forming the prominent headland of Coal Mine or Hardscrabble Point is an example of one of the thickest channel sandstone bodies in the section. Scroll bars and ridge and swale topography visible on the intertidal 'reef' bear witness to emplacement by a meandering river. In fallen blocks adjacent the promontory can be witnessed large parallel traces (*Diplichnites*) of the gigantic myriapod *Arthropleura*.

The sedimentology and paleoecology of Lyell and Dawson's forest, with an examination of Dawson's discoveries, has been the subject of recent research funded by NATO Collaborative Research Grant to A. C. Scott (Royal Holloway), Calder and Gibling (Scott *et al.*, in prep).

West Bay Formation at East Bay, Parrsboro (Stop 6)

Stop leader: John H. Calder, Nova Scotia Department of Natural Resources

Location and Access

From Parrsboro (Fig. 25), follow Main Street south from the town, with the Parrsboro Harbour on your left. At the sharp right turn overlooking the Bay of Fundy and Partridge Island, turn left and park at historic Ottawa House. At this locality just south of the Cobequid Fault Zone, the West Bay Formation of the Mabou (previously Canso) Group is exposed to the west at East Bay, opposite Partridge Island, and to the east at Crane Point below Ottawa House (Fig. 25).

Significance of the Sections

Grey beds of the Mississipian age Mabou Group assigned to the Hastings and West Bay formations constitute a thick, regionally extensive deposit of organic-rich shales largely unevaluated as a hydrocarbon source. Furthermore, their structural deformation stands them apart from the succeeding coal measures of the Cumberland Group. This disparate structural history reflects the stratigraphic position of the two groups with respect to the Mid-Carboniferous break in Nova Scotia (see Fig. 2), an event which has been linked to the Mississippian-Pennsylvanian unconformity in the Appalachian Basin (Rehill, 1996; Calder, 1998).

The West Bay beds, deposited in part under quiescent standing water, yield finely preserved fossils, including limulids and eocarid shrimp. An important record of fossils from these two localities is found in the collection of Eldon George.

East Bay Section

Vertical to overturned beds of late Viséan to early Namurian age (Mississippian) at this locality have yielded an exquisite record of tetrapod trackways (Carroll *et al.*, 1972). The thinly laminated beds, which commonly expose rippled surfaces of considerable extent, are evocative of lacustrine to nearshore environments but display as well evidence of subaerial exposure, including dessication cracks. The westernmost beds in this section are intensely folded adjacent unconformable and faulted exposure of the Parrsboro Formation and Windsor Group.

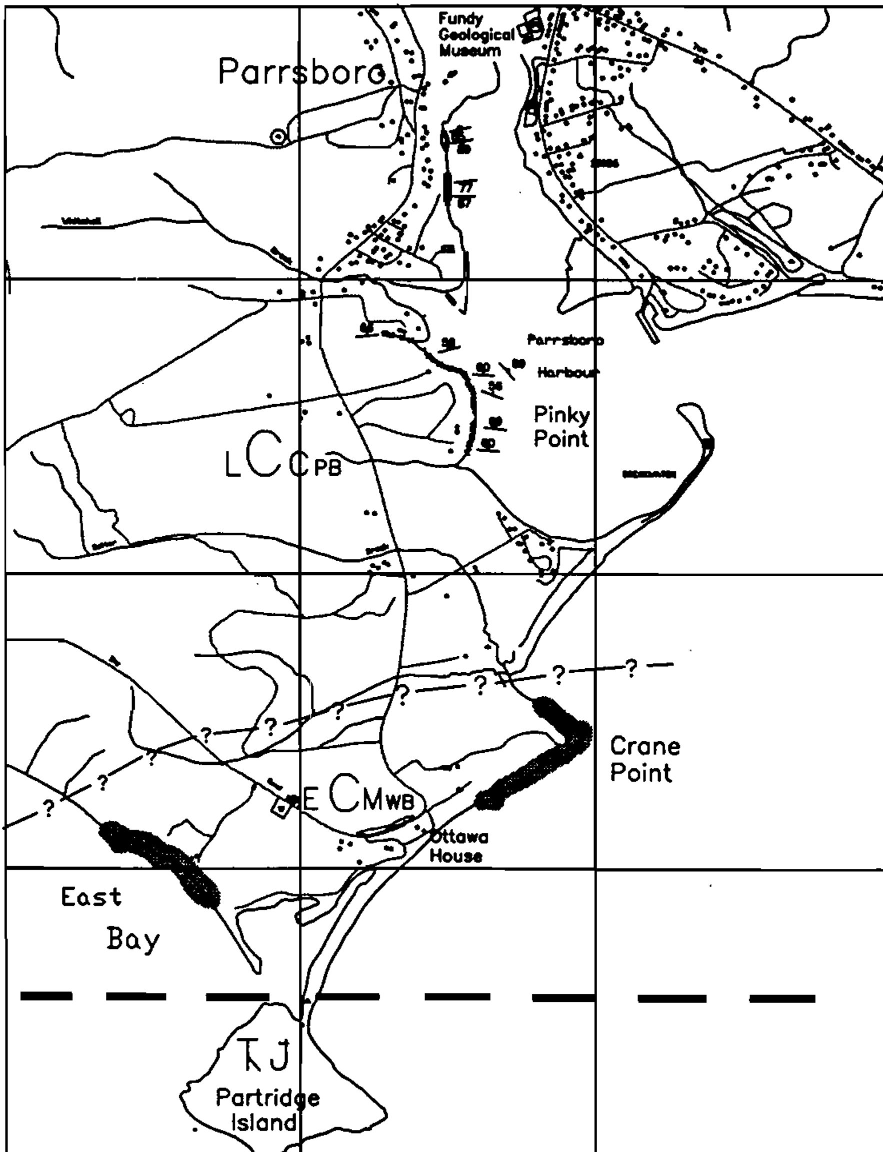


Figure 25. Site map for the West Bay Formation at East Bay and Crane Point (Stop 6) and Parrsboro Formation at Pinkey Point, from a geological map of the Partridge Island sheet in preparation by Calder and Naylor.

Crane Point Section

The organic-rich beds of the Crane Point section (Fig. 25) below Ottawa House exhibit an elevated thermal maturity and are highly indurated, and bear testimony to the complex tectonic history adjacent the Cobequid Fault. The maturity of the Crane Point beds is much higher than the unconformably overlying Pennsylvanian organic-rich beds of the Parrsboro Formation exposed to the north, at and north of Pinkey Point (Fig. 25). The black, slaty shales of the West Bay Formation yield bivalves and a depauperate compression flora. Eocarid crustaceans from the section include *Pygocephalus dubius* and *Pseudotealliocaris belli*. These 'shrimp' are suggestive of marine connections (Schram, 1981; Calder, 1998).

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