

# CONJUGATE MARGINS CONFERENCE 2018

*Celebrating 10 years of the CMC: Pushing the Boundaries of*



## Field Trip 2

**Onshore equivalents of the Cretaceous reservoir rocks of the  
Scotian Basin: Detrital petrology, tectonics and diagenesis**

**Hants County, Nova Scotia, August 19, 2018**

**ISBN: 0-9810595-10**





**HALIFAX 2018**  
**CONJUGATE MARGINS CONFERENCE**

**Halifax, Nova Scotia, Canada**

**August 19-22, 2018**

**Field Trip 2**

**Onshore equivalents of the Cretaceous reservoir  
rocks of the Scotian Basin: Detrital petrology,  
tectonics and diagenesis**

**Sunday August 19<sup>th</sup> 2018**

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**On the Cover:** The Saint Mary's University 2003 Chaswood Formation drilling program at the Vinegar Hill pit, southern New Brunswick, showing pit faces in sand and gravel in the background, and foreground vegetated slope in clay.





## PREFACE

This field trip will visit the only large outcrop of the Chaswood Formation in Nova Scotia, the West Indian Road pit in central Nova Scotia. We will then drive to the subsurface type section of the Chaswood Formation. This trip will also provide visitors from afar with a brief overview of the landscapes and rural economy of Nova Scotia. Chapter 1 of this field guide is a general synopsis of the Chaswood Formation updated from the 2008 version of this field guide and an assessment of the relevance of the Chaswood Formation to studies of the Scotian Basin. We hope that this brings together information scattered in numerous papers, Open Files and theses in a useful manner. Chapter 2 provides specific detailed information on the West Indian Road pit. Chapter 3 consists of notes on our two field stops.

## SAFETY

The West Indian Road pit is a working sand pit. Permission must be obtained from Shaw Resources to enter the pit and all visitors must wear safety boots (steel toed), hard hats, safety glasses, and fluorescent vests. Pay attention to trucks that may be loading from the stock piles. Note that the slopes of the pit may be unstable and liable to landsliding and collapse. Waterlogged sediments on the floor of the pit may liquefy. The deep water on the floor of the pit is a potential hazard. During the field trip, do not scrape faces clean in a manner that might lead to a fall of loose sediment onto yourself or others.

## EMERGENCY SERVICES

**In cases of emergency, dial 911.** Since we are in rural areas, policing is undertaken by the Royal Canadian Mounted Police – RCMP. They and local emergency organizations will be the first responders. Detachments are located in the following communities

- Enfield: 1 (902) 883-7077
- Upper Rawdon: 1 (902) 758-3388
- Shubenacadie: 1 (902) 758-3388



## MEDICAL SERVICES

There are excellent regional hospitals / community medical centres in close proximity of the field trip sites (<50 km / 30 miles / half hour) we will be visiting:

### Lower Sackville, NS

Cobequid Community Health Centre

40 Freer Lane

Lower Sackville, Nova Scotia, B4C 0A2

Operations: Open 24 hours

<http://www.nshealth.ca/locations-details/Colchester%20East%20Hants%20Health%20Centre>

### Elmsdale, NS

Lloyd E. Matheson Centre

15 Commerce Court, Suite 150

Elmsdale, Nova Scotia. B2S 3K5

Tel: 1 (902) 883-8444

Operations: Open 8-5 daily

<http://www.nshealth.ca/locations-details/Lloyd%20E.%20Matheson%20Centre>

### Fall River, NS

Integrated Chronic Care Service

3064 Highway 2

Fall River, Nova Scotia. B2T 1J5

Tel: 1 (902) 860-0057

Operations: Open 8-5 daily

<http://www.nshealth.ca/locations-details/Integrated%20Chronic%20Care%20Service>

## COMMUNICATIONS

All field trip sites are serviced by cell phone coverage. It may be sporadic immediately below cliffs or in depressions, but this is addressed by moving away from them.

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# Chapter 1: The Chaswood Formation

## Introduction

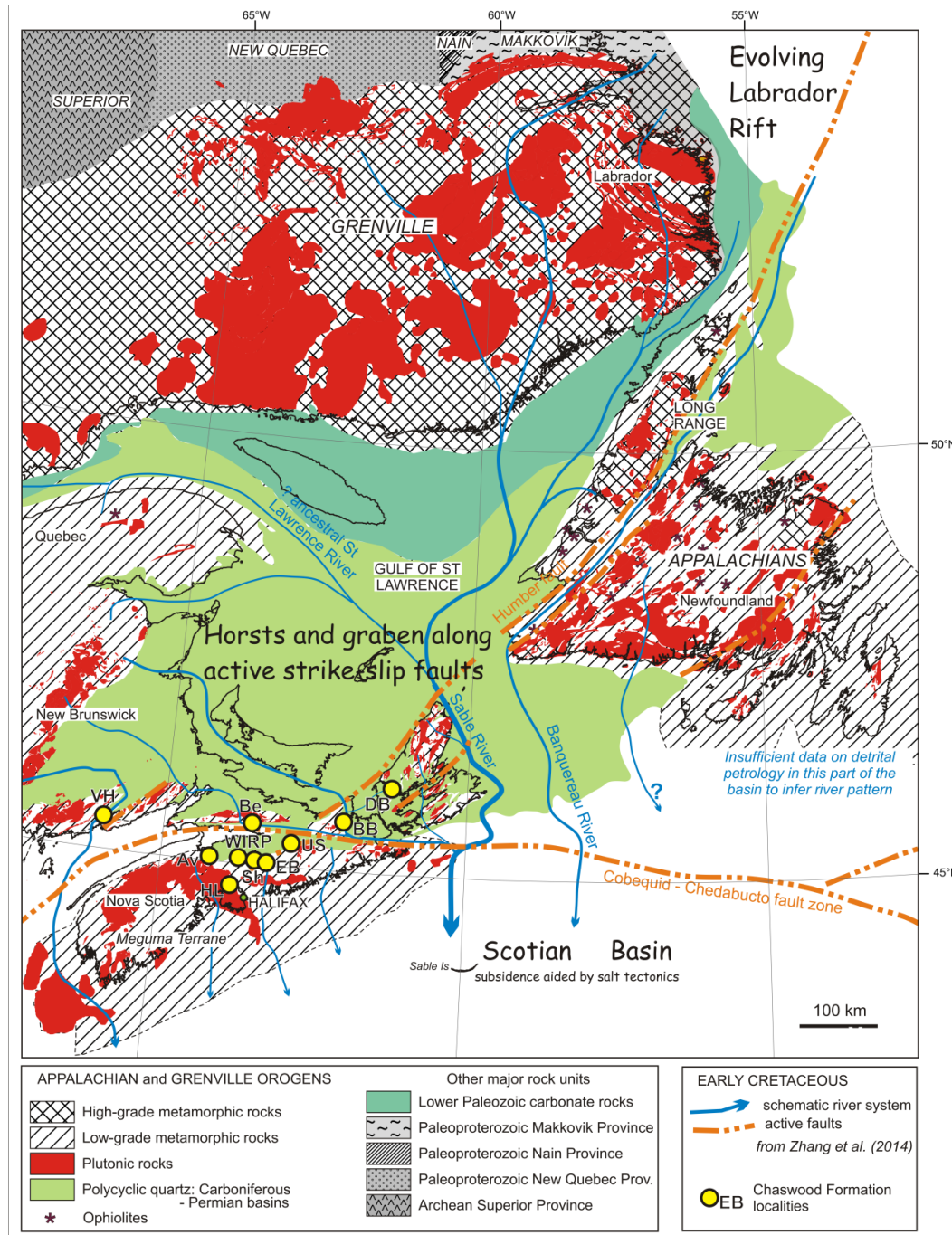
The early Cretaceous was a period of rapid sediment supply from crystalline rocks of the Appalachians as a result of fault reactivation related to the opening of the North Atlantic Ocean (Pe-Piper and Piper, 2004; Tucholke et al., 2007). In addition, uplift of the Labrador Rift supplied large amounts of sediment from the Canadian Shield via the “Sable River” to the Sable sub-basin of the Scotian Basin. The resulting thick deltaic sandstones, which occupy accommodation created by salt expulsion (Kendell, 2012), are the reservoir rocks of the offshore gas and oil fields of the Scotian Basin (Wade and MacLean, 1990). The Chaswood Formation is the stratigraphically equivalent fluvial succession at the margin of the Scotian Basin.

The Chaswood Formation is a 200-m-thick succession of loosely indurated fluvial conglomerate, sandstone, and mudstone of Valanginian to Albian age (Fensome in Stea and Pullan, 2001; Falcon-Lang et al., 2007). It is preserved in several fault-bound basins in the provinces of Nova Scotia and New Brunswick (**Fig. 1.1**). It outcrops in only two sand and gravel pits and one clay pit, and is thus largely known from more than 250 boreholes. Deposition was synchronous with strike-slip faulting, basin formation, and uplift of horsts that shed local detritus (Pe-Piper and Piper, 2004). Synsedimentary tectonic deformation along strike-slip faults led to local uplift that created intraformational unconformities (Gobeil et al., 2006) and these unconformities can be used for regional correlation (Hundert et al., 2006) and are also recognized in the proximal part of the Scotian basin, in the Orpheus graben (Pe-Piper and Piper, 2004; Weir-Murphy, 2004).

The Chaswood Formation is important for understanding the Lower Cretaceous rocks in the Scotian Basin for several reasons. It provides information on the sources of sediment and character of the hinterland for smaller rivers entering the Scotian Basin, although no deposits of the large Sable River are known from the Chaswood Formation. The record of diagenesis provides some constraints on diagenesis in the more proximal parts of the Scotian Basin, particularly the Laurentian sub-basin. The record of tectonism can be correlated with the Jeanne



d'Arc, Whale, and Scotian basins to provide a regional framework for the southeastern Canadian margin in the Early Cretaceous.



**Figure 1.1 Regional map showing principal Chaswood Formation localities and Early Cretaceous tectonics and inferred paleodrainage**

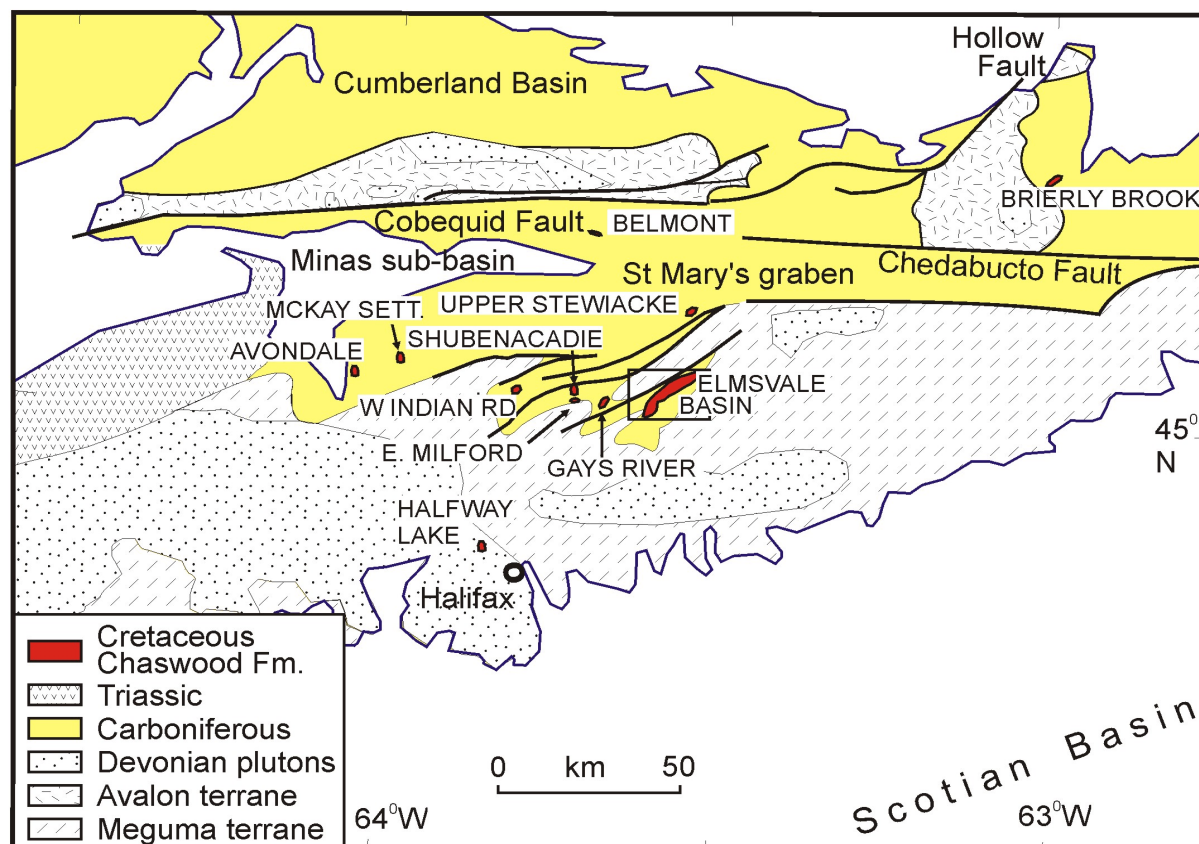


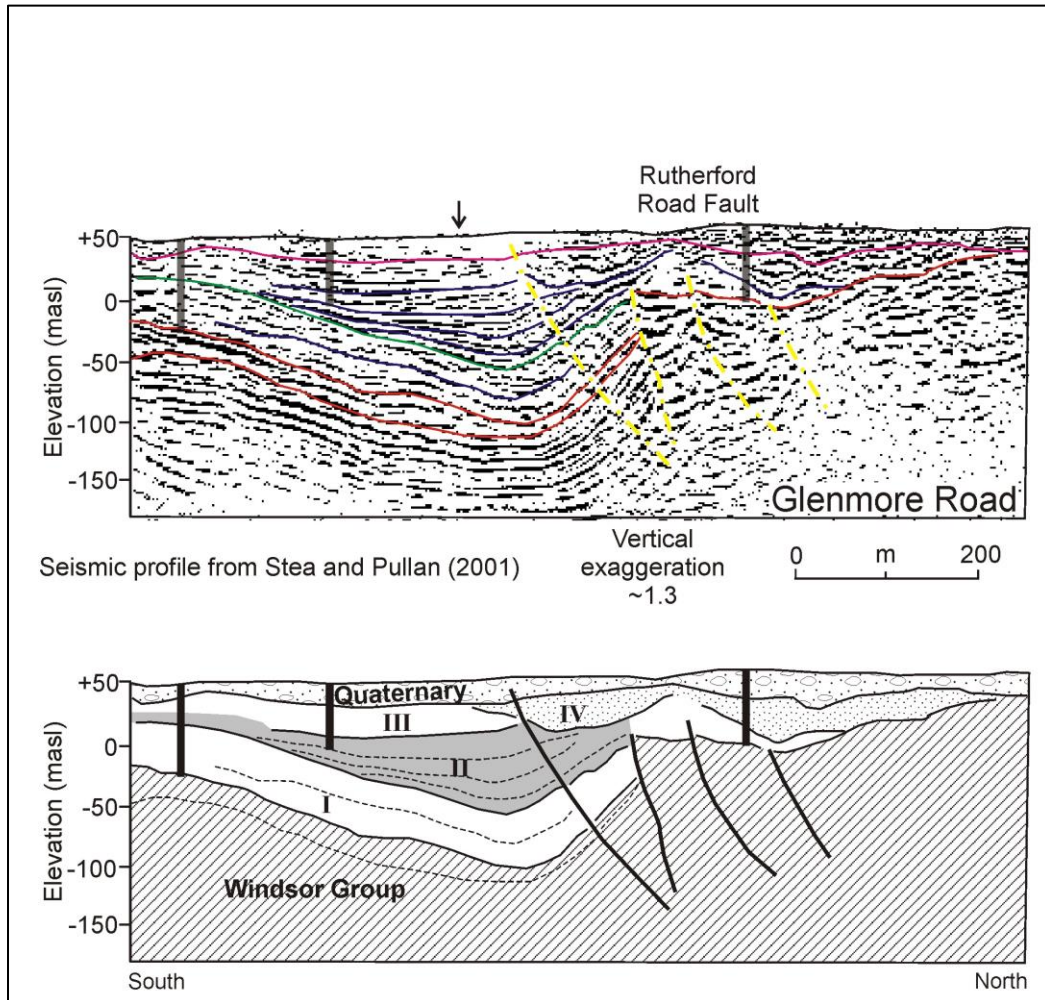
Figure 1.2 Map showing the distribution of the Chaswood Formation in central Nova Scotia.

## Geology of the Chaswood Formation

### Distribution

The Chaswood Formation is best preserved in a series of fault-bound basins in central Nova Scotia, including the Elmsvale basin and outliers at Shubenacadie and the West Indian Road pit (**Fig. 1.2**). Small outliers in northern Nova Scotia include Belmont, Brierly Brook and Diogenes Brook (Dickie, 1986; Stea et al., 1994; Pe-Piper et al., 2005c). The Vinegar Hill outlier in southern New Brunswick (Falcon-Lang et al., 2004) is the only known occurrence of the Chaswood Formation in New Brunswick (VH, **Fig. 1.1**).





**Figure 1.3 (above) Seismic cross section of the Elmsvale Basin and (below) interpretation showing seismic packets I-IV and deformation along the Rutherford Road Fault.**

The Chaswood Formation in central Nova Scotia overlies Carboniferous rocks that are preserved in basins developed unconformably over Meguma terrane basement rocks. The Elmsvale Basin extends some 15 km along the present Musquodoboit Valley and consists of <200 m of Chaswood Formation that thins rapidly across the Rutherford Road fault (**Fig. 1.3**) bounding the northwest side of a half-graben (Stea and Pullan, 2001). The stratigraphy and sedimentology of the Chaswood Formation are well known from the many tens of boreholes cored in the basin during exploration for kaolin clays (Stea and Pullan, 2001; Pe-Piper et al., 2005a; Piper et al., 2005).

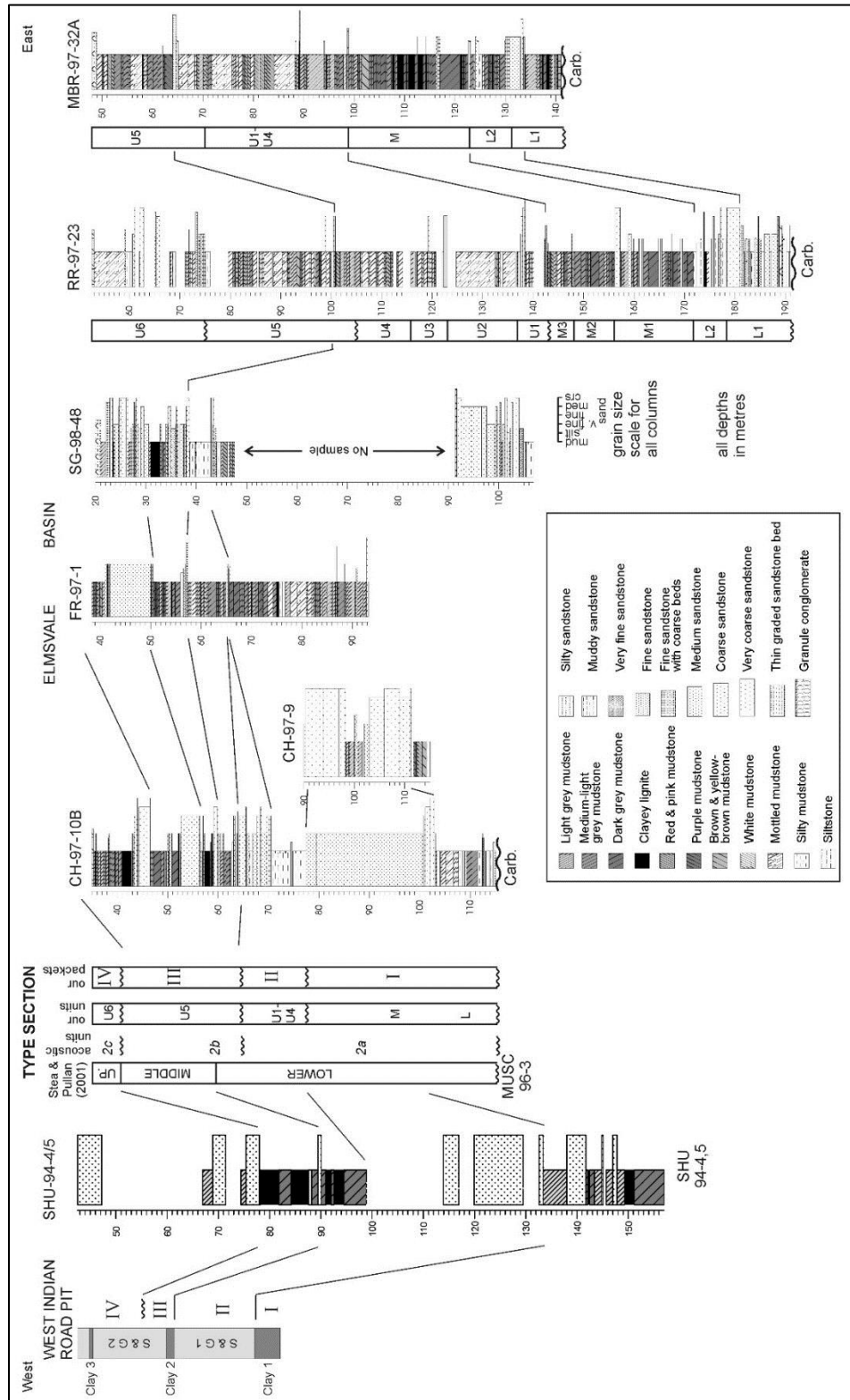
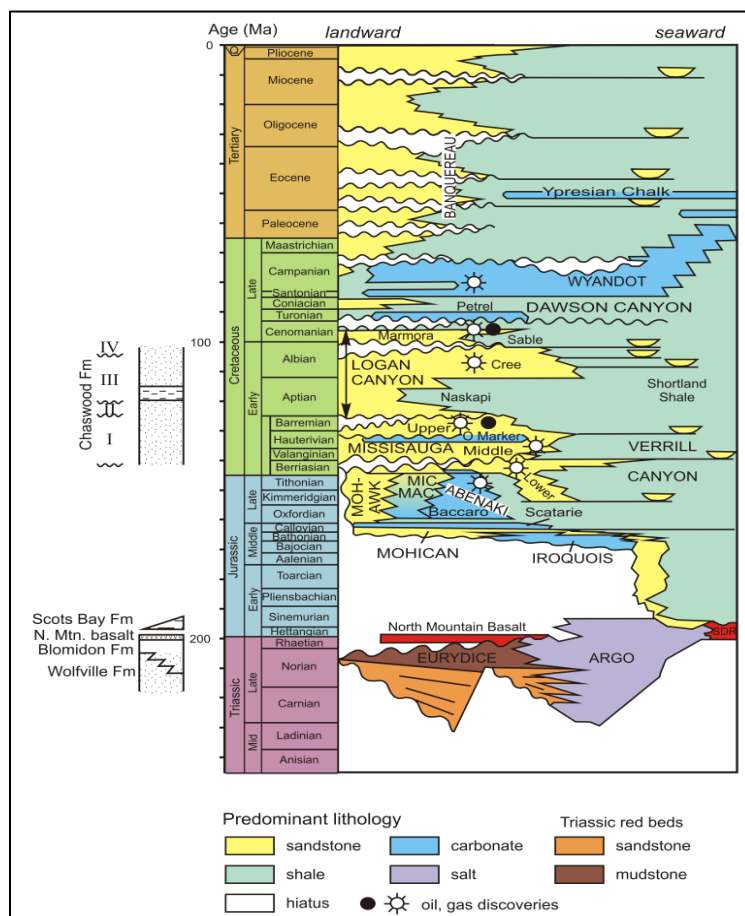


Figure 1.4 Stratigraphic columns from the Elmsvale Basin showing nomenclature of Stea and Pullan at the type section; lithologic unit and seismic packet nomenclature of Pe-Piper and colleagues; and correlation to Shubenacadie and the West Indian Road Pit.



## Stratigraphy and stratigraphic correlation

Based on seismic-reflection profiles, four unconformity-bound seismic packets (**Figs. 1.3, 1.4**) are recognised within the Chaswood Formation of the Elmsvale Basin (Hundert et al., 2006). The basal unconformity separates Packet I from underlying Carboniferous Windsor Group rocks. Packet I is slightly deformed along the Rutherford Road fault and unconformably overlain by Packet II. Packets I and II correspond to the Lower member of the Chaswood Formation defined by Stea and Pullan, (2001). Packets I and II are folded into a monocline along the Rutherford Road Fault and are unconformably overlain by Packet III (Middle Member), which is itself only slightly deformed. The unconformably overlying Packet IV (Upper Member) is only locally preserved (including at the West Indian Road pit) and is undeformed.



**Figure 1.5 Stratigraphic column for the Scotian Basin (OETR 2011) showing likely correlation with Chaswood Formation and early Mesozoic rocks of the Fundy Graben.**





## Biostratigraphy

The middle part of the Chaswood Formation has been generally assigned to the Aptian-Albian, whereas older Early Cretaceous biostratigraphic ages (Valanginian to Barremian) have been determined for some isolated deposits apparently from the lower part of the Chaswood Formation (Falcon-Lang et al., 2007). The Chaswood Formation is thus broadly equivalent to the Mississauga and Logan Canyon formations offshore in the Scotian Basin (Wade and MacLean, 1990) (**Fig. 1.5**) and of similar age to the fluvial Mattagami Formation in the Hudson Bay lowlands of central Canada (Telford and Long, 1986) and the McMurray Formation of Alberta (Benyon et al. 2016).

## Lithofacies

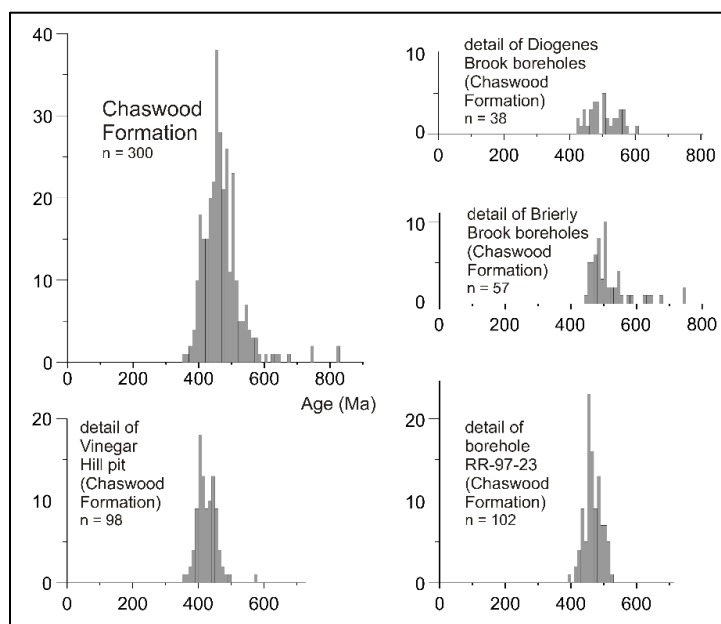
Seven principal facies associations are recognised in the Chaswood Formation, on the basis of frequency of transitions between facies (Pe-Piper et al., 2005a). The **light grey mudstone** facies association consists of light to medium grey massive mudstone that locally contains organic detritus, but overall has low bulk organic carbon content. Some mudstones have pinkish mottling, and where mottling is intense, the beds are included in the paleosol facies association (see below). The **dark grey mudstone** facies association has a higher organic carbon content including charcoal, indicating wildfires (Scott and Stea, 2002). **Carbon-rich sediments** include lignitic mudstone, in beds < 0.5 m thick, which resembles the dark grey mudstone but has more organic material. Lignite (with > 30% organic carbon) is locally present and some contains volcanic ash (Pe-Piper and Piper, 2010). The **paleosol** facies association consists mostly of red, pink, yellow or purple mudstone and lesser fine sandstone. Paleosol features include sub-vertical tubular mottles that may be root traces and diagenetic nodules and mottles rich in hematite on a range of scales. The **debris-flow** facies association consists of contorted blocks of mudstone, in some cases with pebbles, with a mud or mud-sand matrix (Pe-Piper et al., 2005b). The **silty mudstone and muddy sandstone** facies association includes a range of poorly sorted lithologies. Generally it gradationally overlies fine-grained sandstone and passes upward into light grey mudstone. It is distinctly micaceous and commonly contains plant fragments. **Sorted sandstone and conglomerate** is commonly in graded beds with sharp bases. Sandstone beds



typically fine upward into silty mudstone, but some are isolated as individual 1 to 2 metre beds with sharp contacts within mudstone.

### Detrital petrology

Petrographic studies, based on heavy minerals, have indicated that the Chaswood Formation was sourced from local Carboniferous sedimentary rocks and from crystalline Appalachian rocks including granitoid rocks and metapelites (Piper et al., 2007). Studies of lithic clasts in conglomerate in the Chaswood Formation shows that at all stratigraphic levels there was a component of sediment supply from local (< 50 km) crystalline basement and from reworking of Carboniferous sedimentary rocks (Gobeil et al., 2006; Piper et al., 2007). Geochronology of detrital monazite (Pe-Piper and MacKay, 2006) also shows that at all stratigraphic levels there was also a supply of distant travelled detritus from the northern Appalachians (**Fig. 1.6**). The proportion of local and far-travelled components varies stratigraphically, with the greatest amount of local reworked Carboniferous detritus at lower stratigraphic levels in most localities (Gobeil et al., 2006; Noftall, 2007). Muscovite geochronology suggests that most muscovite is second cycle and reworked out of local Horton Group (basal Carboniferous) strata (Reynolds et al., 2010).

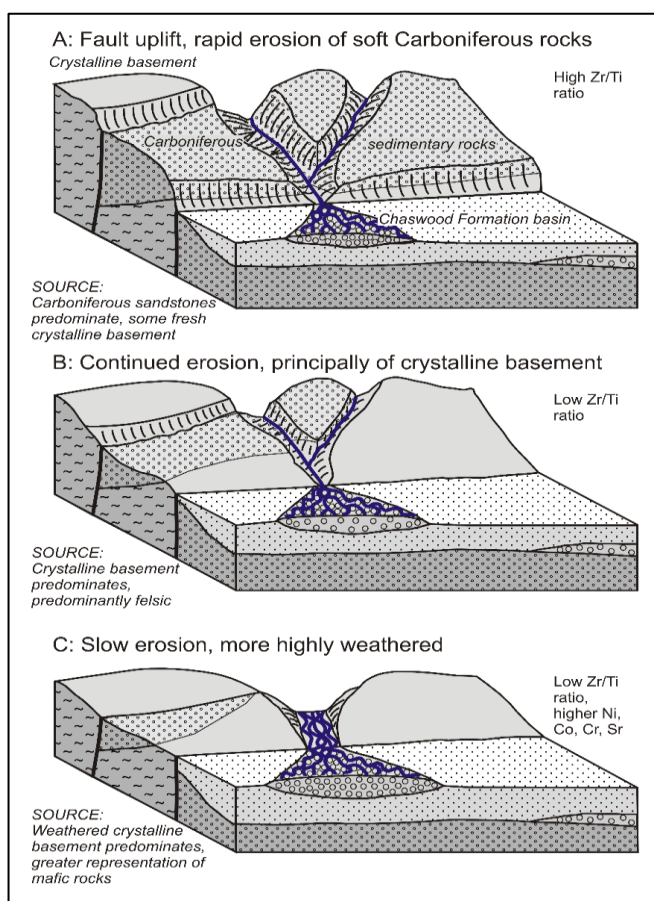


**Figure 1.6 Histograms of ages of dated detrital monazite from the Chaswood Formation, showing Appalachian sources.**



Regionally, studies of detrital monazite on land (Pe-Piper and MacKay 2006) and offshore (Pe-Piper et al., 2008; 2014) and of detrital zircon (Piper et al., 2012), detrital muscovite (Reynolds et al., 2010; 2012), and heavy minerals (Tsikouras et al., 2011) allow an interpretation of the distribution of rivers that deposited the Chaswood Formation and the offshore Missisauga and Logan Canyon formations (**Fig. 1.1**).

The limitation of the petrographic techniques is that they track only sediment sources with characteristic minerals. The geochemistry of 60 samples from a complete section through the Chaswood Formation in borehole RR-97-23 in the Elmsvale Basin (**Fig. 1.4**) shows that the detrital signature is partially obscured by diagenetic processes, which caused the concentration of K, P, Sr, and U at three regional unconformities intersected by the borehole and recognised from seismic-reflection profiles (Piper et al., 2008). The elements Ti (in ilmenite and its alteration



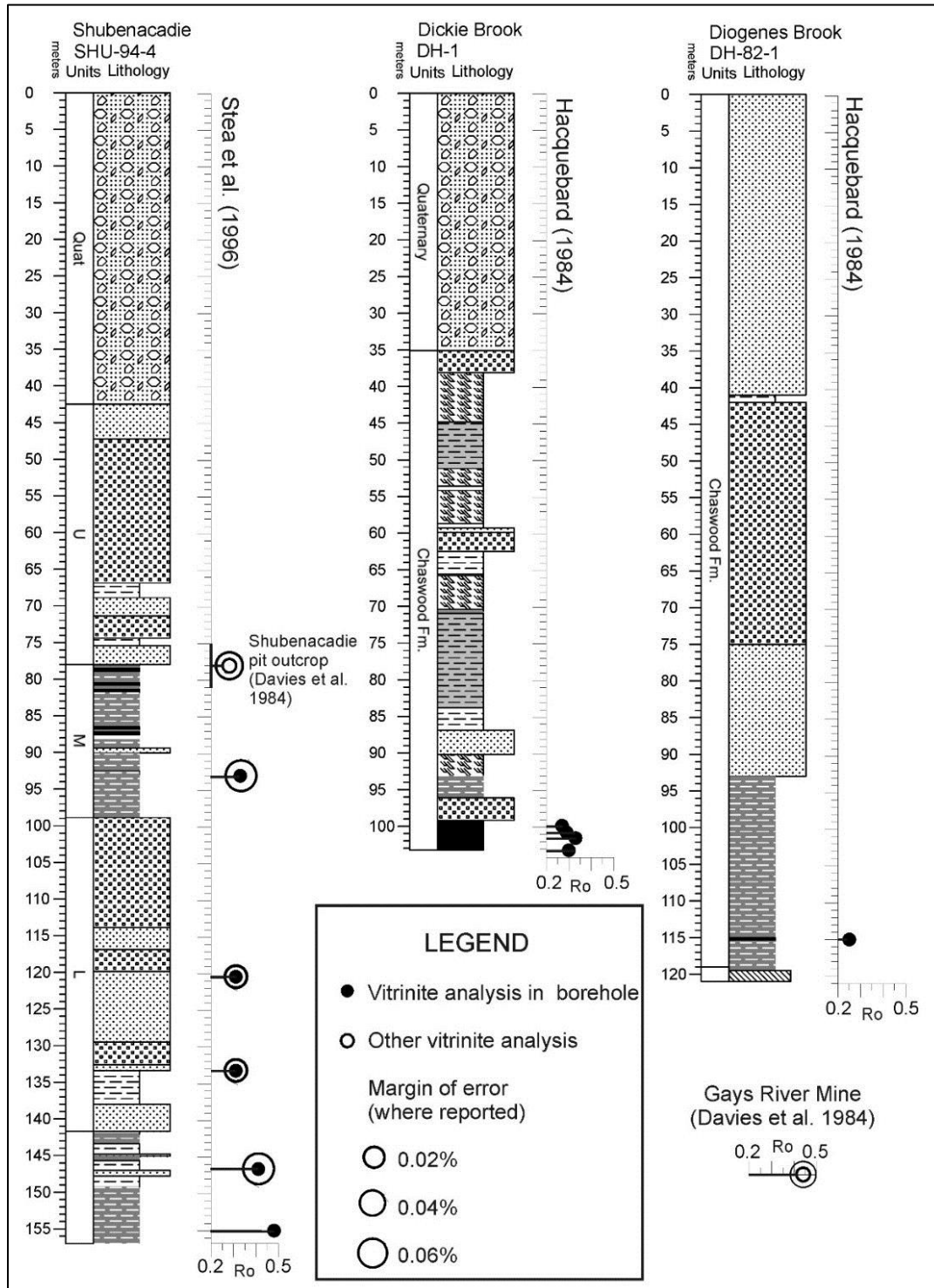
**Figure 1.7 Model of the effect of episodic uplift of horsts on the detrital geochemistry of the Chaswood Formation.**



products), Zr (in zircon), Th, and Y are largely controlled by the abundance of heavy minerals in the rocks. Ilmenite is the dominant first-cycle heavy mineral, whereas much of the zircon is of polycyclic origin, so that the Ti/Zr ratio is a guide to the proportion of first-cycle sediment supply from crystalline basement. High concentrations of Cr (given the absence of detrital chromite) and Sr (except where diagenetic P-bearing minerals are present) and the high Ni/Co ratio in mudstones appear related to supply from weathered mafic crystalline basement. Three cycles of sediment supply are recognised in borehole RR-97-23, each overlying a regional unconformity (**Fig. 1.7**). These reflect uplift of horsts bounded by strike-slip faults that resulted first in shedding of readily eroded Carboniferous sandstones, followed by rapid erosion of crystalline basement and, finally, greater supply of deeply weathered regolith.

### **Burial history and thermal maturation**

Studies at Shubenacadie and nearby localities have shown low vitrinite reflectance ( $R_o$ ) values ( $0.31 \pm 0.02\%$ ) in the Upper and Middle members of the Chaswood Formation, increasing to  $0.41 - 0.48 \pm 0.08\%$  in the Lower member (Davies et al., 1984; Stea et al., 1996) (**Fig. 1.8**). The present Chaswood Formation was probably formerly buried by  $\sim 800$  m of Upper Cretaceous and Lower Tertiary strata: evidence includes the equilibrium moisture content of lignites in the Chaswood Formation (Hacquebard, 1984); apatite fission track data in underlying basement (Arne et al., 1990; Grist and Zentilli, 2003); and the presence of such strata along strike in the Orpheus Graben (**Fig. 1.1**) (Wade and MacLean, 1990; Weir-Murphy, 2004). The steep  $R_o$  gradient was the result of the hydrothermal circulation driven by early Albian volcanism, known from the Logan Canyon Formation's Cree Member in the Orpheus Graben along strike from the Elmsvale Basin (Bowman et al. 2012).



**Figure 1.8 Summary plot showing variation in vitrinite reflectance in boreholes at Diogenes Brook, Dickie Brook (Elmsvale Basin) and Shubenacadie, and from outcrops at Shubenacadie and mine workings at Gays River.**

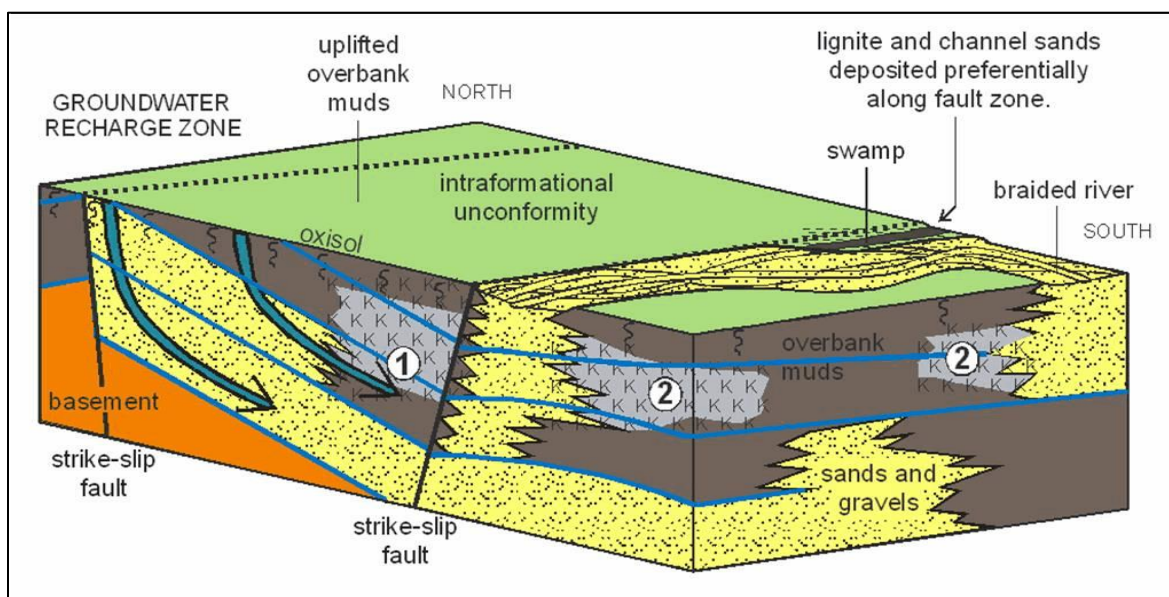




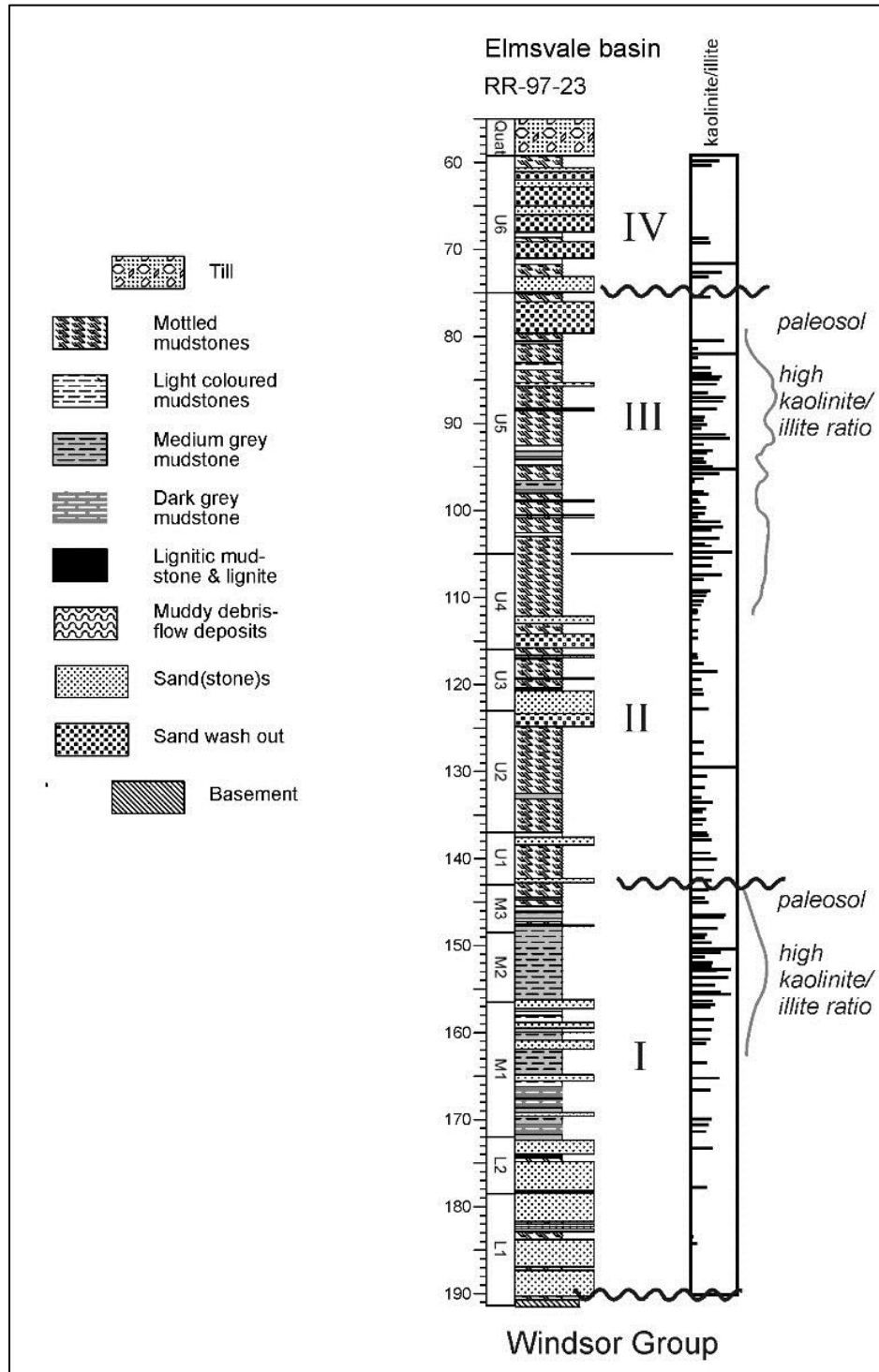
## Diagenesis

Diagenesis in the Chaswood Formation has been shown to involve soil forming processes and widespread kaolinitization by groundwater recharge from meteoric water (Pe-Piper et al., 2005a; Piper et al., 2009) (**Fig. 1.9**). Three styles of soil formation are recognised. The dark grey mudstone facies association is interpreted as deposits in flood plain ponds and as immature grey soils in areas that experienced persistently high water table (Pe-Piper et al., 2005a). In porous gravelly sandstones, highly leached oxisols are developed. Muddy oxidised reddened paleosol horizons are widespread in the Chaswood Formation and are most prominent at regional intraformational unconformities (Hundert et al., 2006) (**Fig. 1.10**).

The kaolinitization of mudstones involved the oxidation of organic matter and whitening of the mudstones, as described from Georgia, USA, by Hurst and Pickering (1997). In the sandstones, unstable minerals including feldspars were altered and kaolin minerals were precipitated in pores. FT-Raman spectroscopy shows the presence of dickite near the base of the Chaswood Formation in Elmsvale basin, supported by images of blocky kaolin crystals. It formed during the short-lived high geothermal gradient resulting from hydrothermal circulation driven by early Albian volcanism.



**Figure 1.9 Schematic model showing relationships between tectonics, sedimentation and diagenesis in the Chaswood Formation.**



**Figure 1.10 Sedimentary log of borehole RR-97-23 showing kaolinite / illite ratio in relation to major unconformities.**



Prominent diagenetic illite in the Upper member of the Chaswood Formation appears to pseudomorph small kaolinite booklets. Larger illite booklets are found in the middle part of the Lower member, again perhaps pseudomorphing kaolinite. Similar blocky illite has been previously reported to pseudomorph dickite from deeply buried sandstones (Patrier et al., 2003). Some evidence that the illite has formed as a result of the reaction of kaolinite and K-feldspar is seen from the presence of small euhedral quartz overgrowths on silt-sized quartz in the Upper member at Belmont. The presence of barite cement in most samples that contain diagenetic illite is further evidence of the role of K-feldspar. The co-occurrence of halloysite and diagenetic illite is rare and the occurrence of diagenetic illite in sandstones with such low vitrinite reflectance ( $R_o = 0.31 \pm 0.02\%$ ) is most unusual.

## Structure

### *Seismic-reflection data*

In the Elmsvale Basin, seismic reflection profiles controlled by boreholes (**Fig. 1.3**) clearly show that the lower Chaswood Formation was deformed prior to deposition of younger units and that this deformation involved both folding and faulting. The main ENE-trending Rutherford Road fault on the north side of the Elmsvale Basin is a complex reverse fault with some evidence for flower structure. The lower part of the Lower Member of the Chaswood Formation (units L and M; packet I) was deposited widely over Carboniferous (early Mississippian) Windsor Group basement, but was then folded into a syncline along the Rutherford Road fault. The upper part of the Lower member (units U1-U4; packet II) onlaps the lower part of the Lower member and is also deformed along the Rutherford Road fault. The Middle and Upper members (units U5 and U6; packets III and IV) post-date formation of the syncline, but show minor fault offset. Steeply dipping brittle fault contacts and brecciated clays in some boreholes confirm that some of the faulting took place after compaction and lithification and parts of the Rutherford Road fault unequivocally cut the youngest Chaswood Formation strata.



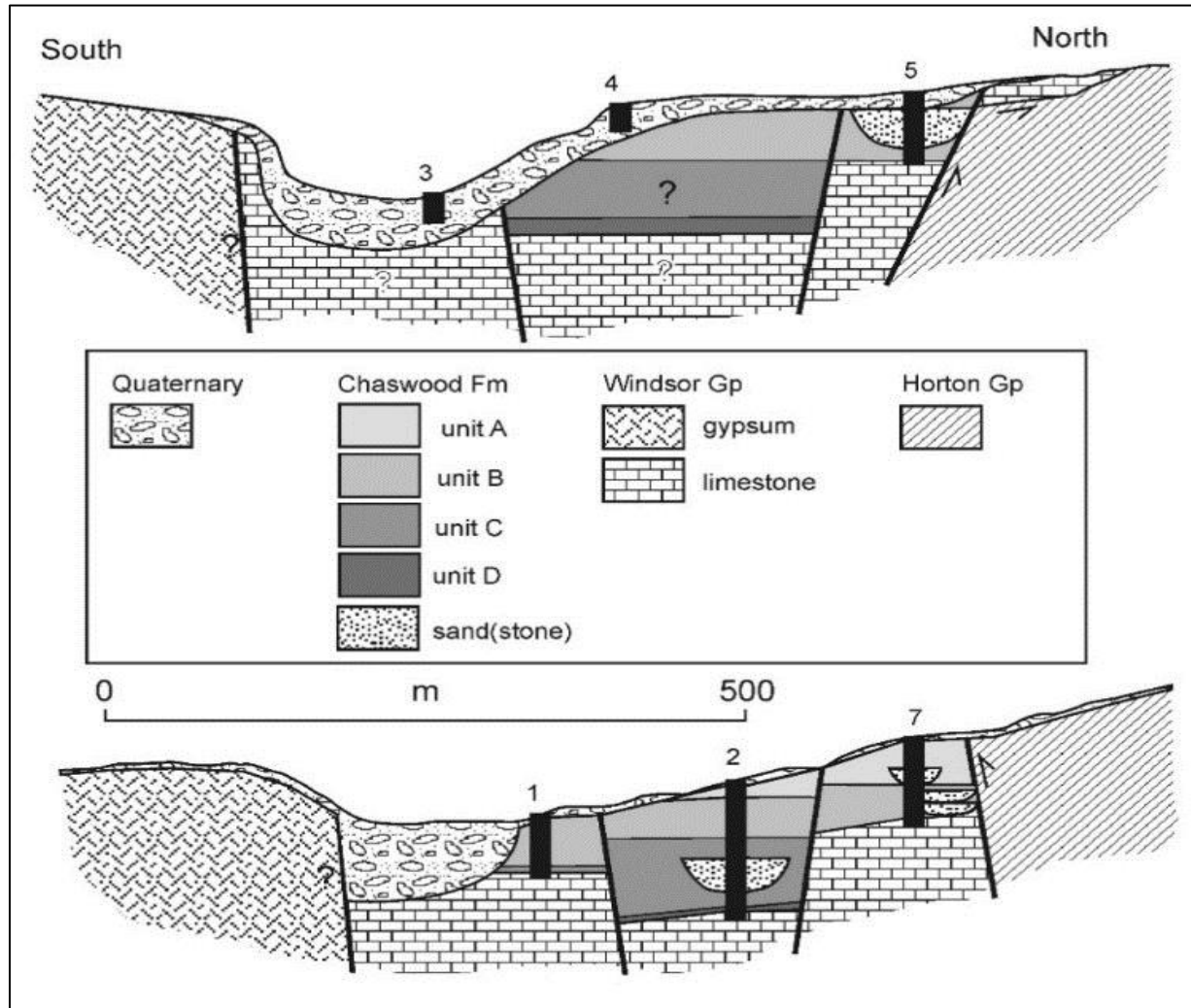


### *Outcrop and borehole observations*

Deposition of the Chaswood Formation appears strongly influenced by synsedimentary faulting. The work of Gobeil (2002) in the West Indian Road pit shows clearly that the thickness of sedimentary units varies rapidly across faults (**Fig. 2.3**), even on a horizontal scale of a few hundred metres. Thickness variations in some cases are much greater than any post-Cretaceous offset on the faults. The most remarkable synsedimentary feature in the West Indian Road pit is the recognition of two local angular unconformities in the east wall of the pit, where beds are locally rotated to almost vertical (**Fig. 2.6**), yet are overlain by sub-horizontal sands and gravels.

In places in the West Indian Road pit, there are rapid lateral facies changes from sand to gravel across faults. Both observations suggest that faults must have created a slight topographic effect on the depositional environment. The observation that paleocurrents in the West Indian Road pit are consistently to the southeast, however, implies that the synsedimentary faulting had little effect on regional river flow direction. Sand injection structures in Clay Unit 2 provide evidence for earthquake-related deformation at the time of deposition.

A 5 km long, 2-5 m thick unit of tilted blocks, interpreted as a large landslide, in western Elmsvale Basin (Piper et al., 2005) confirms that a significant gradient was present at times in the Chaswood Formation to allow failure of many metres of previously deposited sediment. At Brierly Brook, where no seismic-reflection profiles are available, the restriction of units C and D to the central part of the basin and their absence in boreholes only 100 m distant (**Fig. 1.11**) imply synsedimentary faulting. The sedimentary facies are inconsistent with accumulation in a local sink hole.



**Figure 1.11** Structural cross sections at Brierly Brook inferred from correlation of boreholes.

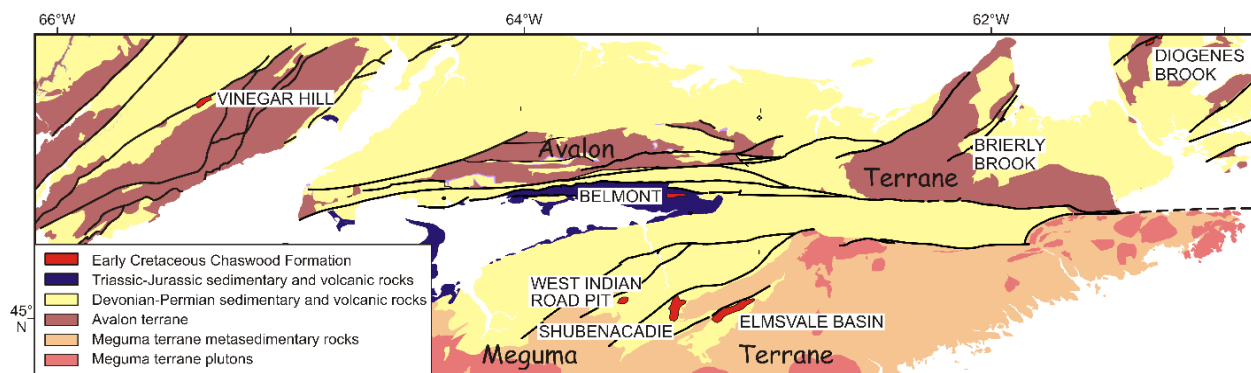
### *Structural evolution*

The structural style of the faulting in the Chaswood Formation is typical of strike-slip faulting, with abrupt local rotation of beds and sediment thickness changes. Most of the major faults bounding the Chaswood Formation strike NE–SW (**Fig. 1.12**), probably reactivating Late Paleozoic dextral strike-slip faults and parallel to the extension direction of the Labrador Rift. In addition, there was renewed movement on the Late Carboniferous-Permian E–W Cobequid-Chedabucto fault. Pe-Piper and Piper (2004) argued that there was mid-Cretaceous dextral slip



on the Cobequid-Chedabucto-SW Grand Banks fault, producing the regional shortening in the Minas Basin and several kilometres of post-early Jurassic dip slip motion on the Cobequid fault system recognised by Withjack et al. (1995). This slip also resulted in 3 km of dextral offset of the early Jurassic North Mountain Basalt on the Gerrish Mountain Fault (Donohoe and Wallace 1985, p. 42). This deformation was synchronous with rotation of crustal blocks in southern Connecticut dated by Roden-Tice and Wintsch (2002) and the development of unconformities between the Missisauga and Logan Canyon formations in Orpheus graben (Weir-Murphy, 2004) and the SW Grand Banks (Pe-Piper et al., 1994).

Pe-Piper and Piper (2004) argued that Oligocene uplift on the eastern Scotian Shelf was also a consequence of strike-slip reactivation of the Cobequid - Chedabucto - SW Grand Banks fault system. It was also likely responsible for the young deformation of the Chaswood Formation in a style quite different from the Cretaceous synsedimentary deformation (e.g., at the West Indian Road pit: **Fig. 2.1**). It could also have been responsible for widespread uplift of the Chaswood Formation, such as that inferred on the northern side of the Rutherford Road fault. Similar uplift was interpreted by Grist and Zentilli (2003) from apatite fission-track modelling. They concluded that at least 700 m of Upper Cretaceous and Palaeocene strata were deposited over a wide area of the southern part of the Maritime Provinces and then eroded in the Neogene. The estimates of depth of burial of lignite by Hacquebard (1984), confirmed by more recent calibration of moisture content of lignite, is consistent with this interpretation.



**Figure 1.12 Major faults likely active in the Early Cretaceous and their relationship to Chaswood Formation basins.**



## Significance of the Chaswood Formation for Petroleum Geology of the offshore Scotian Basin

### A record of Cretaceous and Cenozoic tectonics independent of salt tectonics

A new synthesis of tectonic events in the Scotian Basin and its hinterland is presented in **Figure 1.12**, strongly informed by our work on the Chaswood Formation. Basin-wide unconformities recognised in seismic profiles are taken from the PFA Atlas (OETR, 2011) as modified by Weston et al. (2012).

The Jurassic–Cretaceous tectonic history of the Late Triassic to Middle(?) Jurassic Fundy Basin is poorly constrained. The Rhaetian age tholeiitic basalts of the North Mountain Formation were extruded under conditions of active sinistral deformation in the Minas Fault Zone (Schlische and Olsen, 1989; Pe-Piper and Miller, 1992). Little of the overlying McCoy Brook Formation crops out (including the basal Scots Bay Member), and while at least 2.5 km thickness is known from seismic profiles, only about 180 m has been sampled in the Chinampas N-37 well. The base of the McCoy Brook Member is Hettangian, with its top possibly as young as Aalenian (Wade et al., 1996). Deformation of the Fundy Basin into a syncline may be partly synsedimentary, based on onlap relationships in seismic profiles on the south side of the basin (Wade et al., 1996). However, at the northern margin, North Mountain Basalt is deformed at Wasson Bluff and offset in the Minas Fault Zone at Portapique, and Triassic rocks are overthrust by Carboniferous at Clarke Head and deformed in Chignecto Bay and elsewhere (Baum et al., 2008). The age of this deformation has been assumed to be Cretaceous and related to dextral motion on the Minas Fault Zone (Pe-Piper and Piper, 2004a), but age control is lacking.

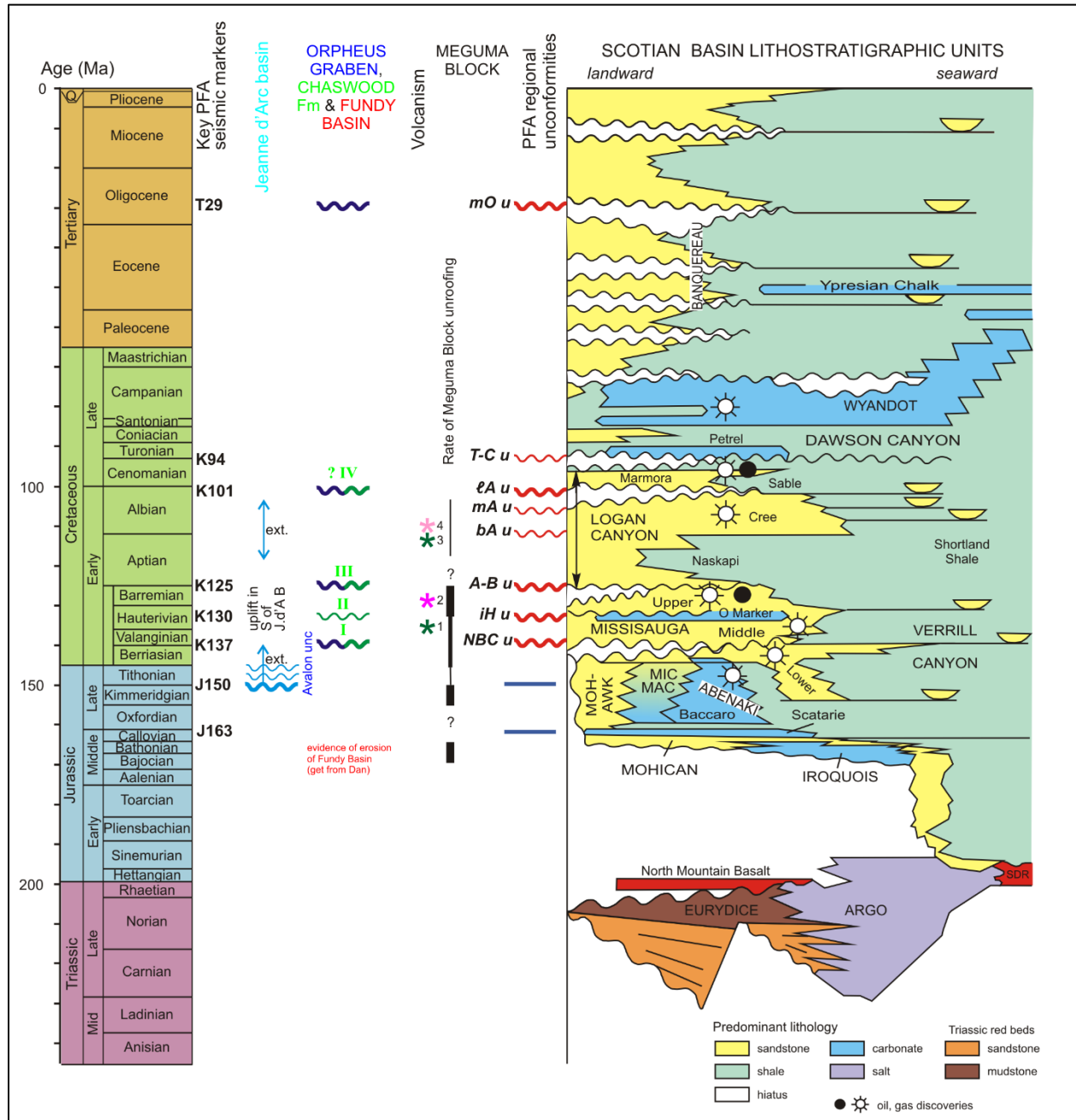
The oldest Cretaceous unconformity is the Near Base Cretaceous unconformity (NBCu) near the Valanginian–Berriasian boundary. Weston et al. (2012) recognised a widespread “biostratigraphic hiatus between overlying Valanginian and underlying Berriasian or Jurassic strata” that they correlated with the NBCu. However, it is unclear to us whether this hiatus might be due principally to the Berriasian lowstand of sea level (Haq et al., 1987), so that the



seismically recognised Base Cretaceous Unconformity of the PFA might be correlative with the important Tithonian unconformities in the Jeanne d'Arc basin (McIlroy et al., 2012), and to the complex “base Cretaceous” unconformity in the North Sea and on the Norwegian margin (Kyrkjebø et al., 2004).

On the other hand, the oldest Chaswood Formation strata are of Valanginian age (Falcon-Lang et al., 2007), suggesting that there is an NBCu younger than Tithonian. Furthermore, even in the SW Scotian Basin, at the Bonnet P-23 well, the NBCu is clearly of Valanginian-Berriasian age (Weston et al., 2012). Reworking of Jurassic dinoflagellates into the interval 1822–2065 m (Valanginian–Hauterivian) in the Bonnet P-23 well (Weston et al., 2012) is likely the result of tilting and uplift of the Meguma block and erosion of Jurassic strata on the inner shelf. Dated detrital muscovite in this stratigraphic interval is almost exclusively derived from the Meguma terrane (Reynolds et al., 2012).

The intra-Hauterivian unconformity occurs near the top of the Mississauga Formation's Barremian O-marker limestones, and is particularly pronounced in inboard wells and those in the eastern part of the basin (Weston et al., 2012). Above this unconformity, the Scotian Basin shows progressive deepening (Cummings and Arnott, 2005; Cummings et al., 2006), but detrital muscovite is almost exclusively derived from the Meguma terrane, implying uplift of the Meguma block (Reynolds et al., 2012). Mass-balance calculations (Reynolds et al., 2009) require a few tens to a few hundreds of meters of exhumation of the inner continental shelf during the Early Cretaceous in order to supply the observed detrital muscovite.



**Figure 1.13. Schematic age model for lithofacies of the Fundy and Scotian basins and the Chaswood Formation, major seismic markers, regional unconformities, volcanic activity. For explanation and details of sources, see text.**



In the Jeanne d'Arc basin, two major tectonic rifting phases with accompanying unconformities and growth faults are recognised (McIlroy et al., 2012). The older is from the base Tithonian to the Valanginian, and the younger from the mid Aptian to Albian. Between these two extensional phases, there was uplift south of the Jeanne d'Arc Basin.

The precise timing of the Aptian-Barremian unconformity in the Scotian Basin is unclear. Weston et al. (2012) found that in the Alma F-67, Cohasset L-97, Dauntless D-35, Glenelg J-48, Glooscap C-63, and Hesper P-52 wells, Aptian strata (Logan Canyon Formation's Naskapi Member) overlie Hauterivian strata, implying a significant unconformity. Seismic profiles also show important tilting, for example on the Banquereau platform, beneath the unconformity (e.g. Bowman 2010, her Fig. 4.5) and the unconformity is clear in Orpheus Graben (Pe-Piper and Piper, 2004a; Bowman, 2010). In Hesper P-52, Weston et al. (2012) identified the intra-Aptian MFS (equivalent to the Selli OAE) at the base of the Naskapi Member, underlying the basalt flow (Bowman et al., 2012).

Yet in other wells, such as Panuke B-90, there appears to be a quasi-continuous section from the Barremian to the Aptian, with possible hiatuses where lowstand sedimentary facies accumulated (Cummings and Arnott, 2005; Cummings et al., 2006; MacRae, 2011). The correlation of organic carbon rich intervals in the lower Naskapi Member at Panuke B-90 with those in Western Europe (Chavez et al., 2016) suggests that in places there is continuous sedimentation across the Barremian-Aptian boundary. The change in style of sedimentation between the Upper Missisauga and Naskapi members is probably due to diversion of the Sable River by uplift of the Meguma terrane (Piper et al., 2011) and should not be used as evidence for an unconformity at the Barremian-Aptian boundary. Sinclair and Withjack (2008) showed that in the Jeanne d'Arc basin, the Aptian-Albian Ben Nevis and Nautilus formations overlie a mid-Aptian unconformity.

In several occurrences of the Chaswood Formation, a synclinal lower unit is overlain by an almost flat-lying upper unit (Piper et al., 2007), related to strike-slip and dip-slip motion on NE-trending faults (Pe-Piper and Piper, 2012). In the Elmsvale Basin, four unconformity-bound





packages are recognised (Hundert et al., 2006; Pe-Piper and Piper, 2010). Paleoclimatic interpretations from clay minerals, and correlation of seismic style along strike to the Orpheus Graben suggest that the major unconformity between synclinal sediments of packages I and II, and almost flat-lying sediments of packages III and IV represents the regional Aptian-Barremian unconformity recognised in Orpheus Graben and the Banquereau Platform. As the Chaswood Formation is nowhere older than Valanginian, the basal unconformity is correlated with the NBCu. Correlation of the other two regional unconformities in the Chaswood Formation is unconstrained and speculative.

The response of different parts of the basin to faulting and tectonic tilting is probably influenced by proximity to major faults (Kyrkjebø et al., 2004; Sinclair and Withjack, 2008) and in some cases to the tectonic behaviour of salt. Regionally, master faults in southeastern Canada appear to trend NE (Pe-Piper and Piper, 2012), a direction inherited from Devonian–Early Carboniferous strike-slip motion that extended to Europe. The Minas Fault Zone and its continuation through the Laurentian Subbasin to the SW Grand Banks transform margin also appear to be a significant fault trend (Pe-Piper and Piper, 2004a).

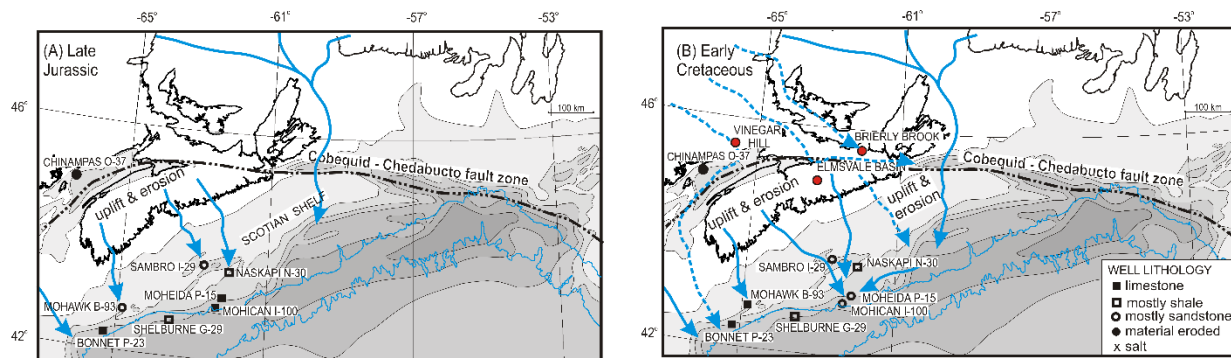
Four phases of volcanism are identified around the Scotian Basin. Phase 1 is represented by the apparent Hauterivian volcanism (based on K-Ar ages), predominantly of basalt flows, at the Mallard M-45 and Brant P-57 wells on the SW Grand Banks. A diabase intrusion on Georges Bank of apparent Valanginian age (Jansa and Pe-Piper, 1988) may be correlative. Phase 2 (Barremian) is more trachytic and pyroclastic volcanism, with minor basalt flows, at Mallard and Brant, with the age based on limited biostratigraphy at Brant. Correlative volcanism in the Laurentian Subbasin is suggested by ages of detrital zircons in sandstones in the Upper Mississauga Member in several Scotian Basin wells (Piper et al., 2012), and the presence of detrital trachytic clasts in the deepwater Newburn H-23 well throughout the Hauterivian, even below the iHu (Sangster, 2016). Phase 3 comprises basaltic flows in the Orpheus Graben of late Aptian age based on palynology (Bowman et al., 2012), and Phase 4 is the overlying trachytic pyroclastic rocks of the Orpheus Graben with early Albian palynomorphs (Bowman et al., 2012).





### A record of the type of sediment supply to the Shelburne Subbasin

Most of the sediment supplied to the central and eastern Scotian Basin is supplied by the Sable River draining the Labrador Rift and river draining Newfoundland. Neither of these catchment areas is represented in Chaswood Formation deposits. Only during the Aptian, when the Sable River was blocked tectonically and diverted was much of the sediment supplied to the Scotian Basin derived from the Meguma terrane (Chavez et al., 2018). At other times, Chaswood rivers may have been diverted along the major Cobequid Chedabucto Fault Zone (Minas Fault Zone) into the main Sable River (**Fig. 1.14B**), where the Chaswood river input from the Appalachians would have been strongly diluted.



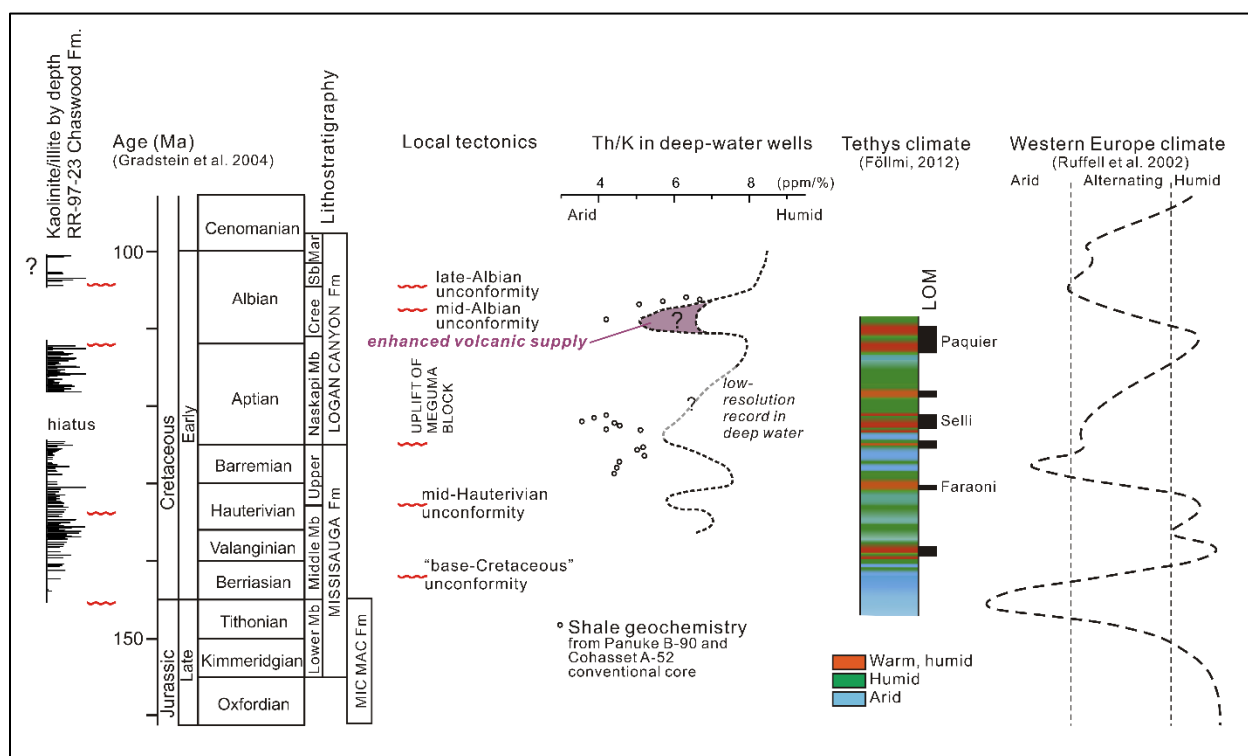
**Figure 1.14 Summary of inferred Late Jurassic and Early Cretaceous river patterns in the western part of the Scotian Basin, based on Dutuc et al. (2017) and Chavez (2017).**

Recent work by Dutuc et al. (2017) on the western Scotian Shelf and Chavez (2017) on the COST G-2 well on Georges Bank have clarified the sources of sediment to the Shelburne Subbasin. There is no evidence for provenance more distant than the Gander terrane of the Appalachians based on detrital zircon geochronology and the paucity of chromite (Chavez, 2017). Most sediment on the western Scotian Shelf appears derived from the Meguma terrane (Reynolds et al., 2009; Dutuc et al., 2017), suggesting that more inboard drainage was diverted along the Cobequid Chedabucto Fault Zone eastward to the Sable River or westward to the Fundy Basin. At the COST G-2 well, abundant staurolite and ilmenite in the Lower Cretaceous is similar to the petrography of the Chaswood sands at Vinegar Hill (**Fig. 1.14**).



## A record of local climatic conditions in the Early Cretaceous

The climatic history of the hinterland may be important in influencing the amount and composition of sediment supplied to the basin. The proportion of kaolinite to illite, reflected geochemically by the ratio of Th to K, is a useful indicator of the degree of leaching of soils under subtropical conditions and hence is a measure of humidity. Th/K has been determined from bulk core samples and from spectral gamma logs in selected offshore wells (**Fig. 1.15**; Gould et al., 2014). Also shown is the kaolinite/illite ratio from reference borehole RR-97-23 (**Fig. 1.10**) that appears to confirm a correlation between packet III and the late Aptian. The derived climate curve shows some similarities to a generalized western European curve (Ruffell et al., 2002) but may mask frequent short period fluctuations (Föllmi, 2012).



**Figure 1.15 Summary of the kaolinite/illite ratio in terrestrial rocks of the Chaswood Formation (Fig. 1.9); Th/K variations from spectral gamma in shale-prone deep-water wells and from shale geochemistry in Panuke B-90 and Cohasset A-52, compared with regional unconformities (Weston et al., 2012) and times of enhanced uplift of the Meguma block (Bowman et al., 2012); and inferred periods of aridity and humidity in western Europe (Ruffell et al., 2002) and Tethys (Föllmi, 2012). Modified from Gould et al. (2014).**



### **A record of thermal evolution at the basin margin, remote from salt tectonics**

The thermal modelling in the PFA (OETR 2011) was based on a simple rifting and lithospheric cooling model with early Jurassic rifting, calibrated using the modern thermal regime in wells (e.g. as summarized by Issler, 1984). However, several lines of evidence known before the PFA indicate that these assumptions are oversimplified. Zentilli and his colleagues have long argued for “thermal inversion” (likely heating events rather than tectonic inversion, given the available well history and seismic data), on the basis of apatite fission track modelling (Grist et al., 1992, Li et al., 1995). Zentilli (2010) showed clear evidence for Late Cretaceous to Paleogene thermal inversion, for which a regional rather than a local explanation was required. Aptian basaltic volcanism has long been known from the Orpheus Graben (Jansa and Pe-Piper, 1985), although Lyngberg (1984) was unable to detect a thermal signature in vitrinite reflectance data. Beck and Housen (2003) showed that there was regional paleomagnetic data in the northern Appalachians for partial thermal resetting in the Early Cretaceous. Wierzbicki et al. (2006) reported late high-temperature fluid inclusions in the Abenaki limestones in the Deep Panuke field. Fluid inclusion studies in the Scotian Basin (Karim et al., 2011; 2012) show in some cases that trapping temperatures inferred from homogenisation temperatures of fluid inclusions are rather higher than the maximum temperature achieved at the corresponding depth in the well based on the PFA modelling. That maximum temperature was achieved under maximum burial conditions, i.e. at the present. Yet primary fluid inclusions in silica or carbonate cements were trapped relatively early in the burial history of the basin. Hydrocarbons are detected in secondary fluid inclusions in fractures, but not in primary inclusions in either quartz overgrowths or later carbonate cements (Karim et al., 2012). Yet the temperatures recorded in the primary fluid inclusions in those cements are at temperatures normally associated with the oil window (Waples, 1980).

Thermal maturation of organic matter requires sustained heating over time (which can be measured by the time-temperature index, determined by Issler (1984), for the Scotian Basin), whereas dissolution and transport of silica and carbonate cements in general will take place faster at higher temperatures (Taylor et al., 2010). The primary fluid inclusion record is thus interpreted



to represent peak temperatures during episodic fluid flow that had more impact on diagenetic cements than on organic maturation. Karim et al. (2012) argued from carbon isotope data that there was a thermal peak affecting organic maturation in the deep basin during Aptian–Albian growth of carbonate cements in the Glenelg field.

Based on work in the Chaswood Formation and the Scotian Basin more generally, there is thus widespread evidence of elevated mantle temperatures on a regional scale in the Aptian, as summarized by Bowman et al. (2012). The evidence includes the enhanced melt production in the Atlantic Ocean at the J-anomaly ridge, thick flood basalts at Scatarie Bank, elevated vitrinite reflectance in the lower Chaswood Formation compared with the upper Chaswood Formation, and paleomagnetic resetting in the adjacent Appalachians (Beck and Housen, 2003). Bowman et al. (2012) showed that vitrinite reflectance in Chebucto K-90 was better modelled by an Aptian high-heat flow event than by early Jurassic rifting alone, although that result was not substantiated by Wong et al. (2016) at South Sable O-59.

Salt detachments, listric faults, and secondary porosity in channel sandstones have provided fairways for deep hot saline fluids in the outer part of the Scotian Basin to advect to the Scotian Shelf (Pe-Piper et al., 2015a). Such advection is concentrated in channel sands, precipitating diagenetic sphalerite, zircon, and fluorine-rich calcite (Pe-Piper et al., 2015a; Sangster et al., 2016). At least at Peskowsk A-99, where sphalerite and secondary fluid inclusions with average 152 °C and 8.3 % salinity are found in Albian sandstones of the Cree Member, burial history requires a Paleogene or younger thermal event. The apatite fission track work of Grist et al. (1992) and Li et al. (1995) from the Logan Canyon Formation of the Venture B-52, Eagle D-21, West Olympia O-51, Kegeshook G-67 and Cohasset A-52 wells clearly show by forward modelling a Late Cretaceous or more likely Paleogene thermal event exceeding 90 °C. Their samples were carefully screened for chemical composition, which may have screened out diagenetic apatite. More recent work by Zentilli (2010) on core from the Venture B-43 and Thebaud I-93 wells, and on cuttings from several other wells, has generally confirmed the presence of a Late Cretaceous to Paleogene thermal event. A Late Cretaceous to Paleogene event



was identified by thermal modelling of vitrinite reflectance in South Venture O-59 (Wong et al., 2016).

Apatite fission track data modeled by Arne et al. (1990) indicated Late Cretaceous temperatures of 60-80°C in basement directly below the Chaswood Formation. Regional apatite fission track data of Grist and Zentilli (2003) yielded mean model estimates of maximum temperature of the top of basement (after Chaswood Formation deposition) of only 45°C. Such temperatures could be achieved with the burial depth of 770 m estimated by Hacquebard (1984) and a geothermal gradient of 20-25°C/km. Such a slightly elevated geothermal gradient is possible given the presence of mid-Cretaceous mafic volcanic rocks in the Orpheus graben (Jansa and Pe-Piper 1985). The missing overlying strata required to give such a depth of burial were likely the Upper Cretaceous Dawson Canyon and Tertiary Banquereau formations, which are hundreds of metres thick along strike in the Orpheus Graben (Wade and MacLean, 1990; Weir-Murphy, 2004). Grist and Zentilli (2003) suggested that erosion of these strata resulted from lower eustatic sea level in the Neogene, whereas Pe-Piper and Piper (2004a) argued that it was related to Oligocene tectonic uplift. Both processes probably played a role.

### **A record of diagenetic evolution at the basin margin**

Diagenesis in the Chaswood Formation sandstones on land in Nova Scotia can be compared with diagenesis in the Scotian Basin. The most advanced diagenesis is known from the Elmsvale Basin, where the Chaswood Formation is up to 150 m thick. Based on lignite moisture content, Hacquebard (1984) estimated a total of 770 m of burial by younger strata, that Pe-Piper and Piper (2004a) suggested were equivalent to the Dawson Canyon and Banquereau formations seen along strike in the Orpheus Graben.

In the Elmsvale Basin, diagenesis has been studied in borehole RR-97-23 (Pe-Piper et al., 2005d), which has loose sands at the top of the formation and lithified sandstones near the base. There is a progressive down-hole increase in suturing of quartz grains and presence of euhedral quartz overgrowths. Suturing of quartz grains is first seen 90 m below the top of the formation,



and is accompanied by brittle and plastic deformation of feldspar/kaolinite and of mica. Some quartz grains seem to be protected by pedogenic clay coats, which predate siderite rims. Probable titania, pseudomorphing phytodetritus, is seen, similar to that in the Scotian Basin. In some more porous sandstones, there appears to be corrosion of quartz adjacent to porosity, creating secondary porosity, which can also result from the dissolution of siderite and feldspar. Fibrous illite is found in pore throats in secondary porosity, and barite cement fills late secondary porosity.

Raman spectroscopy analysis of kaolin minerals from sandstones from the bottom of borehole RR-97-23 by D. Papoulis (pers. comm. 2003) showed the presence of dickite in several samples. He also recognised dickite in the Sable Island C-67 well at 2832 m. Studies in petroleum basins elsewhere suggest that dickite requires substantially elevated temperatures for its formation (e.g.  $> 95^{\circ}\text{C}$  in the Brent field of the North Sea, Girard et al., 2002).

Sandstones at the Belmont outlier are only 25 m thick but are indurated, with prominently suturing of quartz grains (Pe-Piper et al., 2005c) and local evidence for overgrowths. In contrast, sands from Brierly Brook, where the formation is up to 40 m thick, are only slightly indurated.

At both Belmont and Brierly Brook, illite diagenesis appears to be later than kaolinite. At Brierly Brook, diagenetic barite predates illite and some kaolinite, in contrast to RR-97-23 in the Elmsvale Basin, where rare barite is a late pore-filling mineral.

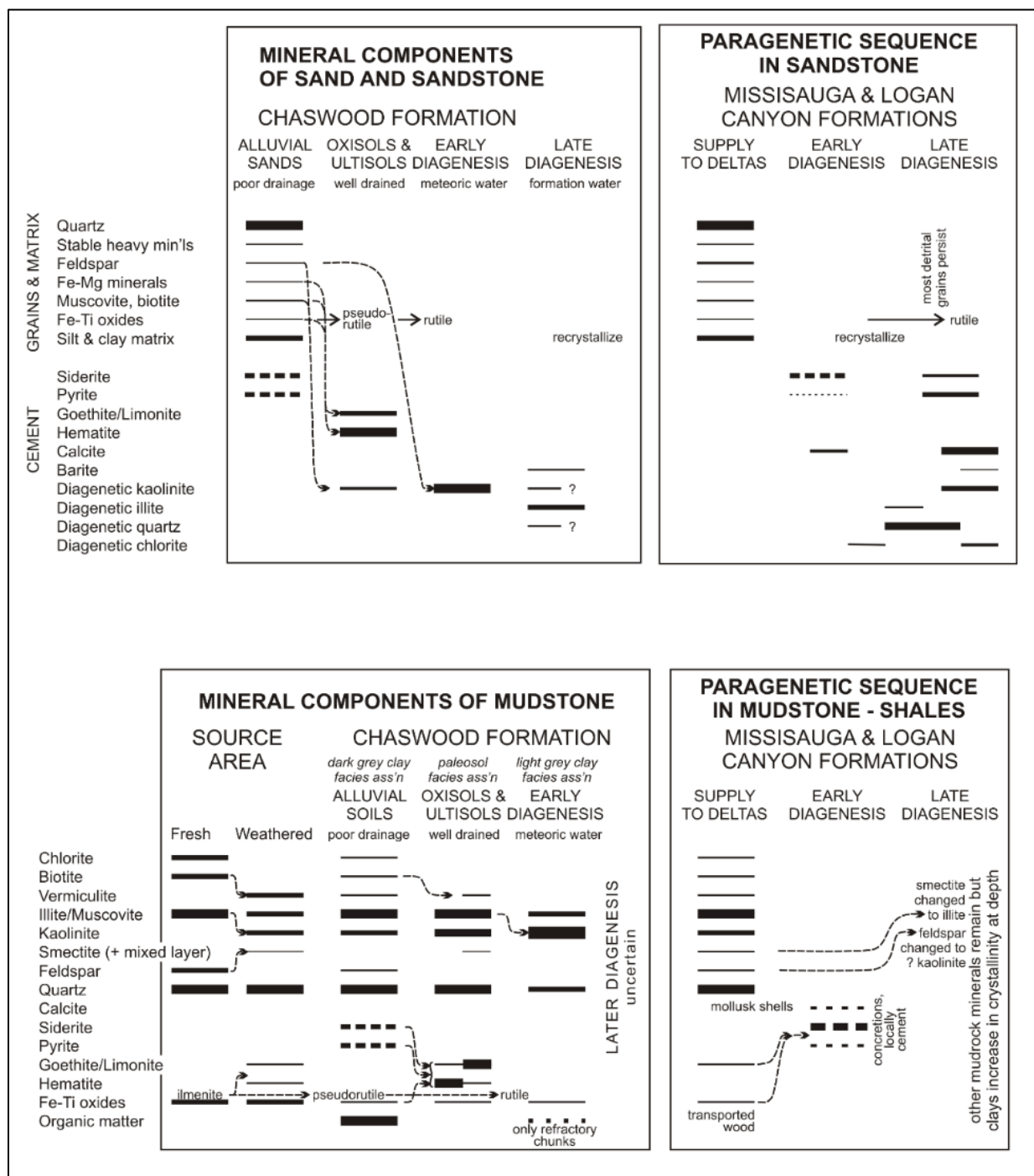
The observations of diagenetic minerals in sandstone from RR-97-23 in the Elmsvale Basin, informed by lesser data from Belmont and Brierly Brook, suggest the following paragenesis (**Fig. 1.16**). Mineralisation of organic carbon under reducing conditions in swamps and ponds produced siderite nodules and framboidal pyrite that formed an early diagenetic cement. These minerals were corroded and oxidized during subsequent falls in base-level or tectonic tilting, with the development of paleosols with early diagenetic hematite, goethite and limonite and the precipitation of limonite spherules in porous sandstone. Iron was in part sourced by the progressive alteration of iron-titanium oxides to titania polymorphs.



Kaolinite is an early cement mineral in many samples, post-dating siderite corrosion. It occurs as rims to quartz, as well-crystallized booklets, and as acicular masses. Kaolinite booklets and vermicules commonly result from early diagenesis by meteoric water in sandstones (e.g., Glasman, 1992; Rossi et al., 2002). In the lower part of the formation, kaolinite cement formed below the water table, at the same time as oxisol formation in units U1-U4. It also formed in sandstones of units U1 to U4 during the cutting of the U5-U6 unconformity.

Illite is also a cementing mineral and sparse data suggest that it postdates the kaolinite. Diagenetic illite occurs throughout the Chaswood Formation and suggests formation waters rich in K, rather than leaching by meteoric water. Within the Chaswood Formation of the Elmsvale Basin, however, there is a remarkable change from well-lithified sandstones in unit L1 to loose sands with only minor clay cements in unit U6 over a thickness of 110 m. There is a comparable rapid change in vitrinite reflectance between the lower part of the formation and the upper (**Fig. 1.8**). The impermeable mudstones within units U1–4 may separate two rather different diagenetic systems. If the Chaswood Formation were buried by 700 m of Dawson Canyon and Banquereau formations, as suggested by the apatite fission track results of Grist and Zentilli (2003) and the lignite moisture contents of Hacquebard (1984), it was likely in hydraulic continuity with the Scotian Basin in the Late Cretaceous and Paleogene. Diagenetic illite is known elsewhere from intermediate burial and temperature conditions similar to those inferred for the Chaswood Formation, for example from the Brent reservoir in the North Sea (Girard et al. 2002). The late barite cement, found only in the lower part of the formation, may be related to release of Ba from K-feldspar in the Scotian Basin, where detrital K-feldspar and late barite cement are common (e.g. Pe-Piper and Yang, 2014; Pe-Piper et al., 2015a). Although Ba might be derived from remobilisation of Carboniferous barite ores in the underlying Mississippian Windsor Group, the lack of carbonate cementation in the Chaswood Formation, despite its abundance in the Windsor Group, suggests a Carboniferous source was unlikely.





**Figure 1.16 Summary of diagenetic paragenesis for sandstones and mudstones of the Chaswood Formation. (Modified from Pe-Piper and Piper, 2004b).**





## Chapter 2: The West Indian Road pit

### General setting

The West Indian Road deposit (**Fig. 2.1**) (also previously referred to as Brazil Lake or Grant Brook) occurs within a fault-bound basin in Carboniferous (Mississippian) MacDonald Road Formation (Windsor Group) gypsum and was originally interpreted as a large sink hole (Dickey 1986). The regular stratigraphic succession and tectonic tilting indicates that the deposit was originally more extensive and occupies its present position as a result of post-Cretaceous faulting and folding into syncline. The pit has been extensively exploited and studied by Shaw Resources (Price 2000). When first developed, it was studied by Stea and Fowler (1981), who noted the presence of exotic gravel clasts. More recently, it was the subject of a M.Sc. thesis by J.-P. Gobeil (2002), with a summary published by Gobeil et al. (2006).

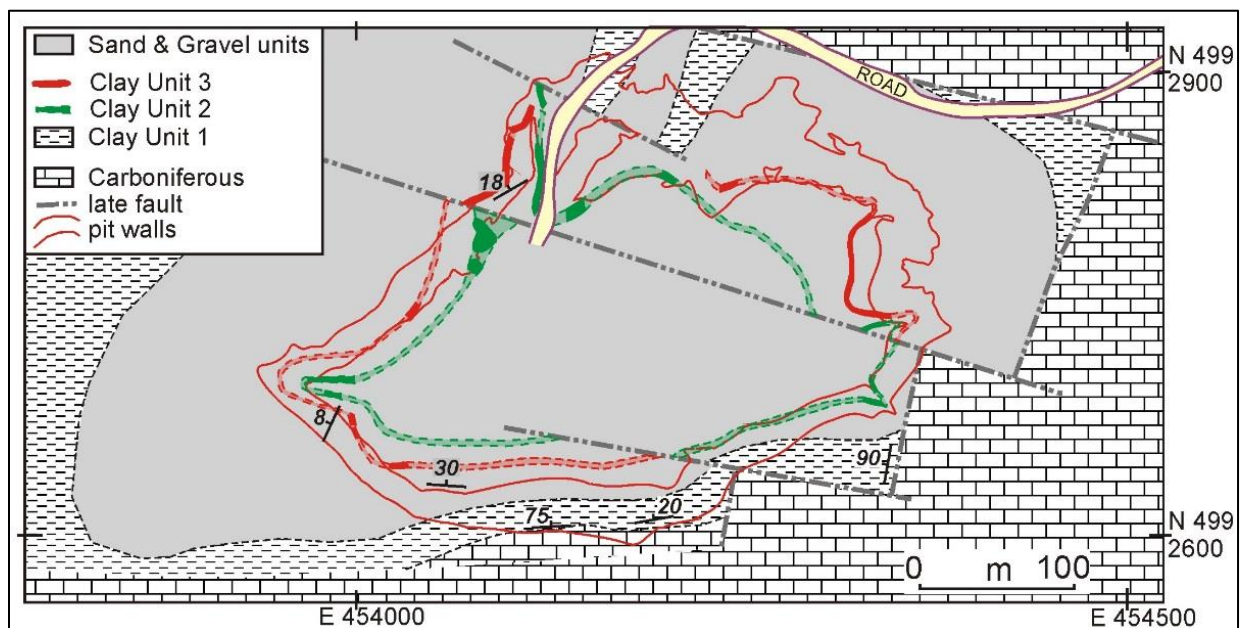
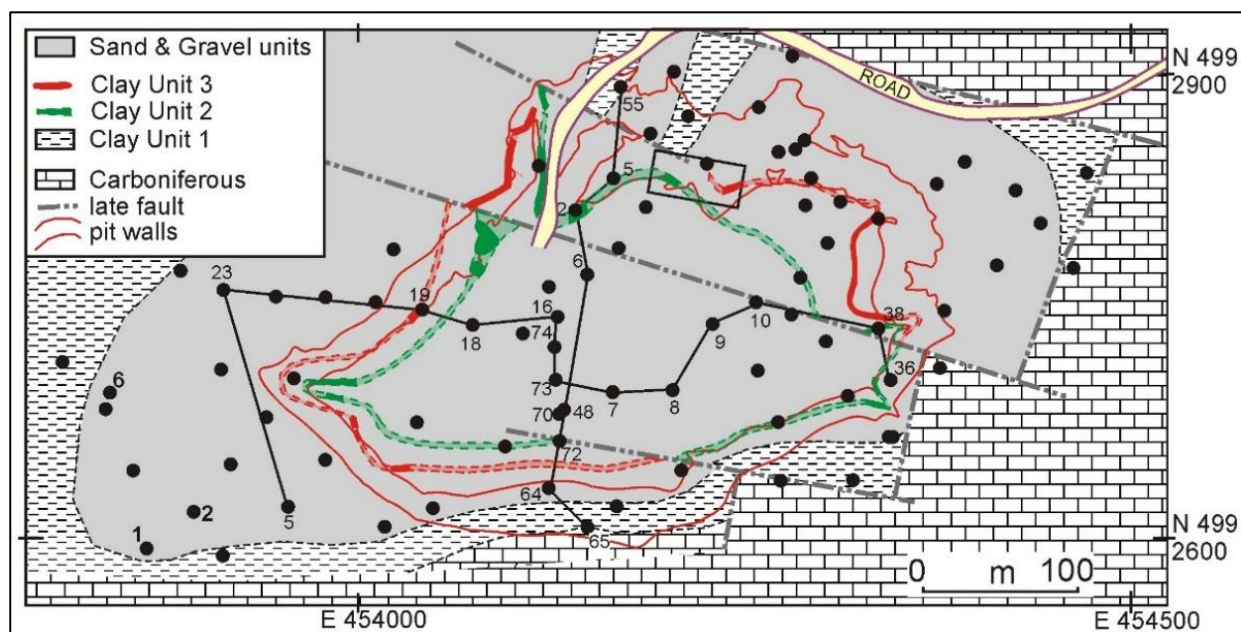


Figure 2.1. General geological map of the West Indian Road pit (from Gobeil 2002).

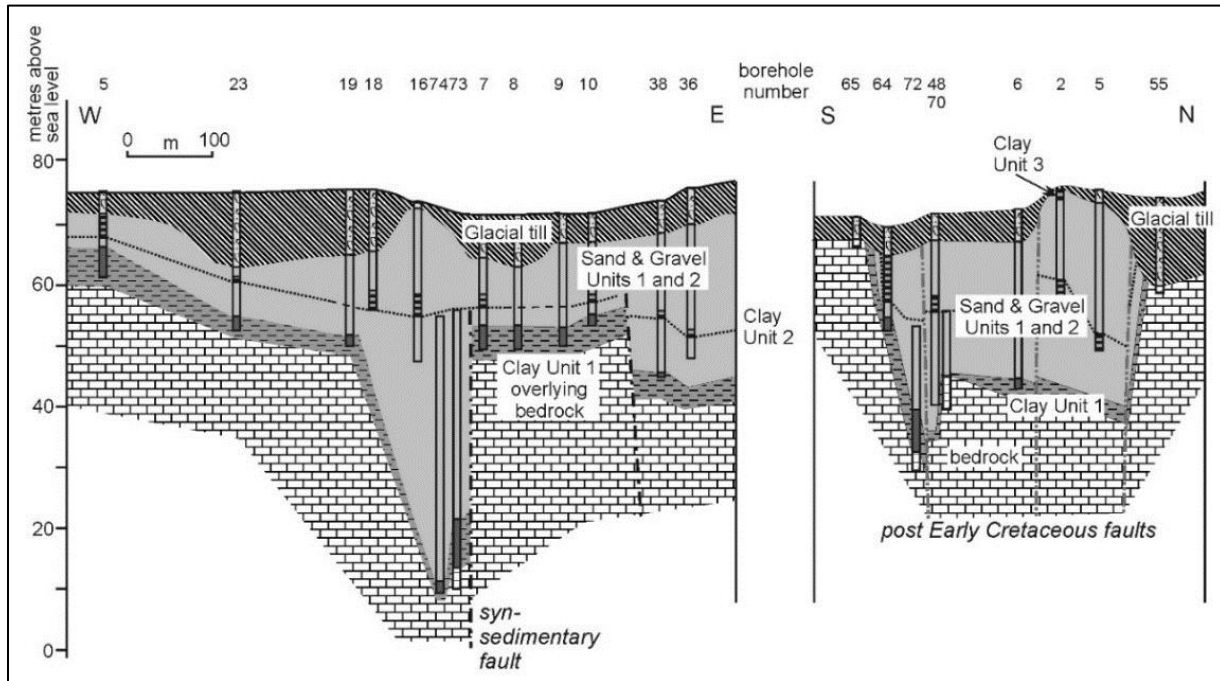


## Stratigraphy

Three mudstone units (Clay Units 1, 2 and 3) are separated by three coarser grained units (Sand & Gravel Units 1, 2 and 3). Boreholes (**Fig. 2.2**) show that thicknesses are rather variable (**Fig. 2.3**). Clay Unit 1 (**Fig. 2.4**) is typically 3 to 10 m thick resting unconformably on the MacDonald Road Formation. It consists principally of dark grey clay, with some interbedded mottled brown, pink, red, purple and green clays and thin sands and gravels. Some clay beds show fine parallel laminations, but others appear to be debris-flow deposits consisting of clay-supported gravel clasts, all cut by both brittle and ductile deformation structures. The clays contain reworked Carboniferous palynomorphs and the gravel clasts consist of vein quartz and Early Mississippian Horton Group calcarenites.



**Figure 2.2** Borehole control in the West Indian Road pit, showing cross sections in Figs. 2.3 and 2.4; box shows detail in Fig. 2.6.



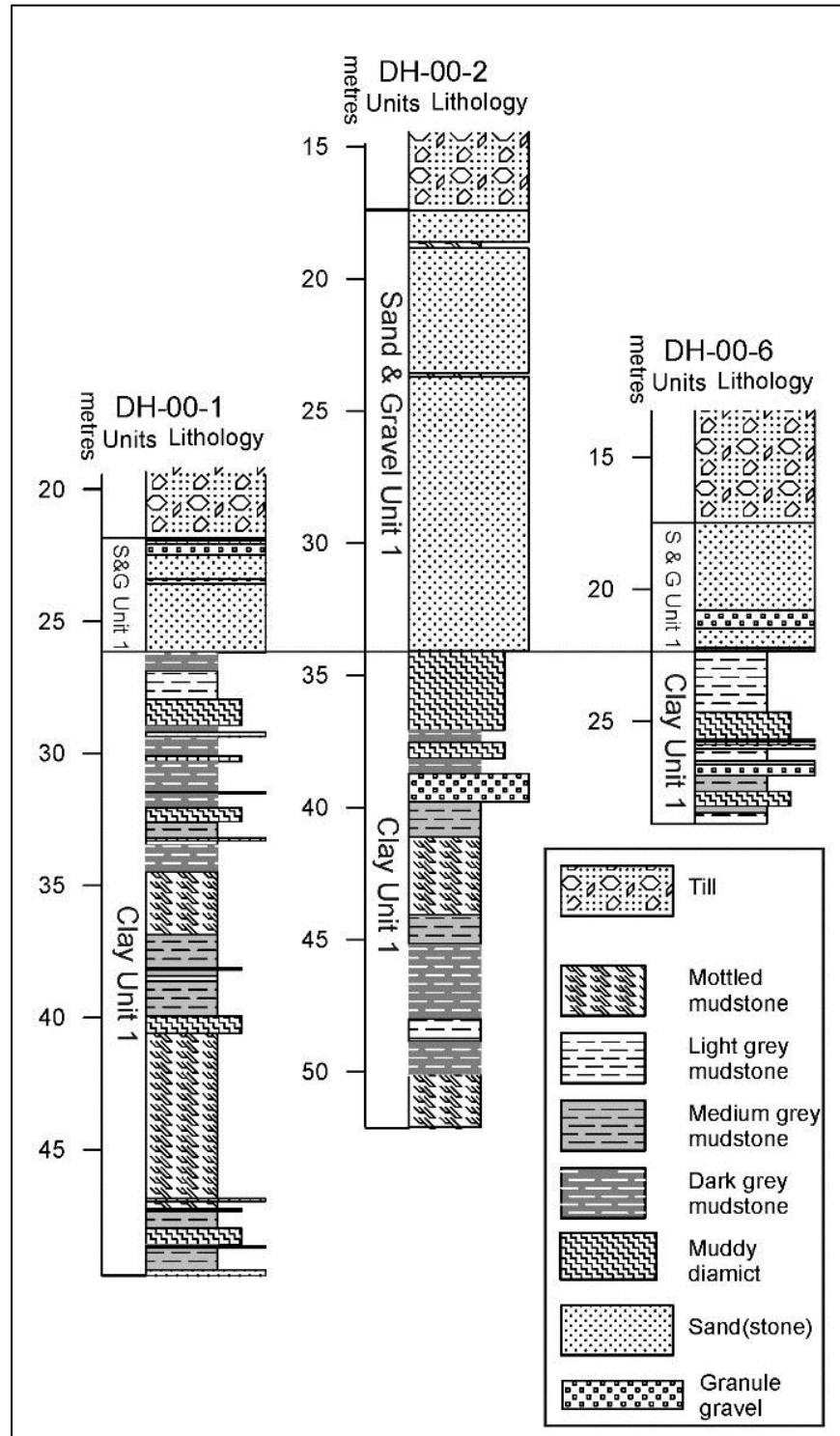
**Figure 2.3 Borehole sections across the West Indian Road pit showing stratigraphic succession and lateral variations in thickness.**

Sand & Gravel Unit 1 is known mostly from boreholes and is 3 - 20 m thick. It consists of conglomerates and sandstones, commonly in fining-upward sequences.

Clay Unit 2 is 0.5 - 3.6 m thick and consists of medium grey clay with pink colouration in its upper 10 - 30 cm. In places it is disrupted by sand injection and was not identified in all boreholes.

Sand & Gravel Unit 2 is typically 15 m thick and consists of cross-bedded pebbly sandstone and lesser conglomerate, with local erosional unconformities (**Fig. 2.5**).

Clay Unit 3 is a 0.5 m thick pink clay bed found throughout the pit. It is overlain locally by thin sediments of Sand & Gravel Unit 3 and then by glacial till.



**Figure 2.4 Borehole logs through Clay Unit 1 in the SW part of the pit (Fig. 2.2).**

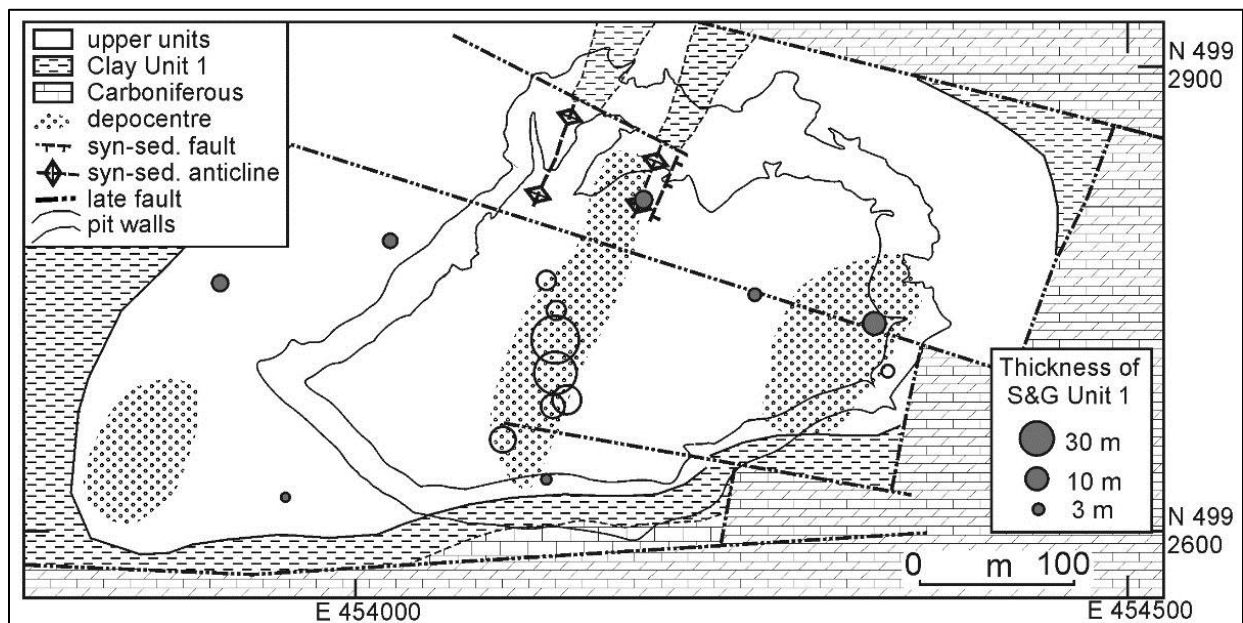




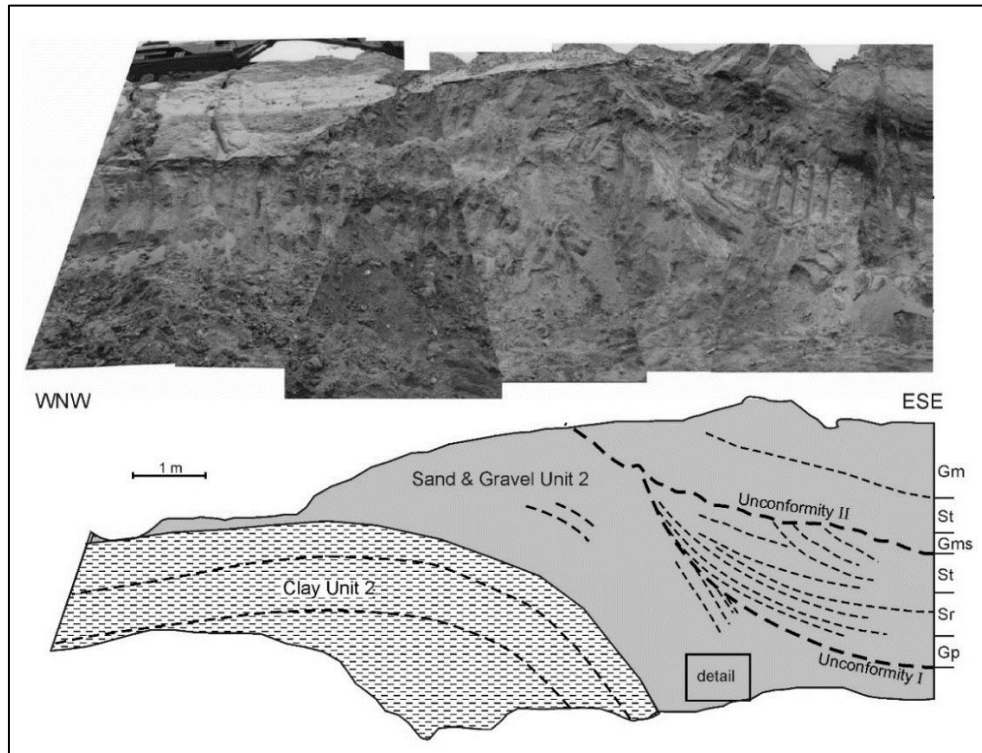
## Structure of the Chaswood Formation

### Synsedimentary deformation

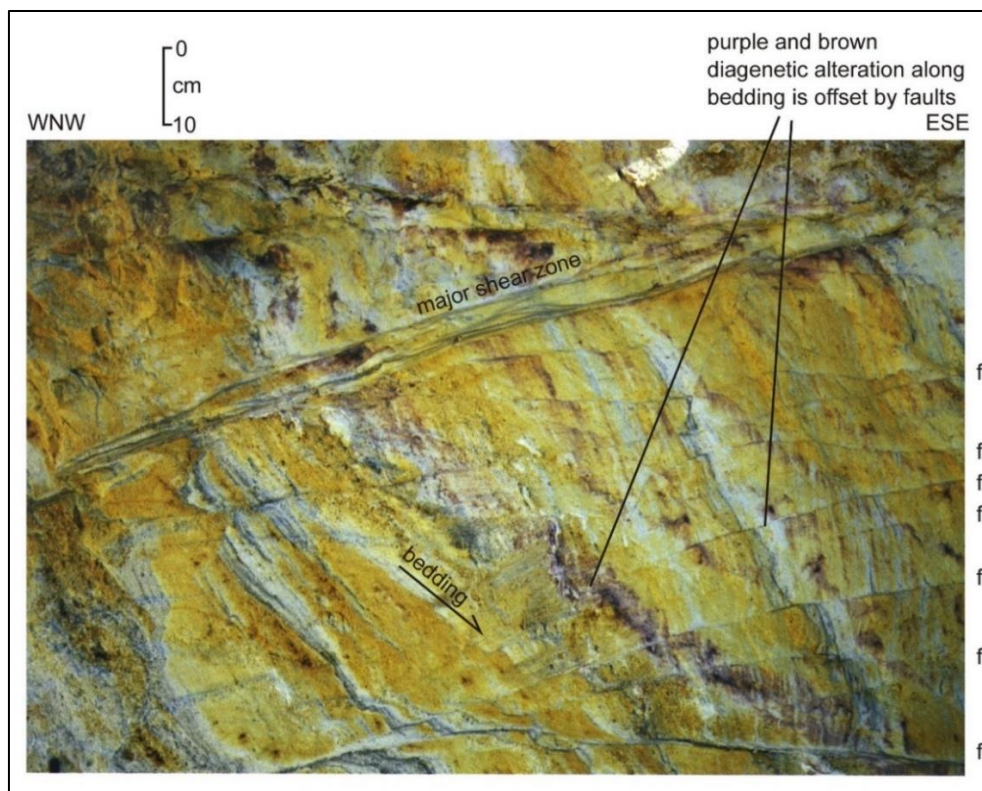
The West Indian Road pit has clear evidence for synsedimentary tectonic deformation. Clay Unit 2 is folded into two anticlines (**Fig. 2.5**), one with a faulted margin on its eastern side, against which Sand & Gravel Unit 2 onlaps with local unconformities (**Fig. 2.6**). Faulted sediments (**Fig. 2.7**) are overlain unconformably by unfaulted sediments, all within Sand & Gravel Unit 2. Within the fault zone, bedding is tilted to sub-vertical and sub-horizontal shear zones predominate. This style of faulting is consistent with strike-slip faulting under a low vertical confining stress. Both the anticlines and the fault zone strike NNE. Rapid variations in unit thickness, particularly in Sand & Gravel Unit 1 (**Fig. 2.2**), are also suggestive of synsedimentary faulting creating accommodation. Major depocentres trend approximately N-S, parallel to the synsedimentary faults (**Fig. 2.5**).



**Figure 2.5** Synsedimentary deformational features and principal depocentres in the West Indian Road pit.



**Figure 2.6** Cut face, now destroyed, showing anticline in Clay Unit 2 and overlying Sand & Gravel Unit 2, cut by two local unconformities. Location in Fig. 2.3; detail in Fig 2.7.



**Figure 2.7** Detail of synsedimentary faulting (now destroyed) on the flank of the anticline shown in Fig. 2.6.





### **Post-Chaswood deformation**

Late deformation folded the Chaswood Formation into an E-W trending syncline, with subvertical dips close to bounding E-W or WNW-ESE trending faults (**Fig. 2.1**). The Chaswood Formation is also faulted against Carboniferous basement at the eastern end of the pit by NNE-trending faults, which parallel the mid-Cretaceous synsedimentary faults and may be reactivated structures. The overall offset of the eastern end of the pit suggests dextral strike-slip on E-W faults.

### **Synthesis of structural evolution**

The structural style of the synsedimentary faulting in the Chaswood Formation is typical of strike-slip faulting, with abrupt local rotation of beds and sediment thickness changes (e.g., Nilsen and Sylvester 1995). The principal faults are inferred to trend NNE, parallel to the anticlines (**Fig. 2.5**) and many secondary faults (**Fig. 2.7**).

The younger deformation that created the E-W syncline and WNW-ESE trending faults at the West Indian Road pit does not appear to be a continuation of the synsedimentary folding and faulting. The orientation of structures is quite different. Deformation on synsedimentary faults ended prior to latest Chaswood Formation deposition at the West Indian Road pit, as shown by the lack of deformation above unconformity II (**Fig. 2.6**) and the apparent lack of significant growth faulting from sediment thickness variations above Clay Unit 2 (**Fig. 2.3**).

The termination of syndepositional deformation prior to latest Chaswood Formation deformation has also been interpreted from seismic-reflection profiles in the Elmsvale basin (Piper et al., 2005). Neither in the Elmsvale basin nor at the West Indian Road pit is there any control on the age of the younger deformation.

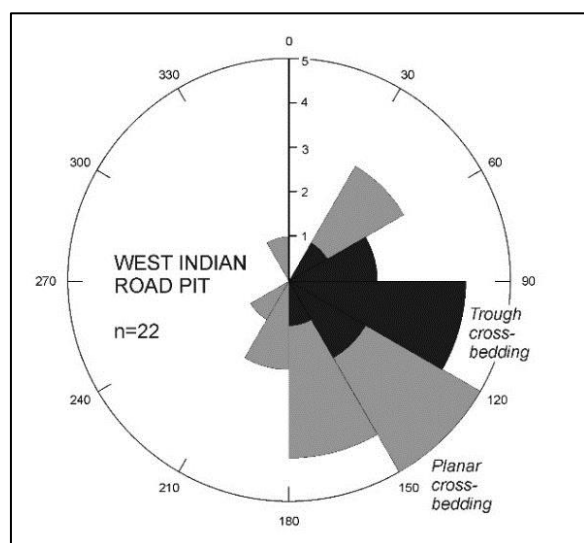


Figure 2.8 Photomosaic view of the West Indian Road pit when it was pumped dry in 2001.



## Sedimentology of sand and gravel facies

When the pit is pumped out (**Fig. 2.8**), the following sand and gravel facies can be recognised (Gobeil et al., 2006). Massive to horizontally laminated gravel (**Gm**) beds form the base of fining-upward successions, in places forming amalgamated beds up to 1.5 m thick. Clasts may be either pebble or granule size. Massive graded gravel (**Gms**) beds are 0.5 to 0.8 m thick, generally with an erosive base with a pebble lag. Trough cross-bedded gravel (**Gt**) occurs in multiple sets 0.3 - 0.5 m thick interbedded with other types of gravel deposit. Planar cross-bedded gravel (**Gp**) forms single sets 0.4 - 2.1 m thick. Crudely cross-bedded sand with an erosional scoured base (**Se**) forms beds up to 0.8 m thick, with a pebble-granule lag at the base. In places, this facies passes laterally into massive sand (**Ss**) with broad, shallow scours and in some beds normal grading. Planar cross-bedded sand (**Sp**) forms single sets 0.2 - 0.7 m thick. Trough cross-bedded sand beds (**St**) occur in multiple sets 0.2 - 1 m thick, commonly with granule lags at the base of sets. They pass up into horizontally laminated sand beds (**Sh**) and then into thin ripple cross-laminated sand (**Sr**). Within the lower part of Sand & Gravel Unit 2, several metre-scale fining upward successions are developed with gravel facies (**Gm**, **Gms** or **Gp**) at the base, passing up into **Sp** or **St**. In the upper part of the unit, the most common succession is **Gm** and **Sh**. Paleocurrents in the Sand & Gravel units, determined principally from facies **Gt** and **St**, are unimodal to the SSE (**Fig. 2.9**).



**Figure 2.9 Measured paleocurrents in the West Indian Road pit. Black – trough cross bedding; grey – planar cross bedding.**



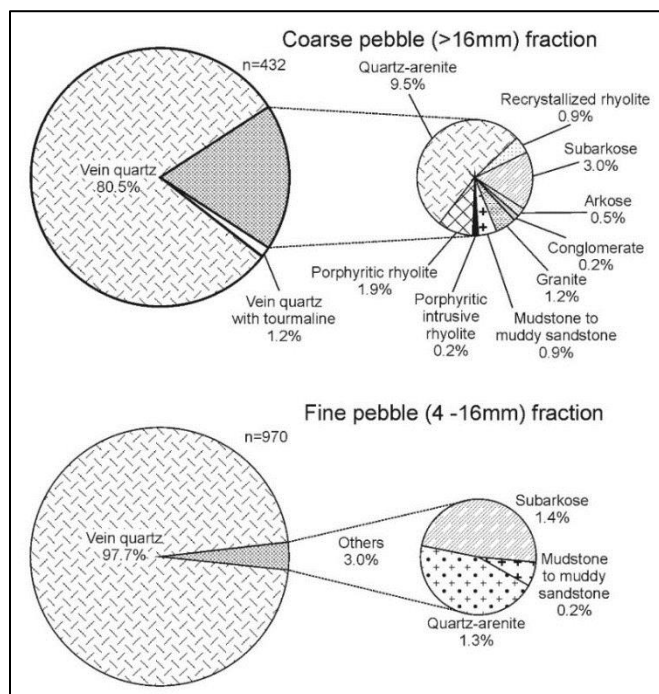
Groups of beds can be correlated over distances of hundreds of metres by their relationship to the Clay units, but single beds can only rarely be traced laterally for distances of more than 10 to 20 m. Prominent channels were not recognised; visible erosional surfaces at the bases of beds have relief of only 1 m although lateral correlation between measured sections shows variation in thickness of groups of beds of several metres.

The sand-gravel facies are characteristic of deposition in coarse-grained bedload rivers (e.g. as summarized by Collinson, 1996; Lunt et al., 2004). In Sand & Gravel Unit 2 in the northeast part of the pit, there is a repetitive sequence of erosion surfaces overlain by gravel facies (**Gm**, **Gt**, **Gms**) that pass up into cross-bedded sands (**Sp** or **St**). Two of the erosion surfaces correspond to the local unconformities in **Figure 2.5**. Individual facies can be interpreted, but lateral relationships are rarely seen. Facies **Gm** and **Gms** probably developed in longitudinal bars under high flood conditions, with erosive bases and pebble lags representing channel erosion, whereas planar cross-bedded facies **Gp** and **Sp** are developed at bar margins (e.g. Miall, 1977). Trough cross-bedded sands (**St**) in places are seen to occupy metre-deep channels. Rippled sands (**Sr**), interpreted as deposited during low water stages (Smith, 1971), and may overlie any of the other facies. In the upper part of Sand & Gravel Unit 2, the lithofacies are principally massive gravel (**Gm**) overlain by horizontally bedded or trough cross-bedded sands (**Ss**, **Sh**, **St**), with a 2.5 m deep inferred channel in one locality of trough cross-bedded fine gravel (**Gt**). Thus deposition appears dominated by bars in the lower part of Sand & Gravel Unit 2 with a greater importance of channel deposition in the upper part of the unit. Paleocurrents in trough cross-bedded facies developed in channels are consistently to the ESE, with a much greater spread in planar cross-beds that typically develop at bar margins (**Fig. 2.8**). The width of individual channels is not well constrained, although observations suggest a width of tens of metres, rather than metres or hundreds of metres, for the gravel filling channels at the top of Sand & Gravel Unit 2.



## Detrital petrology

Pebbles were visually separated into about 20 lithologic types (**Fig. 2.10**). Most pebbles are quartz-rich lithologies, either vein quartz or quartz arenite or subarkose (Gobeil, 2002). Pebbles are subrounded to well rounded, with low to moderate sphericity. The quartz arenite and subarkose pebbles contain detrital resistant heavy minerals including zircon and tourmaline. In addition, however, there are deeply weathered Aexotic® pebbles including numerous mafic igneous rocks, originally gabbro or diorite. Some pebbles consist of hornblende largely altered to actinolite, plagioclase, ilmenite, and K-feldspar; others consist principally of epidote, chlorite and feldspar. Other exotic pebbles include pink granite and both porphyritic and recrystallized rhyolite. Pebbles also include clasts of pebbly sandstone with a cement of opaque iron oxide (probably ilmenite) and fractured vein quartz with ilmenite filling the fractures. No systematic differences in pebble petrology could be detected between Sand & Gravel units 1 and 2. No pebbles of the distinctive Meguma Group metasediments have been found, but vein quartz with tourmaline resembles veins cutting the Meguma Group to the north of the pit (Strathdee, 2010).



**Figure 2.10 Gravel petrology and the West Indian Road pit (from Gobeil, 2002).**





In Clay Unit 1, the pebbles consist only of vein quartz and quartz arenites resembling Horton Group sandstones. These clays contain predominant reworked Carboniferous palynomorphs (R. Fensome, pers. comm. 2002).

Sand grains are predominantly of sub-angular quartz, with a few percent of mica and traces of heavy minerals. Heavy minerals have been analysed from Sand & Gravel Unit 2, where they are concentrated as lags along foresets in cross-stratified sands. The dominant heavy minerals are ilmenite and its alteration products (cf. Pe-Piper et al., 2005d), rutile, zircon and tourmaline, with lesser staurolite, andalusite, monazite, and cassiterite. This assemblage is similar to that found in nearby boreholes at Shubenacadie and in the Elmsvale Basin (**Fig. 1.2**) (Pe-Piper et al., 2004; 2005a).

Single-crystal  $^{40}\text{Ar}/^{39}\text{Ar}$  age determinations have been made on detrital muscovite from three samples in the West Indian Road pit. The ages are a little older than the muscovite ages for the South Mountain batholith determined by Carruzzo (2003), but the mean of 374 Ma is within the range of precise U-Pb ages for the batholith and its satellite plutons as summarized by Kontak et al. (2004).

## **Interpretation of paleogeography**

Most of the Chaswood Formation is of similar lithologic character throughout the southern Maritime Provinces, comprising well sorted fluvial sand(stone) (locally gravelly) and overbank mudstones with paleosols and some lignite beds (Dickie, 1986). The coarsest-grained sediment are found at the Vinegar Hill pit in southern New Brunswick (Falcon-Lang et al. 2004), suggesting a northerly provenance.

The earliest Chaswood Formation deposits at West Indian Road pit, Clay Unit 1, include small fluvial channel deposits and locally derived debris-flow deposits, suggesting deposition in a steep-sided local basin. Analogous local sediment supply to a confined basin is inferred for the oldest Chaswood Formation at Brierly Brook (Pe-Piper et al., 2005c). Overlying Sand & Gravel





Unit 1 and younger strata contain clasts with a more distant provenance and are the deposits of a coarse bedload river system that deposited more widely over Nova Scotia than is represented by the present erosional remnants in outliers.

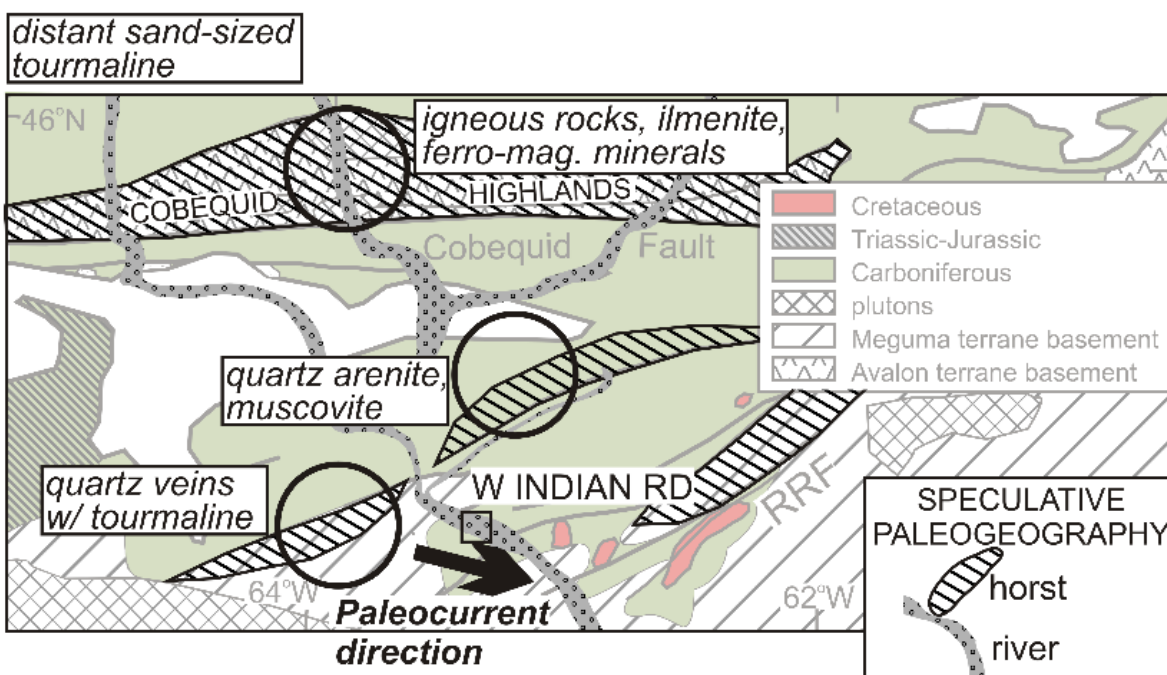
During deposition, there was ongoing tectonic deformation, resulting in the folding, faulting and local unconformities at the West Indian Road pit. Sedimentation kept pace with the creation of accommodation, so that local unconformities were overlain by further sand and gravel deposits and the mean paleocurrent direction to the SSE was almost orthogonal to the most active synsedimentary faults. Similar patterns are seen in many modern actively deforming basins (e.g., Leeder and Jackson, 1993). The deformation of unconformities (**Fig. 2.6**) suggests that sediment accumulation may have taken place over a long period of time in the Early Cretaceous, with most fluvial sediment bypassing and accumulation taking place only as accommodation was created. Cessation of coarse sediment supply during deposition of Clay Units 2 and 3 could have been the result of tectonic deformation temporarily diverting the river to a new course.

Horsts within the Maritime Provinces shed coarse-grained detritus, including quartz arenites from the Horton Group of central Nova Scotia and igneous rocks from the Cobequid Highlands. Regionally, detrital monazite from boreholes yield predominantly Ordovician ages (**Fig. 1.6**), suggesting important sediment supply from rocks deformed in the Taconic orogeny in northern New Brunswick (Pe-Piper and MacKay, 2006).

The West Indian Road pit has a higher proportion of sand and gravel facies (> 90 %) compared with other parts of the Chaswood Formation. Only the Vinegar Hill pit (Falcon-Lang et al., 2004; Piper et al., 2007) has a similarly high proportion of coarse-grained sediment. Diogenes Brook (Dickie, 1986) and Belmont (Pe-Piper et al., 2005c) have about 70% sand; the eastern Elmsvale basin (Stea and Pullan, 2001; Pe-Piper et al., 2005b) has as little as 10% sand. Grain size analysis shows that gravel units at the West Indian Road pit are coarser grained than sand and gravel in the Chaswood type section (Stea and Pullan, 2001) and the Shubenacadie



outlier (Stea et al., 1996), suggesting that the West Indian Road pit lay on the principal drainage route from the northwest (**Fig. 2.11**).



**Figure 2.11 Sources of detritus for the West Indian Road pit and speculative paleogeography.**

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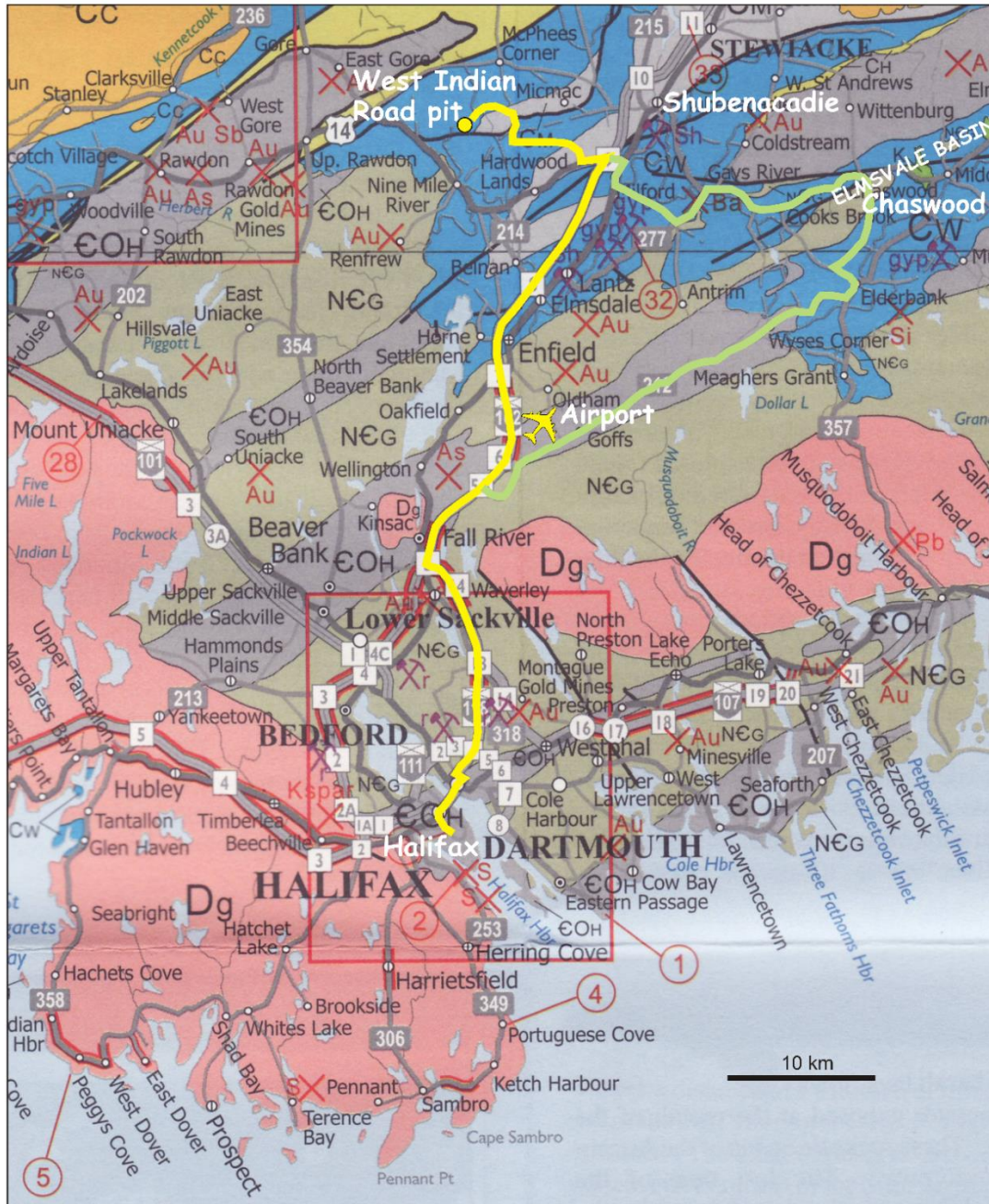
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## Chapter 3: Field Stops



Extract from the Geological Highway Map of Nova Scotia (3rd edn.) showing the route of the field trip.

Principal rock types that we cross are Meguma Supergroup metasediments ( $NC_g$  = Goldenville Group sandstones;  $CO_h$  = Halifax Group slates); Devonian granites (pink,  $D_g$ ); and Carboniferous Windsor Group limestones, gypsum and shales ( $C_w$ ).



## BRIEF DESCRIPTION OF STOPS AT THE WEST INDIAN ROAD PIT

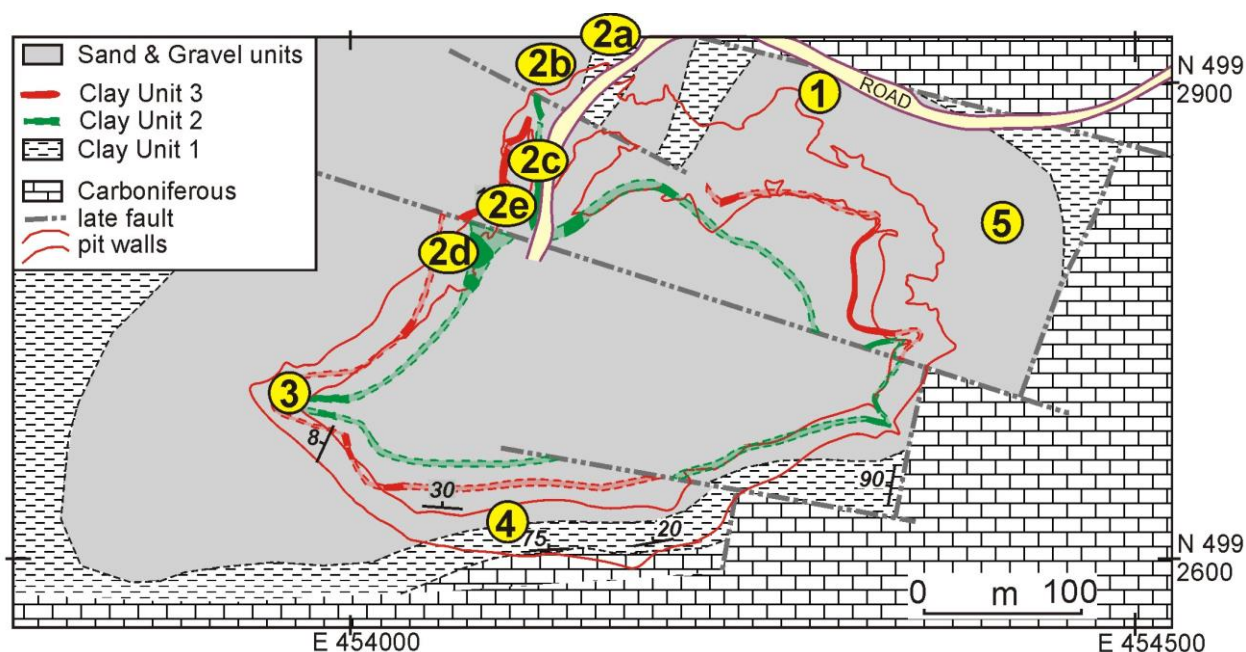


Figure 3.2 Map of the West Indian Road Pit showing possible stops.

**Stop 1.** Walk to the edge of the pit and discuss overview of pit

**Stop 2a.** Anticline in Clay Unit 1. Faulted margin of unknown age.

**Stop 2b.** Sedimentology of Sand and Gravel Unit 1.

**Stop 2c.** Clay unit 3; Clay Unit 2 farther back in cliff.

**Stop 2d.** Sedimentology of Sand and Gravel Unit 2. Apparent syndimentary deformation of fine sands.

**Stop 2e.** Sedimentology and structures in Sand and Gravel Unit 2. Possible analogue of Fig. 2.7.

**Stop 3.** *This outcrop is under water in August 2018.* Clay unit 2 here shows deformation. Sedimentology of sands is visible.

**Stop 4.** Bedding plane surfaces in Clay Unit 1.

**Stop 5.** Stock pile. Examine clast petrology.



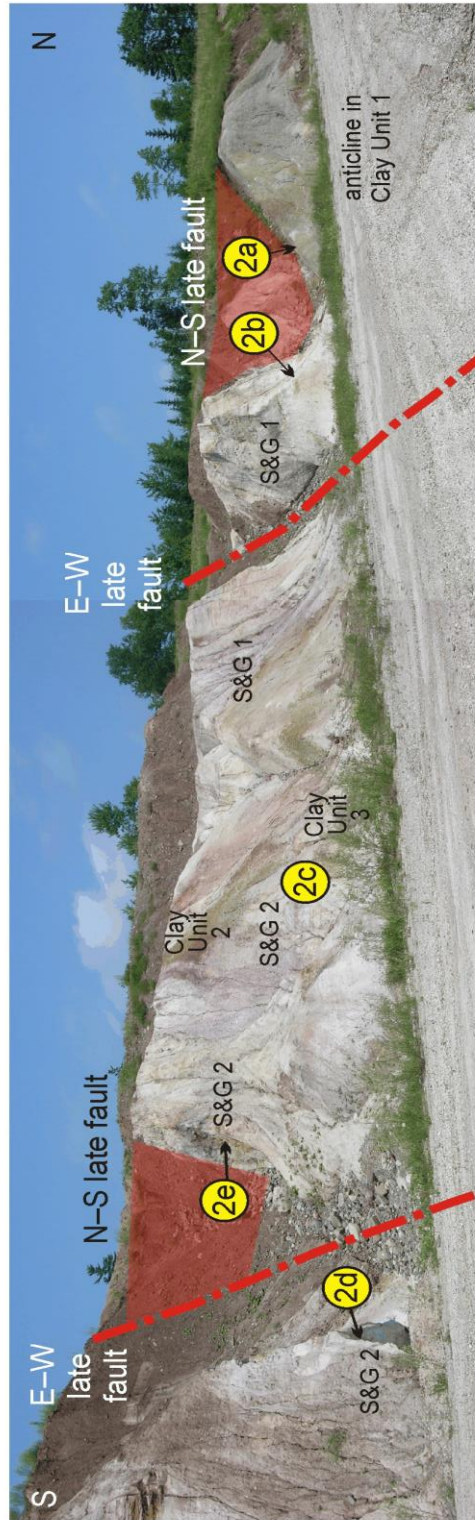


Figure 3.3 Localities on the north wall of West Indian Road Pit.

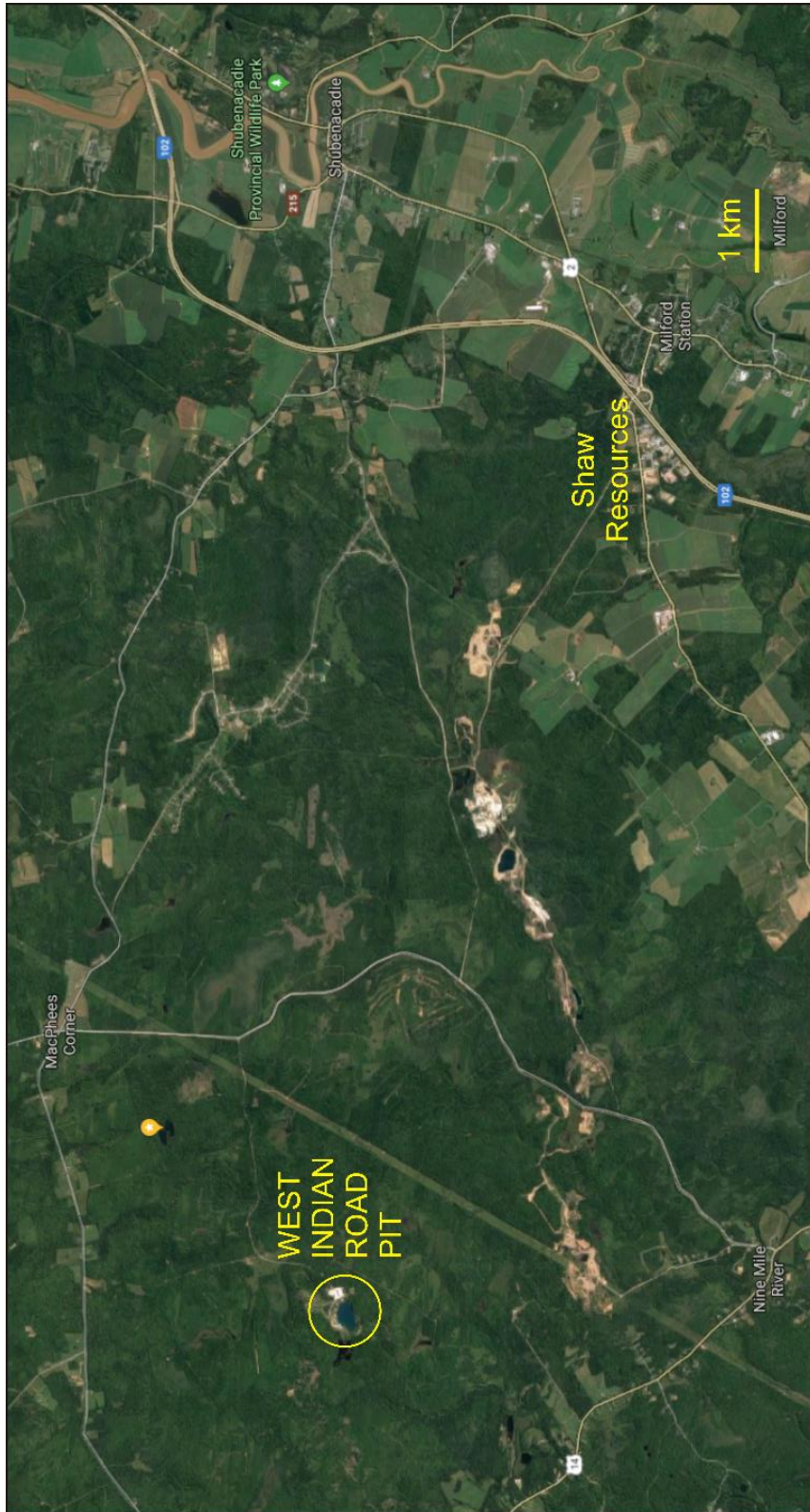


Figure 3.4 General location of the West Indian Road Pit.





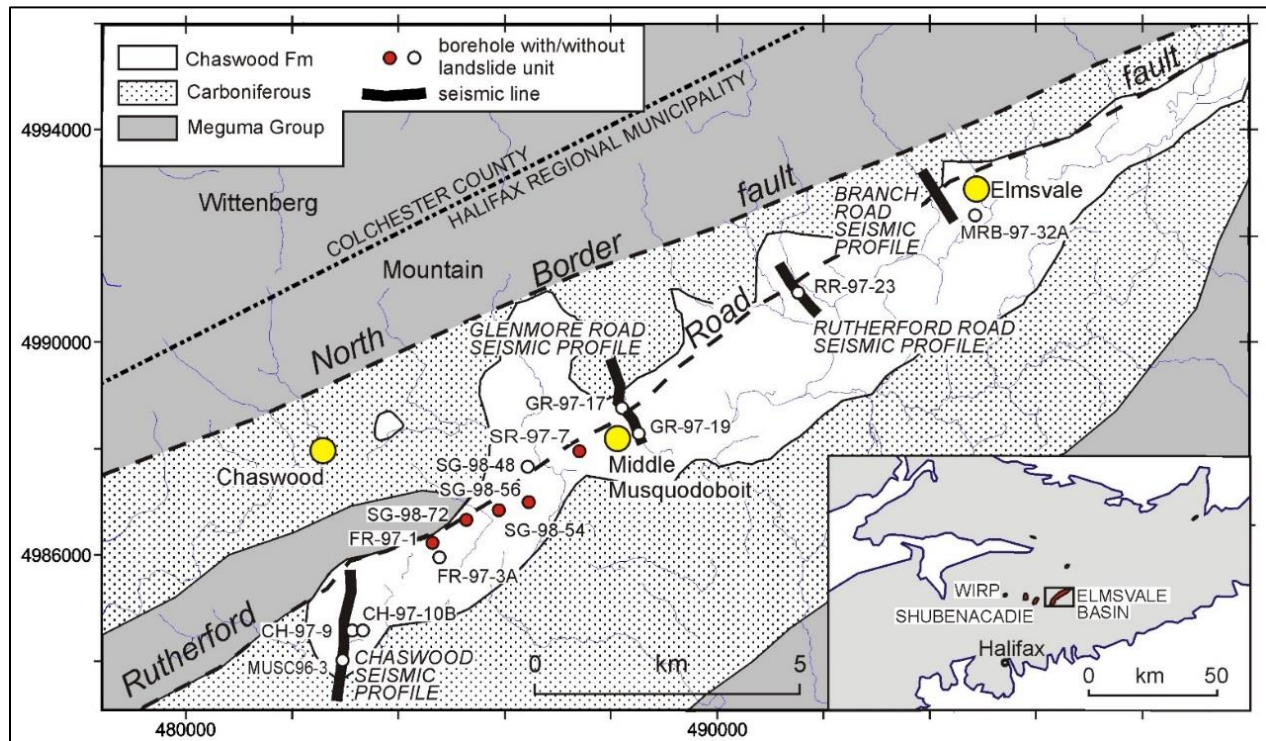
## THE CHASWOOD TYPE SECTION



Figure 3.5 General location of the Chaswood type section.



In the middle of Chaswood, take Meadow Road south towards Elderbank. On descending from the hill about 2 km south of Chaswood, there is a view to the east of the Rutherford Road Fault line in the topography and the type section of the Chaswood Formation from seismic and boreholes across the flat land to the south.



**Figure 3.6 Chaswood Formation in the Elmsvale Basin. Chaswood Seismic Profile (lower-left) is shown in Figure 3.7 (next page).**



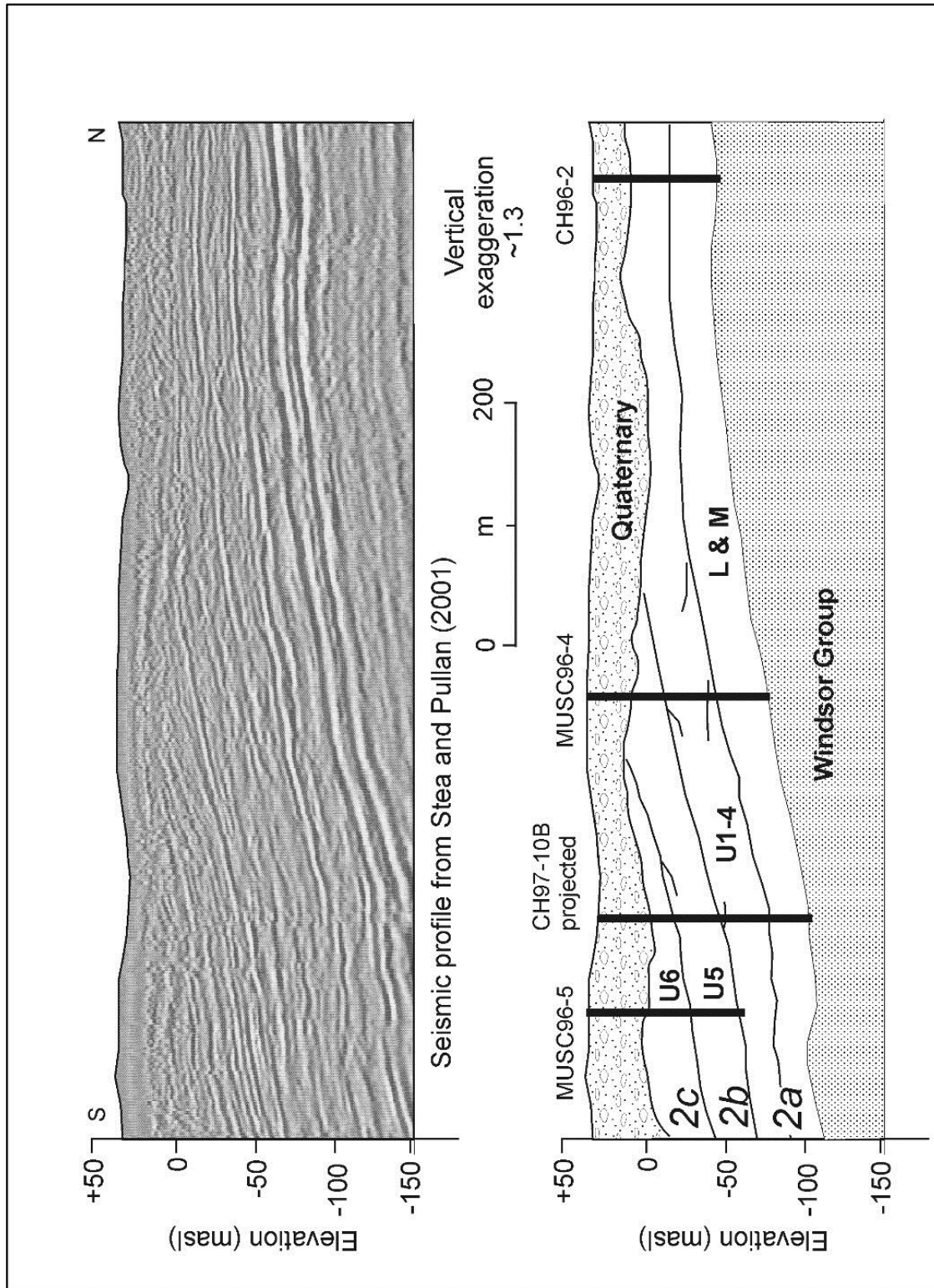


Figure 3.7 Seismic and boreholes at the type section of the Chaswood Formation.



## NOTES



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