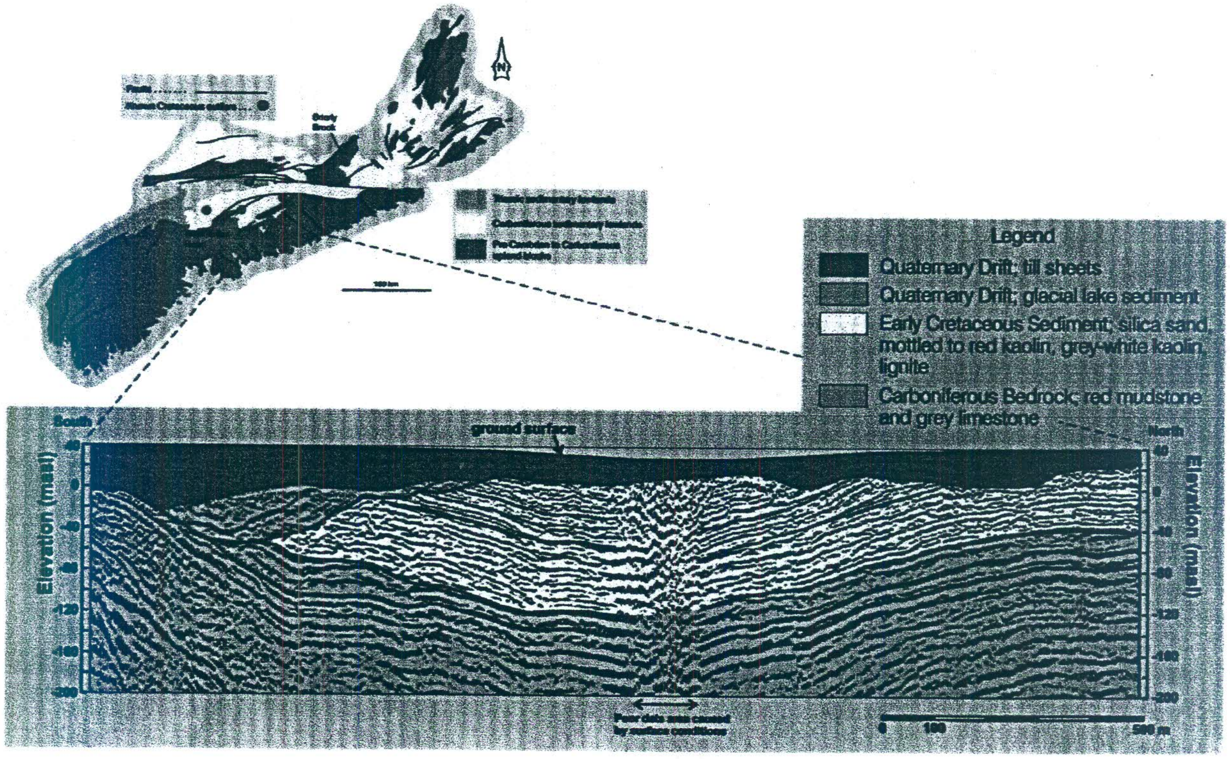
Field Trip 405, Halifax '03

FIELD TRIP GUIDEBOOK

Hidden Cretaceous Basins in Nova Scotia

R.R. Stea, S.E. Pullan, J-P. Gobeil, H.V. Donohoe

Nova Scotia Department of Natural Resources
P.O. Box 698
Halifax, NS
B3J 2T9



THE GEOLOGICAL SOCIETY OF AMERICA

Atlantic Geoscience Society

Northeastern Section, The Geological Society of America
Atlantic Geoscience Society
Joint Meeting
Halifax, 2003

with

Eastern Section American Association of Petroleum Geologists (AAPG)
Council on Undergraduate Research (CUR), Geoscience Division
Society of Economic Geologists (SEG)

Department of Earth Sciences
Dalhousie University
Halifax, Nova Scotia, Canada
B3H 3J5

ISBN 0-9683988-7-1
AGS Special Publication Number 19

Hidden Cretaceous basins in Nova Scotia

Geological Society of America (Halifax-2003)

March 20, 21, 2003

Field Guide

Field trip Leaders
R. R. Stea
S. E. Pullan
J-P. Gobeil
H. V. Donohoe

Itinerary

Day 1 (March 30 th)

Time	**Event**
8:30	**Muster at front foyer, Westin Hotel**
9:30-10:30	**West Indian Quarry (Stop 1)**
11:00-12:00	**Shubenacadie clay pit (Stop 2)**
12:00-12:30	**Lunch**
1:00-1:30	**Chaswood (Stop 3)**
1:45-2:30	**Sibley Road (Stop 4)**
3:15-4:15	**Branch Road (Stop 5)**
5:00-5:30	**Belmont (Stop 6)**
6:00	**Arrive at Motel, Truro.**

Day 2 (March 31)

8:30	**Leave Motel**
9:30-11.00	**Arrive at Clark Head (Stop 1)**
11:30-12:30	**Museum Tour (Fundy Geological Museum)**
13:30-1:30	**Lunch**

Trip ends. Drive back to Halifax. Arrive ~4:00 pm.

Introduction

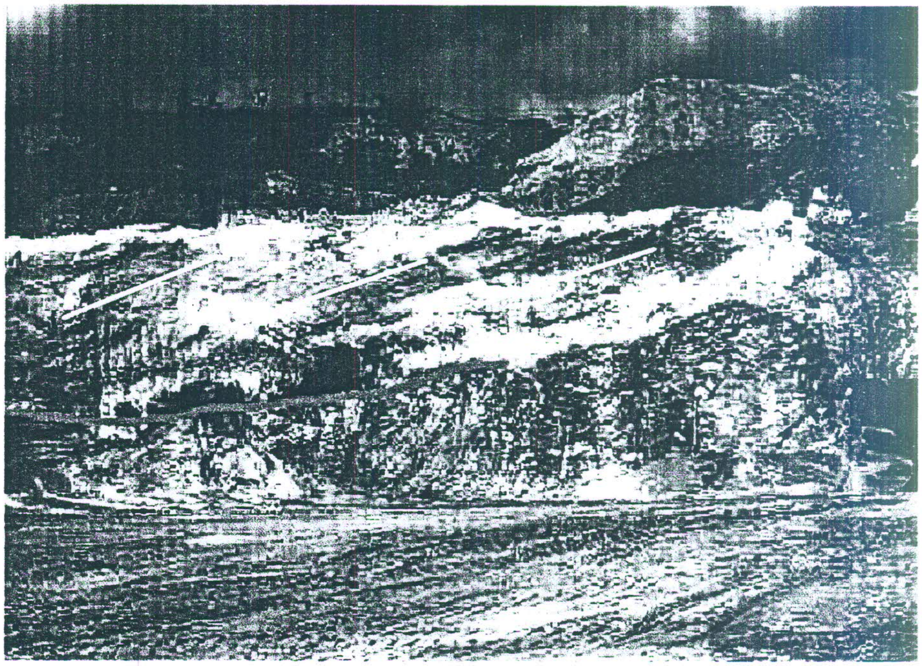
Buried under a thick blanket of glacial drift in the Carboniferous and Triassic basins of Nova Scotia are the remains of formerly vast deposits of unconsolidated, quartz-rich sand, kaolinitic clay and lignite (Faribault 1899; Ries and Keele 1911; Stevenson 1959; Lin 1971; Fowler 1972; Dickie 1986; Figs. 1, 2). Stevenson (1959) first established an Early Cretaceous age for these unique deposits which have long been mined for refractory clay, aggregate and glass-sand (Fowler, 1972). A 3-D mapping program initiated in 1992 by the Nova Scotia Department of Natural Resources (NSDNR) and the Geological Survey of Canada (GSC) further defined the extent and stratigraphy of these Cretaceous deposits in central Nova Scotia. As this mapping program progressed it became apparent that small outliers poking up through the drift were the "tip of the iceberg", and subsequently larger "hidden" basins were defined through drilling and reflection seismic techniques. In these basins kaolin deposits with potential for use in the paper industry were discovered (Finck et al., 1994, 1995; Stea et al. 1996; Pullan et al. 1997; Stea et al. 1997). A local company (KAOCLAY inc.) was formed to evaluate the kaolin deposits, and they undertook an ambitious seismic and drilling program (eg. Gillis, 1998). We will be looking at some of the industry data on the field trip.

Ongoing studies on these Cretaceous deposits are being led by Georgia Pe-Piper of St. Mary's University funded through the Sable Offshore Energy Project (SOEP) and NSERC. The purpose of this project is to further examine the stratigraphy and provenance of these deposits in order to construct a regional paleogeographic model of the Early Cretaceous linking the onshore fluvial deposits with the deltaic marine oil and gas reservoir systems offshore. The Sable Island gas fields are principally in sandy reservoirs of the offshore deltaic Mississauga Formation equivalent in age the terrestrial Early Cretaceous Chaswood Formation which we will be looking at on this trip.

The itinerary will take us across the Shubenacadie and Musquodoboit River valleys in the Carboniferous lowlands of central Nova Scotia, and then over to the Bay of Fundy. (Figs. 1, 2, 3). The Shubenacadie and Musquodoboit valleys are underlain by Lower to Upper Carboniferous strata composed of marine evaporites, including gypsum, anhydrite and salt, as well as carbonates and grey and red siliclastic rocks. These are divided into the Horton, Windsor and Mabou Groups of the Shubenacadie and Musquodoboit Basins (Giles and Boehner, 1982). We will then cut across a prong of Cambro-Ordovician metasedimentary rocks forming a low relief highland, then make our way towards a major terrane boundary, the Cobequid-Chedabucto Fault System, which divides the Avalon and Meguma terranes (Keppie, 2000), and the Cobequid Highlands from the lowlands of the Minas Basin and Bay of Fundy (Figs. 1, 2).

During this trip we will look at the some of the "iceberg tips" of the Early Cretaceous and attempt to piece together the sedimentary environments and paleogeography of the Early Cretaceous, as well as focus on the Cretaceous tectonic events that formed the hidden basins and resulted in the present Nova Scotia landscape. On day 2 we will look at a classic bedrock section on the Bay of Fundy (weather permitting!) showing deformation of Triassic strata along the Cobequid-Chedabucto Fault System.

Fig. 1 Field trip stop locations and geology



Channel sand with lateral accretion? beds over silty-clay overbank facies, West Indian Road Quarry

Stop 1. West Indian Road Quarry

Leaders: J-P Gobeil and R. R. Stea

Purpose: To look at the best exposed section of Late Mesozoic sediments in Nova Scotia

Introduction

On the Scotian Shelf, Lower Cretaceous deltaic sandstone reservoirs are being exploited for gas and explored for oil. Correlative strata on land, the Chaswood Formation, consist of silica sand and quartz-rich gravel associated with kaolinite-rich clay beds. It outcrops in a few pits from central Nova Scotia to Cape Breton Island (Figs. 2, 3). The best exposure is the West Indian Road pit, near Shubenacadie, where silica sand and quartz-rich gravel are intercalated with three major clay units, and occur in a fault-bounded sedimentary basin. The age of the West Indian Road sands and clays have not as yet been determined although the unconsolidated nature of the deposit and the unusual quartz arenite lithology imply a correlation with Early Cretaceous (Valanginian-Albian) quartz sand deposits elsewhere in the province (Dickie, 1986).

The Cretaceous sediments exhibit distinct fining-upward cycles, starting with erosional lower contacts, then well-rounded cobble-gravel grading upwards into a coarse-medium sand and finally mottled silty clay. Stripping operations in 1997 exposed a vertical face of Cretaceous sediments showing a succession of cut and fill channels 2-20m in width, infilled with gravel-sand dominated facies (Fig. 1). White clay "balls" were found within the basal gravelly-sand facies within these channels. Zones of Fe-cemented gravel-sand were found at the contact between channels and lower clay deposits.

Quartz is the most abundant mineral in the sands accounting for >98% of all minerals observed. The grains range in shape from angular to subrounded, exhibit poor roundness sorting and consist of strongly undulose single and composite types. Kaolinitic clay and muscovite are major constituents in silty clay units. Feldspar is a rare constituent of the sand facies comprising <1%. Gypsum was present in gravelly-sand units as brown, rod-shaped, brittle grains concentrated in the finer fractions.

Stratigraphy

The stratigraphy of the pit can be subdivided into three fine grained units, (clay units 1-3) and two coarse-grained clastic units (sand and gravel units 1-2; Figs. 4, 5). Clay Unit 1, at the base of the pit, consists principally of a dark grey clay, rich in organic matter, showing a few zones with charcoal and/or lignite fragments and pyrite nodules. This suggests a calm, closed and oxygen-reduced environment of deposition (eg. Calder et al., 1998). The occurrence of charcoal within the clay and the lack of marine fossils suggest a subaerial environment. Clay Units 2 and 3 are oxidized, variegated silty clay units. All clay units show color changes and mottling, especially near the top of fining-upward sequences which are interpreted as paleosols. These factors combined suggest a lacustrine or marsh environment as the first stage of deposition of the Chaswood Formation in the study area. Clay Units 2 and 3 are interpreted as floodplain deposits in a braided river system.

Silica-rich sand and gravel units within the West Indian Road pit typically show a light grey color, locally masked by strong orange, pink or purple staining. Grain size varies from very fine to very coarse sand to pebble gravel. These sands show a few percent of muscovite and traces of heavy minerals. A great variety of sedimentary structures such as trough cross-bedding, planar cross-bedding, parallel lamination, ripples and grading were observed in the sand and gravel units (Fig. 6). Lithofacies successions show a general fining upward sequence, composed of several superposed small fining upward sequences and a mean paleoflow direction to the SE. These sand and gravel units are interpreted to have been deposited in a braided river environment (Fig. 7).

Two major fault systems define a graben type structure for the West Indian Road pit deposit (Figs 4, 5). Syn-sedimentary deformation features such as major angular unconformities, bed thickness changes and coarsening of correlative facies across faults are preserved in the sand and gravel units, and suggest underlying bedrock block movements. Although they show evidence of syn-depositional motions, the lack of basement clasts in the sediments and the mean paleoflow direction at high angle to the fault systems suggest post-depositional motions along the major faults as well. Faulting on subsidiary fault systems could be related to movement on the major Cobequid-Chedabucto Fault, ~100 km away to the north (Fig. 2).

A provenance study of the sand and gravel units was conducted using heavy minerals assemblages, pebble petrography and 40Ar/39Ar dating of detrital muscovite grains. The most abundant heavy minerals are rutile, altered ilmenite, zircon, and tourmaline, and in lesser amount staurolite and andalusite. The concentration of these resistant minerals suggests recycling. The gravel fraction of the sand and gravel units is mainly vein quartz and vein quartz with tourmaline. However, it has a low but significant percentage of exotic pebbles such as granite, diorite, and rhyolite. Petrographic study of the pebbles has suggested a Cobequid Highlands source for the granite, diorite and rhyolite pebbles, and Horton and Pictou groups sedimentary source rocks for the quartz-arenite, subarkose, arkose, mudstone to muddy sandstone, and conglomerate pebbles (Figs 1, 2). The 374 Ma 40Ar-39Ar age for the muscovite grains suggests a primarily South Mountain Batholith origin. The grains are interpreted to be recycled from the surrounding Horton Group muscovite-bearing sandstones.

Stop 2: Shubenacadie Outlier

Leaders: R. R. Stea and S. E. Pullan

Purpose: Look at a pit exposing lignitic organic sediment and discuss the exploration seismic and drilling programs.

Introduction

Cretaceous strata in Nova Scotia have been known and described for many years, but until recently a formal stratigraphic nomenclature had not been introduced. The lithic and seismic stratigraphic data collected during the 1992-1995 drilling and seismic project have enabled the authors to formalize elements of the stratigraphy including the definition of type sections for the Chaswood Formation (Stea et al. 1996, 1997; Stea and Pullan, 2001). In central Nova Scotia the Chaswood Formation is confined to narrow, steep-sided basins within the Musquodoboit and Shubenacadie valleys (Fig. 3). The largest area of subcropping Cretaceous sediment is a NE-SW basin confined to the Musquodoboit valley (herein termed the "Elmsvale" basin) extending for 15 km along the Musquodoboit Valley with a maximum width of 4 km. The Elmsvale Basin consists of two wide parts, joined by a narrow neck near Middle Musquodoboit. A smaller basin, termed the "Shubenacadie Outlier" is located near the village of Shubenacadie. The pit which we will be visiting is in the village of Shubenacadie and is currently mined for refractory kaolinitic clay by Shaw Resources Ltd. for use in a brick plant, a few miles down the road.

Stratigraphy

The margins of a faulted, Cretaceous sedimentary basin in the Shubenacadie Valley have been defined using 13 drillholes and other stratigraphic databases (Fig. 3). The extent of known Cretaceous deposits has been expanded from the vicinity of the pit to approximately 15 km^2 . Cretaceous sediments are overlain by Quaternary deposits ranging in thickness from 13 m to 80 m. A west to east, cross-basin drillhole transect is shown in Figure 8. Seven unconsolidated lithostratigraphic units were defined that comprise the Early Cretaceous Chaswood Formation and overlying Quaternary sediments. The stratigraphic package is consistent with that described by Dickie and Murphy (1992) for the main Shaw Resources clay pit.

Base:

Upper Windsor(?) limestone bedrock and limestone breccia.

Chaswood Formation:

Lower member: (Unit 1) Black, organic-rich silty clay with associated lignite fragments, (ii) lignite and marcasitic lignite, (iii) dark to light grey silty clay. Individual beds of black clay, grey clay or lignite cannot be correlated between

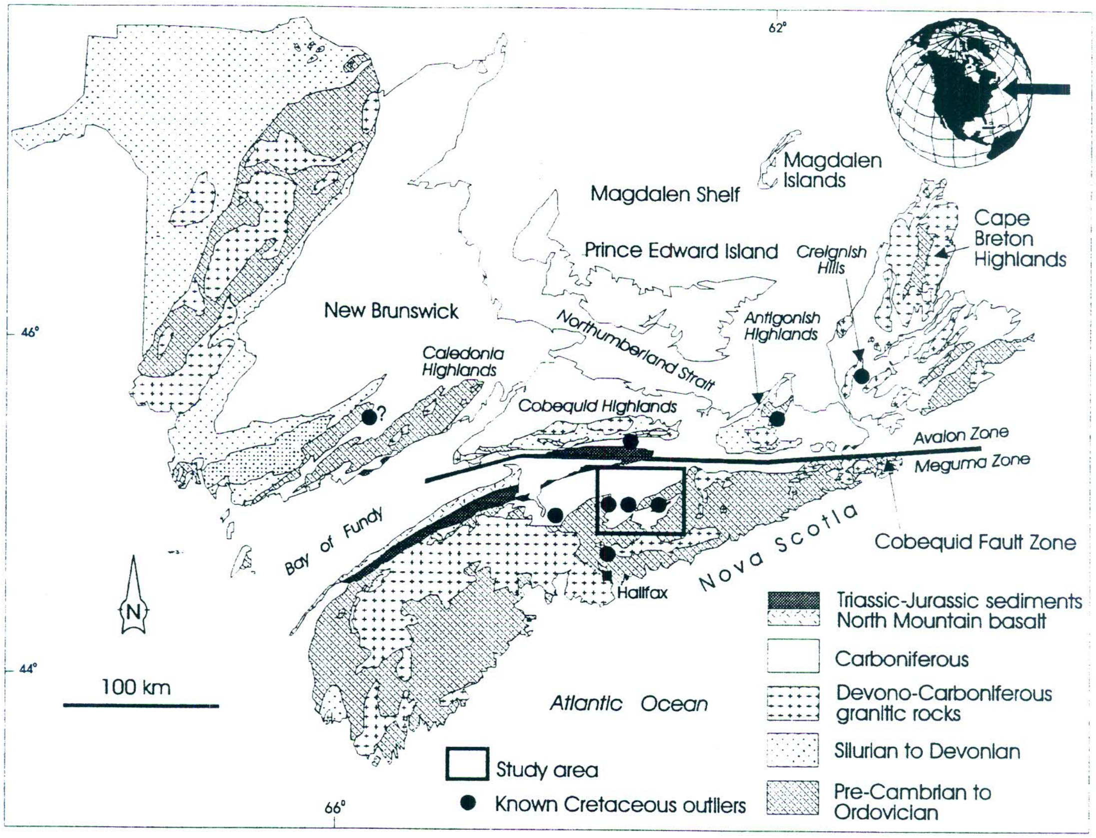


Fig. 2 Generalized geology of Maritime Canada and location of Cretaceous outliers.

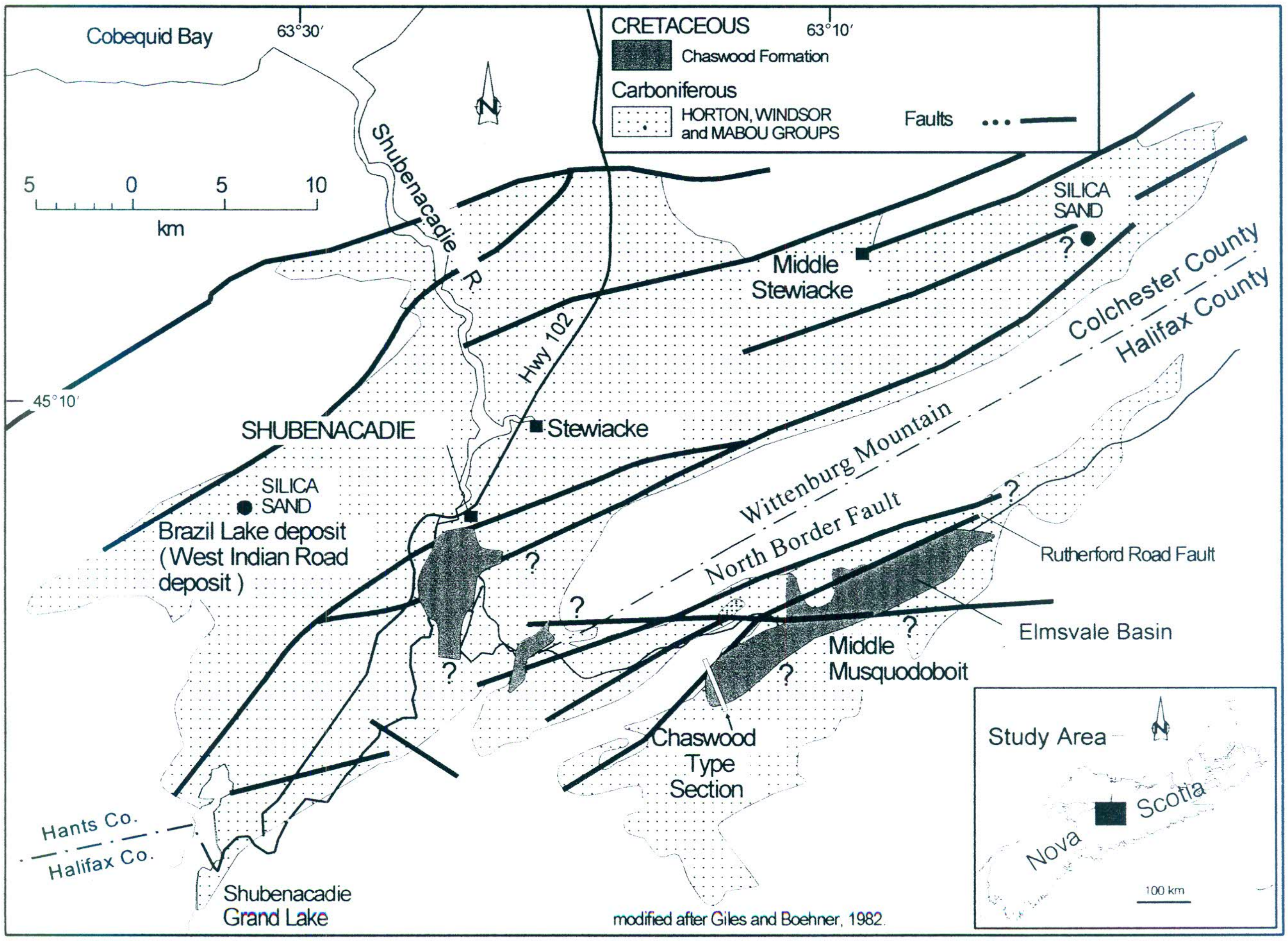


Fig. 3 Detailed map of the Chaswood Formation in central Nova Scotia

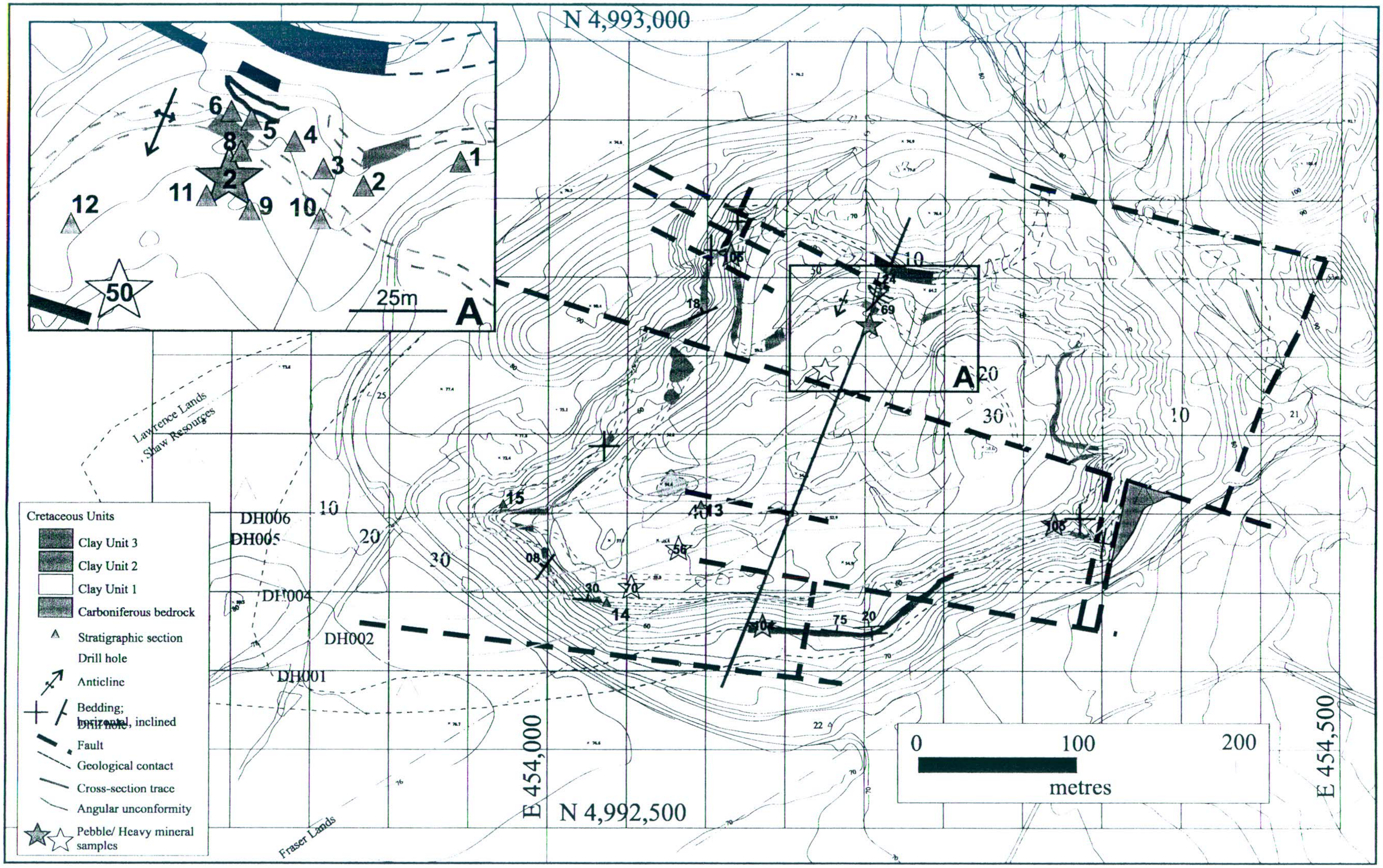


Fig. 4. Geological map of the West Indian Road pit showing the main geological units and faults.

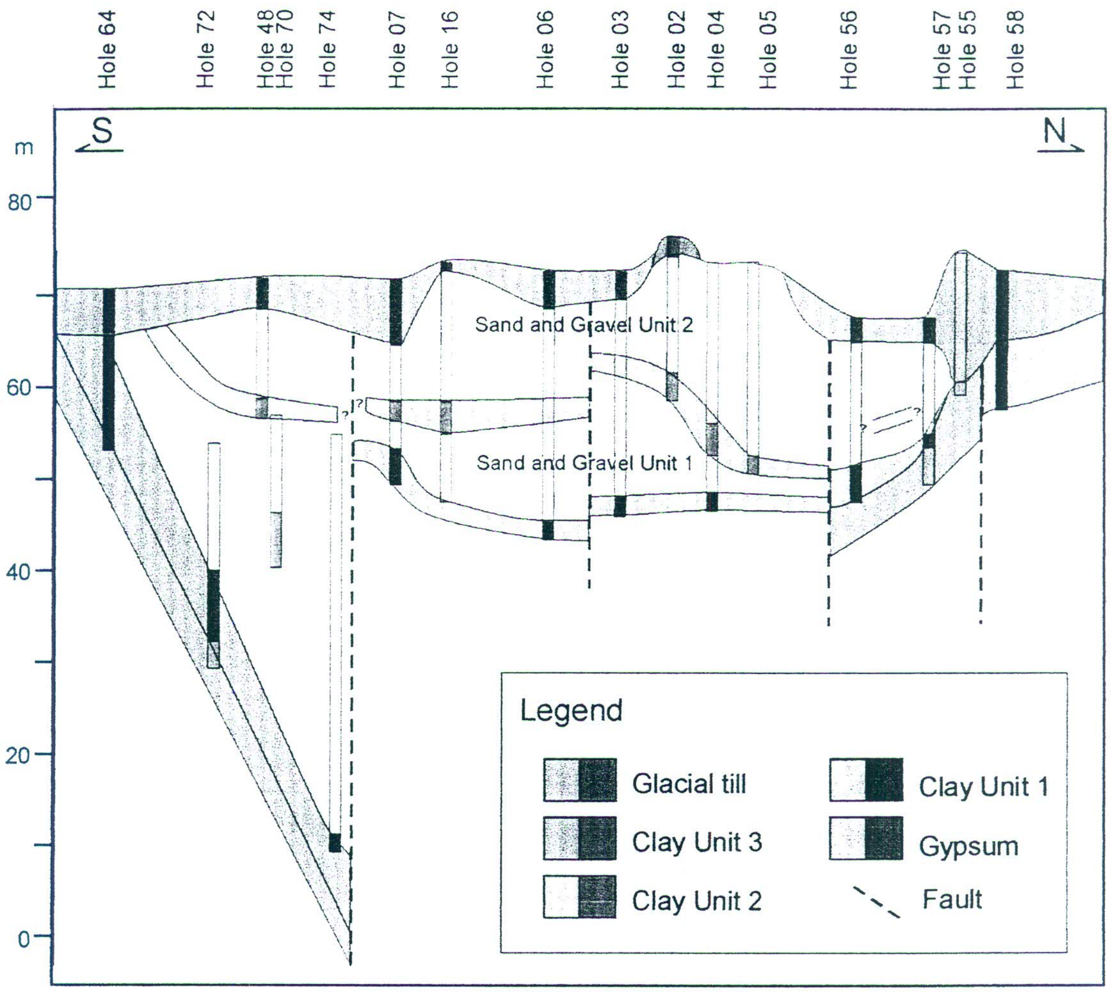


Fig. 5 North-south schematic cross-section of the West Indian Road pit showing the main stratigraphic units of the Chaswood Formation. Note the thickness chnages across mapped faults. Location of section on Fig. 4.

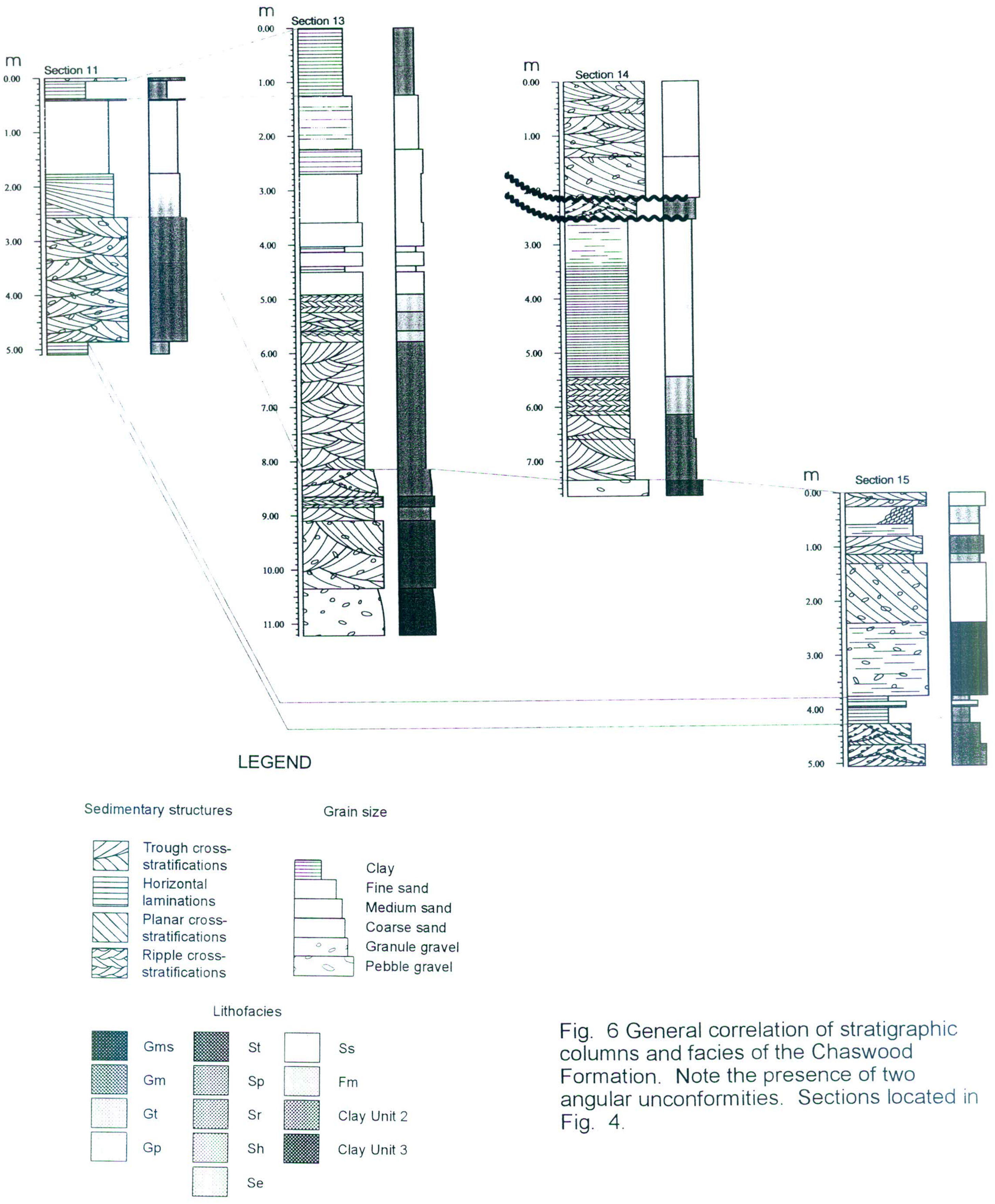


Fig. 6 General correlation of stratigraphic columns and facies of the Chaswood Formation. Note the presence of two angular unconformities. Sections located in Fig. 4.

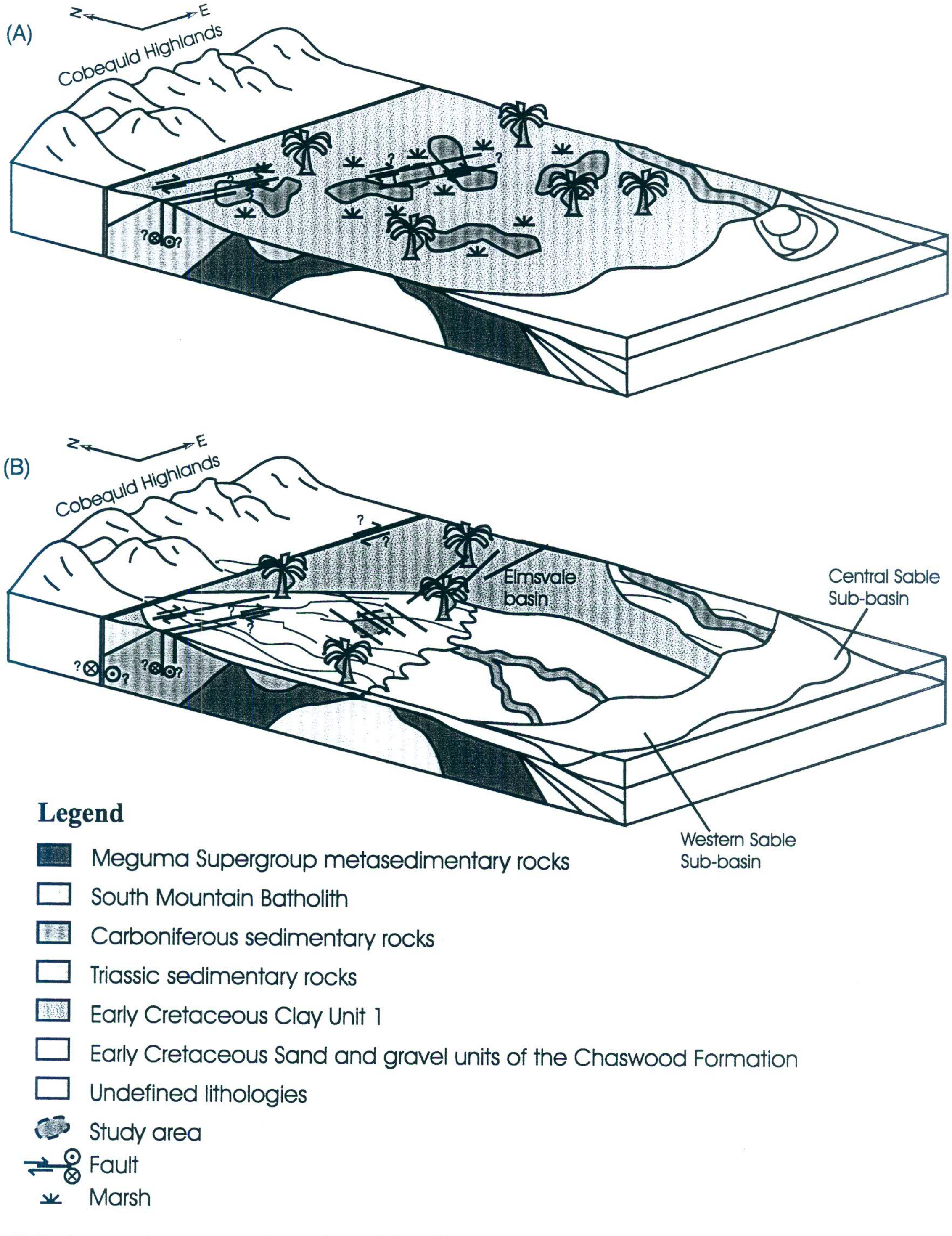


Fig. 7 Paleoenvironmental model of the Chaswood Formation in Early Cretaceous time (A) Deposition of the basal clay unit in a lacustrine-paludal environment. (B) Deposition of the sand and gravel units in a braided river system, flowing northwest to southeastward. crossing the Cobequid Highlands.

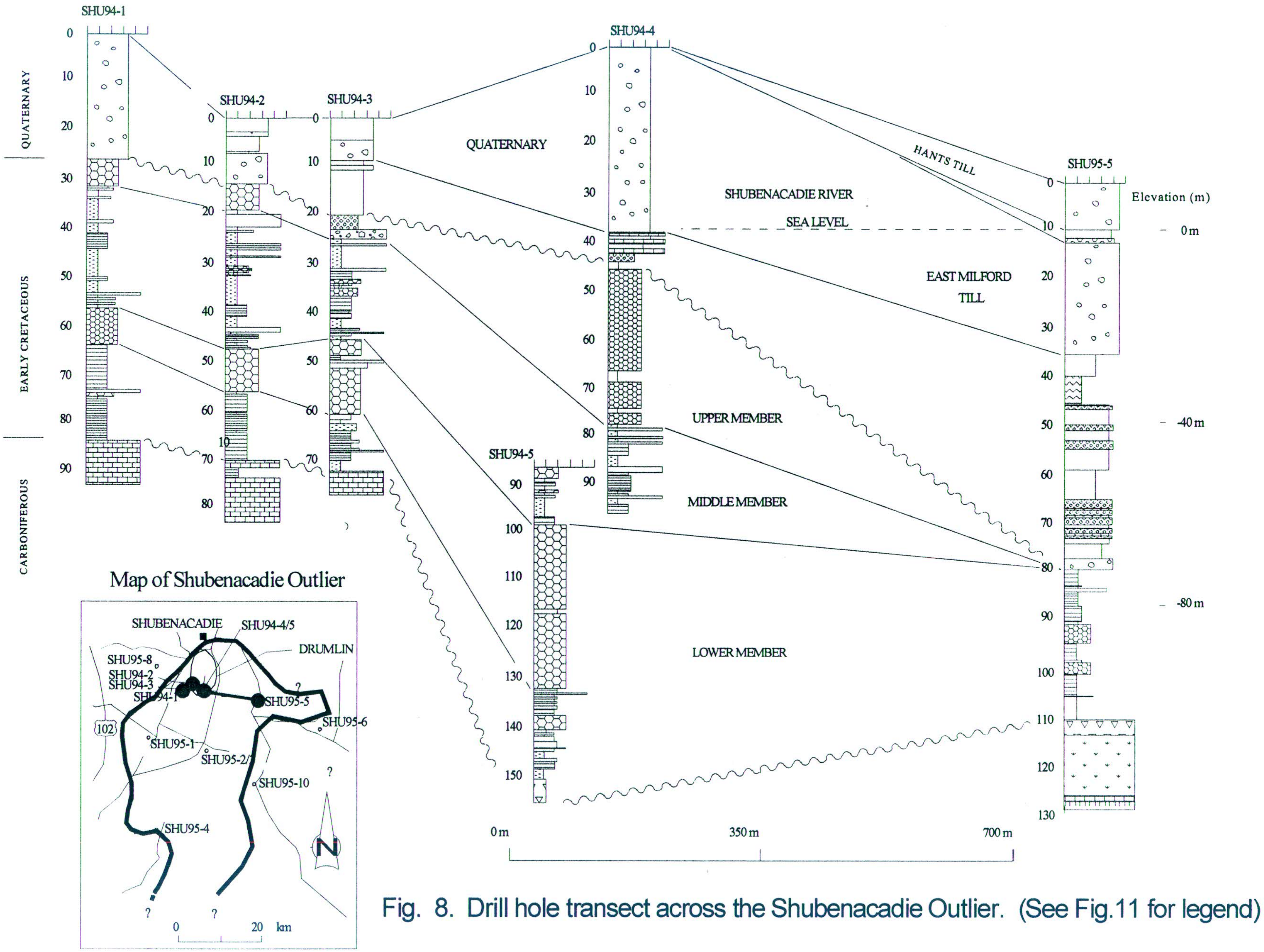


Fig. 8. Drill hole transect across the Shubenacadie Outlier. (See Fig.11 for legend)

drillholes. The term `lignite clay' is used to describe silty clay (based on qualitative observation) that contains visible fragments of organic material and silt- to clay-sized organic material. The black organics impart a dark colour to the silty clay, which varies from black to dark grey (10YR, 2.5Y or 5Y 4/1). Based on visual estimates, grain size of the lignite clay decreases as the percentage of fine-grained organic particles increases. The lignite clay may grade into or abruptly change to lignite breccia, composed of large fragments of lignite (typically up to 50%) in a black, silty clay matrix. The lignite is 'very hard' and scratches a dull reddish-brown. Thin lenses and layers of sand associated with the lignite may be replaced by marcasite.

Unit 2: Medium-to coarse-grained quartz (silica) sand in a white to light grey clay matrix. Opaque minerals are predominantly marcasite, ilmenite and magnetite (G. Dickie, personal communication, 1994). There are zones of gravel sized, well-rounded, quartz pebbles. The actual thickness of these gravel lags could not be estimated due to lack of core recovery. The top of the silica sand unit (Unit 2) strikes 022° and dips 6.5° to the east-southeast. The thickness of the unit is relatively consistent along strike between holes SHU94-1 and -2, but increases down-dip between holes SHU94-2 and -4. Unit 2 pinches out or was eroded between the 1994 drillholes and SHU95-5 (Fig. 8)

Middle Member: Alternating layers of black and grey clay, essentially the same as those described above for Unit 1.

Upper member: Medium- to coarse-grained quartz (silica) sand with minor to trace feldspar and opaque minerals in a white to light grey clay matrix. Unit 4 increases in thickness to the east, between drillholes SHU94-1 AND SHU94-5, but pinches out across the Shubenacadie River at SHU95-5. The bed strikes 143° and dips 4.5° to the northeast based on triangulation of the upper surface of the sand horizon between drillholes SHU94-1 and SHU94-4.

Quaternary sediments:

Unit 5: Matrix-supported grey-brown sandy diamicton, striated pebbles, (East Milford Till)

Unit 6: Alternating beds of poorly-sorted, feldspathic sand, medium and coarse gravel (sandy?) with rounded to subangular volcanic, plutonic, metamorphic and metasedimentary lithologies, and reddish-brown silty clay.

Unit 7: Matrix-supported silty diamicton, reddish-brown, calcareous, striated clasts, Cobequid Highland igneous erratics (Hants Till); sand and gravel zones.

Stratigraphic Summary

Much of the glacial constructional topography of the Shubenacadie Valley near the village of Shubenacadie is underlain by unconsolidated Mesozoic coarse and fine-grained sediments. Figure 9 is a digital terrain model of the region south of the town of Shubenacadie at the location of the Densmore seismic line. It shows the relationships between actual topography and stratigraphy based on the reflection profiles and diamond drill holes. The Mesozoic basin is interpreted as a half-graben structure due to the presence of a thick faulted limestone breccia at the base of drillhole SHU95-10. The NE-trending Meadowvale fault mapped by Giles and Boehner (1982) crosses the east side of the Shubenacadie Valley near drillhole SHU95-10. These faults are post-Carboniferous but their exact age is uncertain (R. J. Boehner, pers. comm, 1996).

Within the Shubenacadie Basin, thick deposits of Quaternary(?) gravel, sand and varved clays underlie the surface drift sheets (Fig. 8). High-resolution reflection seismic surveys conducted across the basin indicate that these deposits have a channel morphology with reflectors pinching out and forming an unconformity against underlying and surrounding Cretaceous sediments. In the vicinity of SHU95-10 a large channel has been carved out of bedrock and infilled with Quaternary fine-grained sediments. At the base of the Quaternary sediments are boulders or blocks of limestone.

The surface Quaternary drift in the Shubenacadie study region is composed of two distinct till units, the Hants and East Milford Tills (Stea et al., 1997). The topography is strongly rolling and the drift is shaped into southward-tapering drumlins. Average drift cover over much of the Shubenacadie Valley is 20 m with a maximum thickness of 50 m on drumlin crests (Fig. 9).

Stop 3: Chaswood Type Section: Another hidden Cretaceous Basin

Leaders: R. R. Stea and S. E. Pullan

Purpose: To discuss the seismic and drilling data in the largest buried Cretaceous basin in Nova Scotia

Introduction

The Elmsvale Basin in the Musquodoboit Valley (Fig. 3) is the largest basin defined during the 1992-1995 drilling and seismic program. Bedrock maps of the area (eg. Fig. 1; Giles and Boehner, 1982) showed a very restricted distribution of Cretaceous deposits based in part on an assumption that the deposits were deposited and preserved in karst depressions associated with the limestone and gypsum facies at the base of the Windsor Group (R. G. Boehner, pers comm, 2003). The coherent sedimentology of the Cretaceous deposits as demonstrated at the West Indian Road quarry, and widespread distribution over Triassic and Carboniferous clastic facies mitigates against a solution collapse origin for these basins.

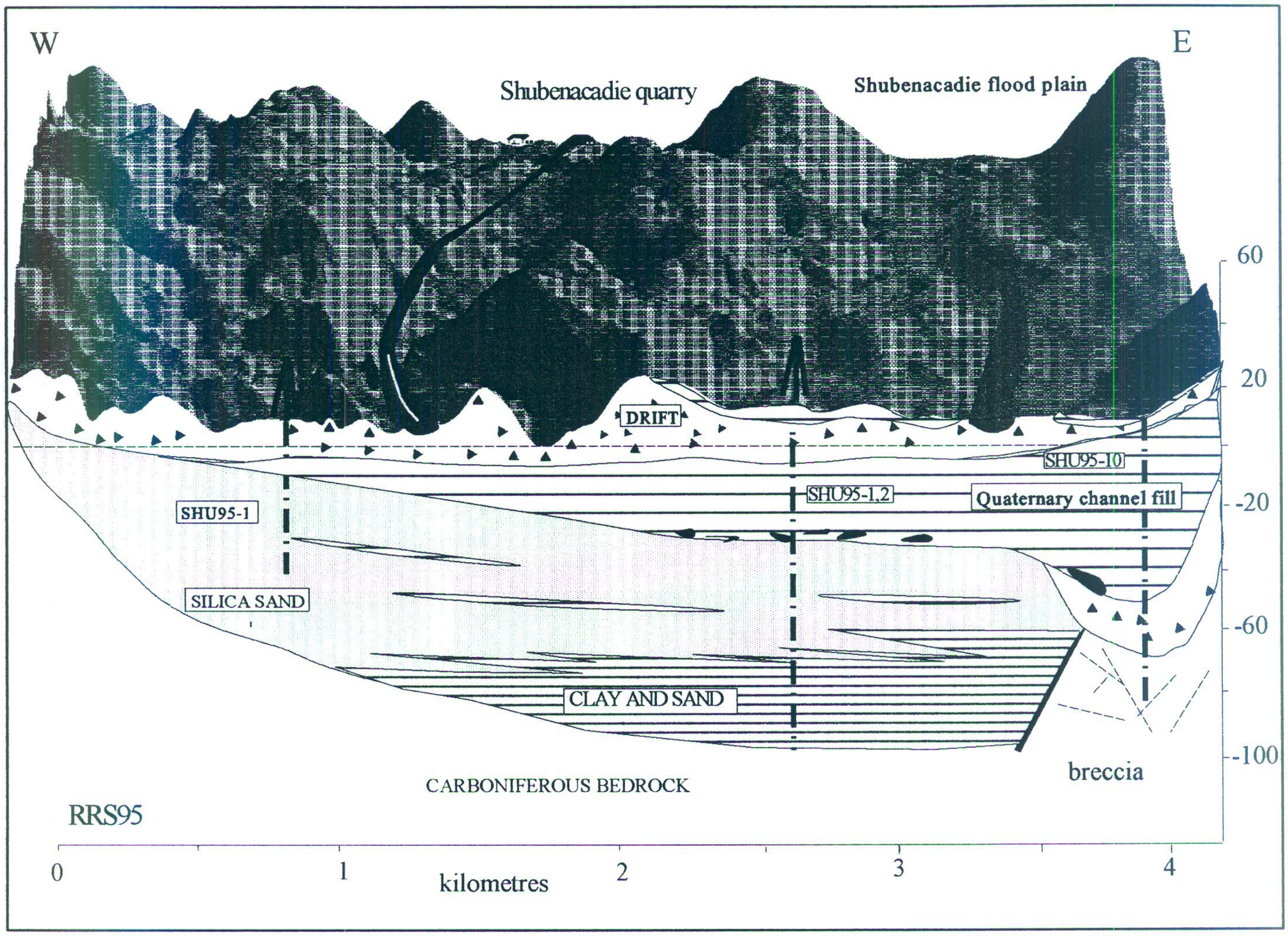


Fig. 9 . Schematic cross section of the Shubenacadie Outlier.

Chaswood Meadows Type Seismic Transect

The Chaswood Meadows seismic line (Fig. 10) is a north-south transverse profile across the western Elmsvale basin (Fig. 3), approximately 2 km in length. Figure 10 has been converted from two-way travel time to depth using velocity information obtained from the seismic records themselves and from a downhole seismic survey (Stea and Pullan, 2001). Poor data were obtained in swampy surface conditions in the centre of the line (area of low surface topography).

The section clearly shows many strong subsurface reflections which outline:

1. A large, roughly symmetrical basin, 2 km+ wide and 130 m deep filled with unconsolidated Cretaceous sediments.

2. An asymmetrical, smaller channel at the south end of the line, cut into Cretaceous sediments, approximately 0.5 km wide and 50 m deep, filled with Quaternary sediments.

A drillhole transect (Fig. 11), provides abundant ground truth for the interpretation of the seismic section and confirms that this profile delineates a valley infilled with Cretaceous sediments. A series of continuous, high amplitude reflections characterize Sequence 1 (Carboniferous bedrock), though the bedrock surface itself can be difficult to identify clearly. Data from the downhole seismic survey in MUSC96-4 suggest that this is due to the interference of reflections from stratal surfaces within the upper Carboniferous sequence. Impedance contrasts between unconsolidated, low velocity, breccia and mudstone units and hard limestone and mineralized (pyrite-calcite) layers within Sequence 1 produce large amplitude reflections to depths of 10's of metres below the Cretaceous-Carboniferous contact.

Sequence 2a is a thick (>50 m) unit defined by discontinuous, low-moderate amplitude reflections with some evidence of local structural variations. Weak and sporadic reflections within Sequence 2a suggest that it is more massive than overlying Cretaceous deposits The base of Sequence 2b is defined by a prominent continuous, high amplitude reflection. Between MUSC96-4 and 96-5 there are indications that the contact between Sequence 2a and 2b is an unconformity. Though not clearly imaged in Figure 10 an unconformity in the middle of the Cretaceous sequence is well documented on other seismic profiles in the Elmsvale Basin (eg. Fig. 12). These reflections are from lignite and/or lignitic clay layers in the middle member of the Chaswood Formation which are characterized by large reflection coefficients. A distinctive calcareous-cemented sand also produces a high-amplitude reflection within Sequence 3 (Fig. 11). The contrast between higher amplitude reflections in Sequence 2b and the more transparent Sequence 2c suggests that the Cretaceous sediments become sandier and less organic higher in the section. The upper member of the Chaswood Formation defined in the basin drillhole transect (Fig. 11) is correlative with Sequence 2c in the seismic section (Fig. 10).

Northward-dipping reflections of Sequences 1 and 2 are truncated by an asymmetric valley at the south end of the section filled with Quaternary deposits (Fig. 10). Within the valley two seismic sequences are observed; a lower sequence with hummocky facies (3a, likely coarse-grained sediments), and an upper sequence, largely reflection-free (3b, likely fine-grained

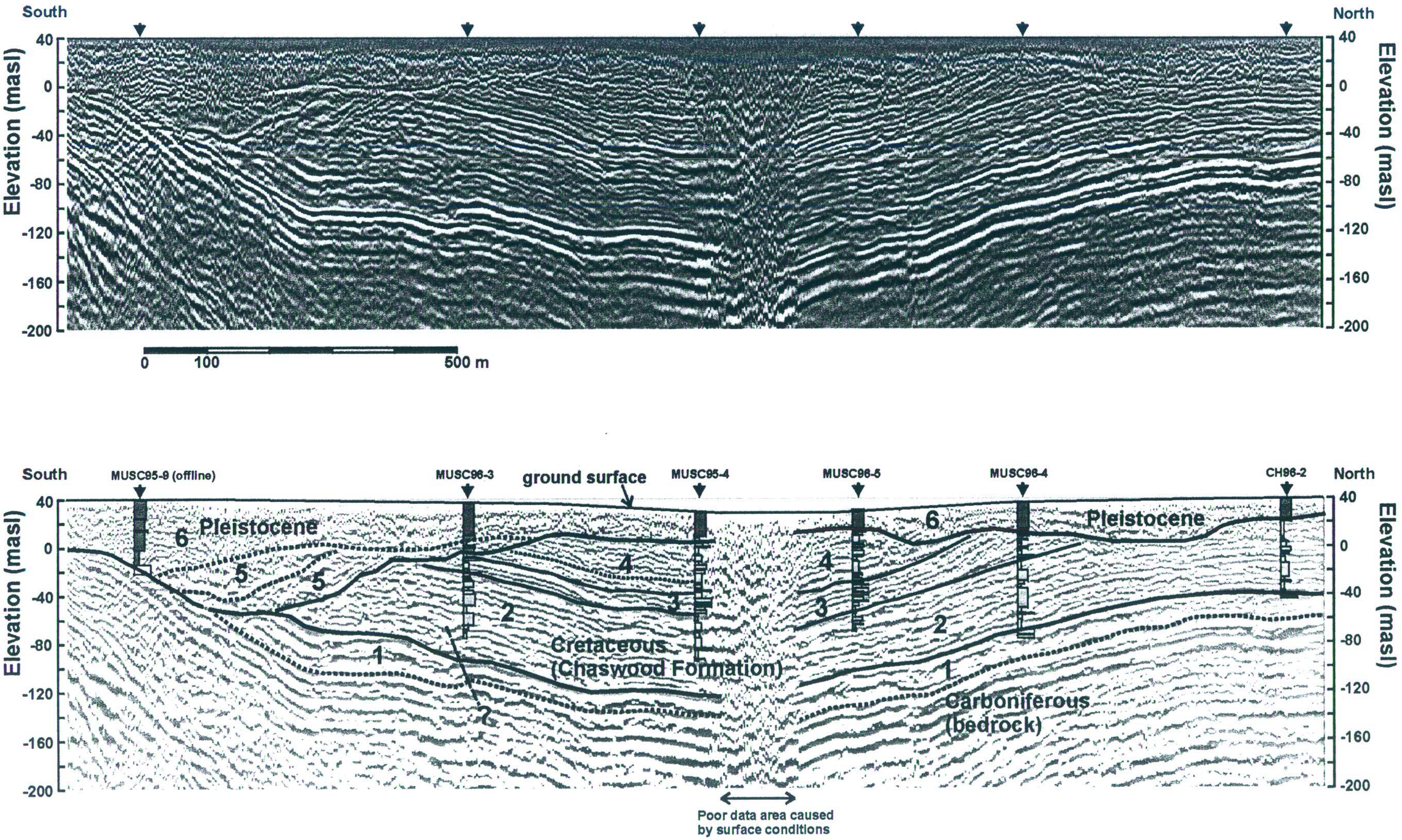


Fig. 10 Reflection seismic profile across the western part of the Elmsvale Basin

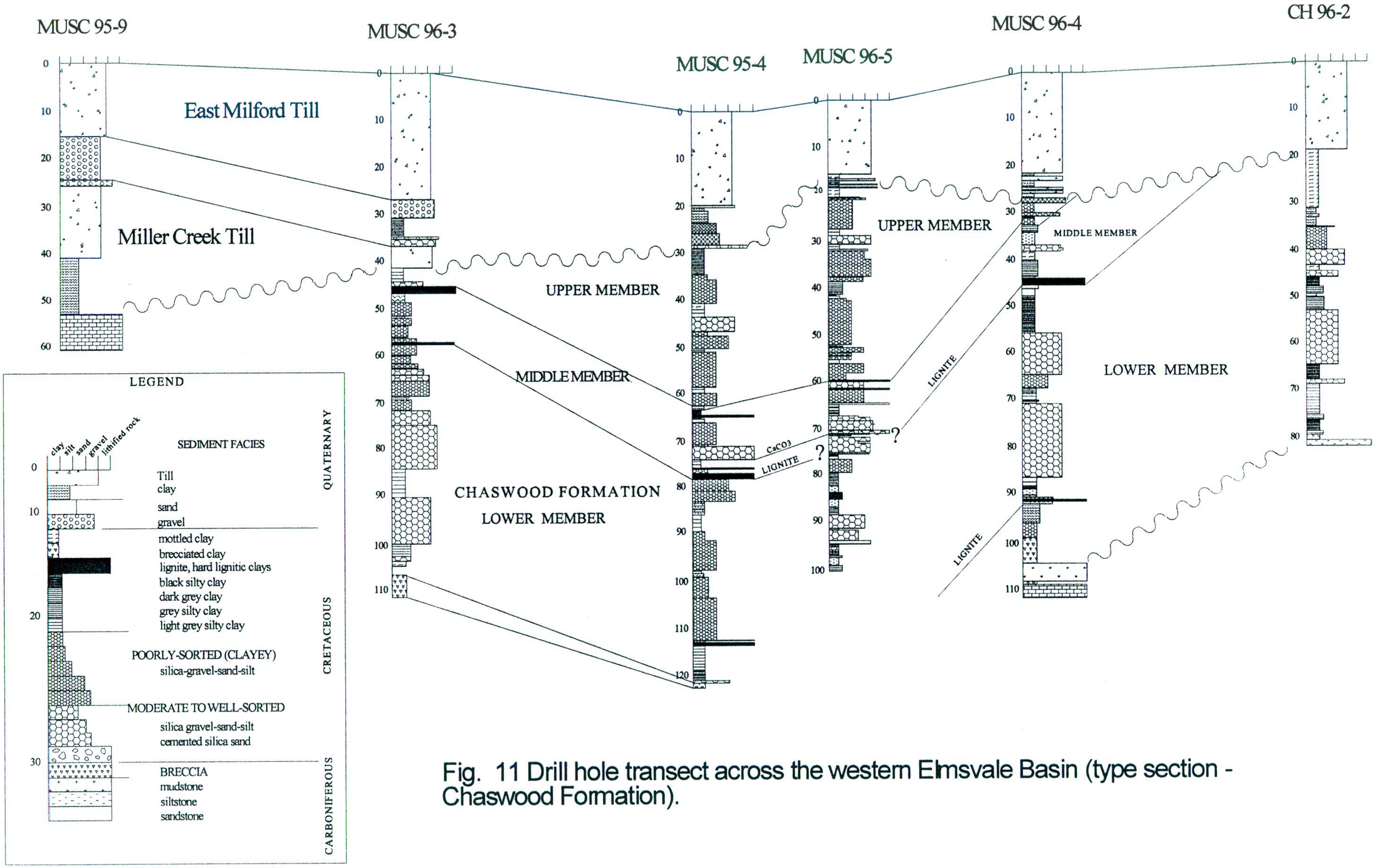


Fig. 11 Drill hole transect across the western Elmsvale Basin (type section - Chaswood Formation).

deposits). A low-moderate amplitude, gently-dipping, reflection truncates the valley fill. It marks the base of Sequence 3c on the north and south ends of the profile. In the centre of the line, the Pleistocene-Cretaceous contact is close to the upper limit of reflection definition on the seismic profile. The resolution of these data are not high enough to differentiate lithological variations within Sequence 3c, though some borehole logs suggest that there are glaciolacustrine sediments underlying the surface till sheets which make up most of the sequence (Fig. 11).

Stop 4: Sibley Road drilling (KAOCLAY)

Leaders: R. R. Stea

Purpose: To look at some exposures of Chaswood Formation silica sand and kaolin

Introduction

Kaoclay Inc. was formed soon after the drilling results of the1992-1995 mapping project in central N.S. were made public (Stea et al., 1996). The company raised money to explore for kaolin and silica sand over most of Nova Scotia. Kaoclay Inc. geologists identified several areas of interest within the Elmsvale Basin area and chose this area for initial detailed evaluation (Gillis, 1998; Gillis and Stea, 2000). The Sibley Road area covers approximately 3 km^2, and is located just west of the village of Middle Musquodoboit (Fig. 2). This area of Mesozoic sediments is on the up-thrown side of the Rutherford Road Fault Zone (Stea and Pullan, 1998; 2001), south of which lies the thickest Mesozoic section. The silica sand and kaolin deposits are within 4m of the surface at this locality and we may be able to see a silica mine in the first stages of development!

Initial results from this detailed exploration program were very encouraging and resulted in the identification of a consistent stratigraphic package, referred to by Kaoclay geologists as the Sibley Road unit. This unit includes light-grey kaolinitic clay and sand of economic interest. Beneficiation of initial test pit and drill core samples returned encouraging results with a number of samples meeting brightness specifications established by the paper industry (Gillis and Stea, 2000)

Stop 5: Rutherford Road Fault Zone (Mid-Cretaceous)

Leaders: R. R. Stea and S. E. Pullan

Purpose: To look at the type seismic section of the Rutherford Road Fault Zone

Introduction

At this stop we will look at seismic profiles across the northern flank of the Elmsvale Basin.

Each of the transects reveal a fault zone that separates thick Cretaceous basin sediments to the south (>150 m) and a thin Cretaceous veneer over Carboniferous bedrock to the north. The sediments in the fault zone are folded and faulted with dip-slip movement as much as ~100 m. The recognition of significant fault displacement of these Cretaceous sediments adds a new chapter to the tectonic history of Maritime Canada which has been poorly documented after the Triassic rifting episode.

Stratigraphy and structure

The Glenmore Road seismic transect (Fig. 12) runs approximately north-south through the Village of Middle Musquodoboit a few kilometres southwest of Rutherford Road (Fig. 2). The thick basin sediments to the south are essentially undisturbed until the "hinge line", where they are abruptly tilted and show sharp breaks. North of the area of deformation, herein termed the "fault zone" most of the Cretaceous sediments have been removed. The bedrock surface has an apparent vertical offset of more than 100 m across a horizontal distance of 200 m (350-550 m, Fig. 12). This fault zone is termed the Rutherford Road Fault Zone (RRFZ). Boehner (1977) mapped a fault system called the North Border Fault along the southern margin of Wittenburg Mountain which may be an equivalent to the Rutherford Road Fault Zone (RRFZ). Horne et al. (2000) emphasized the compressional nature of the tectonics which formed the boundary fault between older Paleozoic rocks of the highlands and basinal Mesozoic sediments.

At the Glenmore Road transect, south of the RRFZ coherent reflections within the Cretaceous sequence dip northward to -140 m (i.e. metres above sea level; sea level is approximately 50-60 m below ground surface in the area), whereas north of the discontinuity acoustic basement lies at -20 m or shallower. Diamond-drill hole GR-97-19, approximately 350 m south of the RRFZ, intersected Carboniferous siltstone bedrock at 85 m depth (-35 m). Above bedrock, the core consists of 70 m of unconsolidated sand and clay (Chaswood Formation), overlain by 15 m of glacial drift. In this borehole, the lower 20 m (-15 to -35 m) of Chaswood Formation consisted predominantly of silica sand, while the upper section (35 to -15 m) was predominantly clay. North of the RRFZ, GR-97-17 intersected Carboniferous siltstone at a depth of 65 m (-5m). This was overlain by Cretaceous Chaswood Formation strata (predominantly sand) between 23 and 65 m depth (~37m to -5 m), and 23 m of surficial glacial drift. As along the Rutherford Road section (Fig. 7), the deepest part of the Cretaceous basin on Glenmore Road (Fig. 6) is just south of the RRFZ (at 400 m), where the basin reaches a maximum thickness of 170m. Defining the basin are three seismic sequences (1-3). Sequence 1 consists of northward-dipping, high amplitude reflections with the uppermost reflection interpreted to be the contact between Carboniferous bedrock (C) and overlying Mesozoic/Cenozoic unconsolidated sediments. In this profile, the Cretaceous deposits (Sequence 2) south of the RRFZ are very clearly differentiated into two sequences (2a and 2b). The lower sequence (2a) is characterized by relatively low-amplitude reflections draped on the underlying bedrock surface. A drill hole (GR-97-19) in this unit shows thick sections of silica sand, interbedded with thin silty-clay horizons, characteristic of the lower member of the Chaswood Formation (Stea et al. 1997). In contrast, sequence 2b consists of relatively flat-lying, higher-amplitude reflections; with the lower reflections clearly truncated against the 2a/2b unit boundary (Fig. 12). These high amplitude reflections may indicate lignite horizons, which are common in the middle member of the Chaswood Formation. Sequence 3

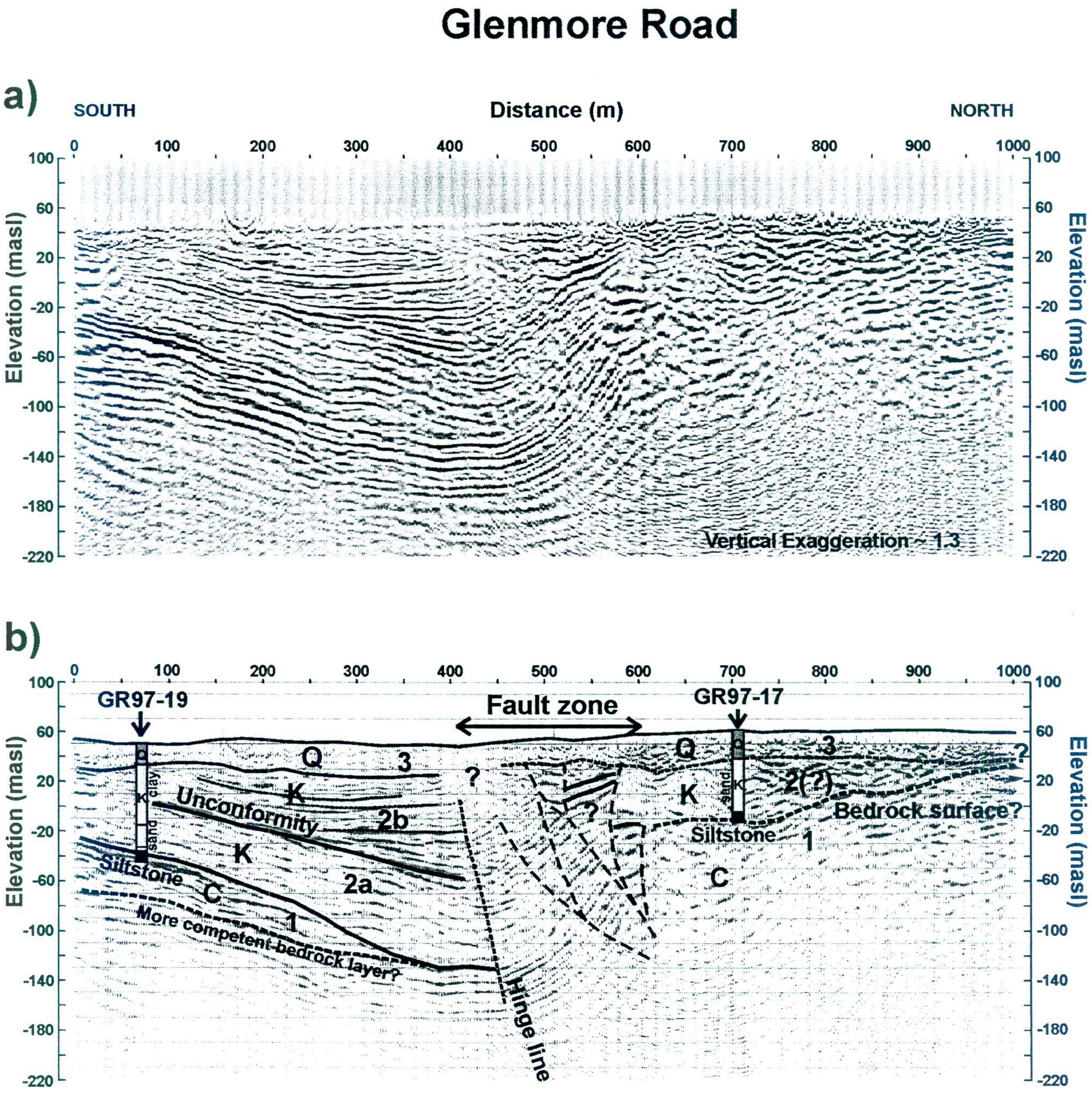


Fig. 12. Reflection seismic profile across the Rutherford Road Fault Zone in the Glenmore Road area.

corresponds to glacial drift cover, but because of the shallow depths involved, it is not well resolved on these reflection profiles.

Stop 6: Belmont occurrence: Early Cretaceous over Triassic strata

Leader: R. R. Stea

Purpose: To look at an exposure of Cretaceous strata over Triassic sandstone

This occurrence reveals silica sand (undated) overlying Triassic sandstone. The significance of this locality is that the deposit is not found over Windsor Group strata and therefore its preservation cannot be attributed to active sinkholes in evaporitic strata. At about 30 m elevation, the deposit is well above present sea-levels that have been prevalent for the last 10 Ma, and occurrences in Cape Breton have been found at elevations as high as 150 m. Coeval, terrestrial Cretaceous deposits within the faulted Elmsvale Basin are as low as -60 m suggesting a complex tectonic history of uplift and subsidence.

We will examine a drillhole from the deposit done recently as part of the SOEP-NSERC research project.

Deformation of the Chaswood Formation and regional tectonics

A number of authors have previously noted deformation of Early Cretaceous sediments (Guernsey 1927; Fowler 1972; Stea and Fowler 1981; Akande and Zentilli 1984; Davies et al., 1984). The seismic transects described in this study delineate a major subsurface structural discontinuity, the Rutherford Road Fault Zone, on the northern side of the Elmsvale Basin (Fig. 6). The RRFZ at the Rutherford Road section (Stea and Pullan, 2001) is interpreted as a fault-related fold with north-side up movement. At the Branch and Glenmore Road sections (Fig.12) a steep reverse fault is indicated, although the sense of movement is not clear. The Elmsvale Basin at least, appears to be a half-graben, with most of the movement on the north side. Faulting and fault-related folding of the Chaswood Formation is post Early Cretaceous, the inferred age of the Chaswood Formation (Stea et al. 1997). It is difficult to determine whether some of the deformation was contiguous with deposition (ie. growth fault), as much sediment has been removed from the upthrown side of the fault. A pronounced unconformity within the Chaswood Formation indicates the start of regional uplift, a precursor to more intense tectonism later manifested in faulting and folding of the Cretaceous sediments. At the West Indian Road reference section (Gobeil, 2002) there is evidence that at some stage tectonism was contiguous with deposition.

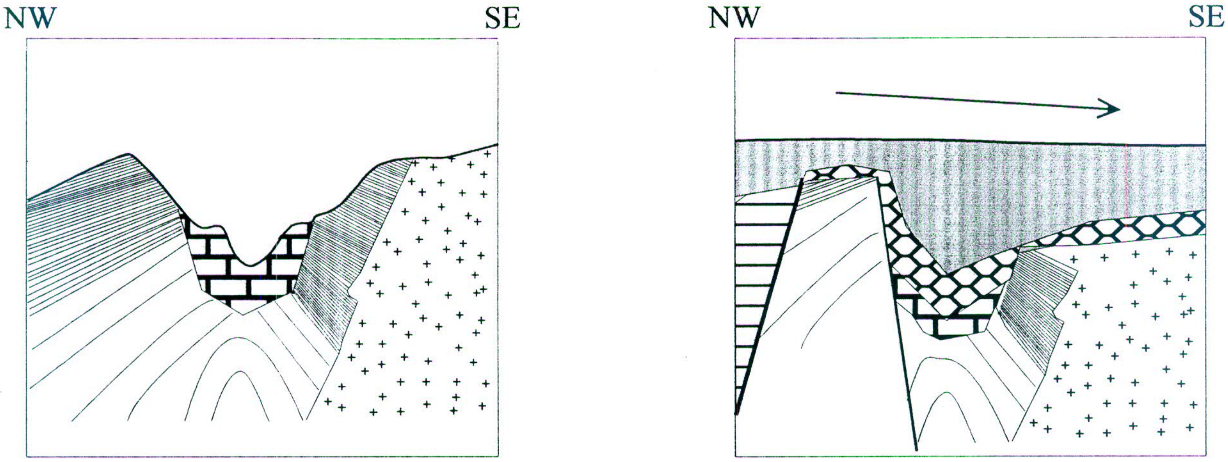
It appears that all the known Cretaceous outliers are associated with faults, some of which are major thrust faults which separate lowland Carboniferous basins from highlands and basement rocks. The implication of these studies is that the Cretaceous strata define a minimum age of movement on these major fault systems in Nova Scotia. Post-Jurassic reverse faulting and folding of Triassic rocks in the Bay of Fundy are well documented, but the minimum age of deformation could not be established locally (Swift et al. 1967; Greenough 1995; Withjack et al., 1995; Wade et al., 1996). Greenough (1995, p. 586) linked the Fundy Basin deformation with the Orpheus Graben offshore, a continuation of the Cobequid Fault system (Fig. 1). In the Orpheus Graben evidence of Early-Mid Cretaceous diastrophism includes volcanism and a major mid-Cretaceous (Avalon) unconformity (King et al. 1970; Jansa and Pe-Piper 1988). Pe-Piper et al. (1994) invoked reactivation of transform faults defining the Orpheus Graben during the final separation of Iberia from the Grand Banks. This tectonic event may have been propagated throughout pre-existing NE-trending subsidiary faults of the Cobequid Chedabucto Fault such as the Rutherford Road Fault. According to fission-track analysis by Roden-Tice et al. (1998), Mid-Cretaceous fault-related uplift and exhumation occurred as far south as the Adirondacks. She further suggests that the rift-grabens are Early Cretaceous rather than Triassic. White et al. (2000) has proposed that uplift and erosion throughout the late Mesozoic in eastern North America was caused by plate migration over the Great Meteor hotspot. Regional uplift and subsidence is implicated through the Mesozoic-Cenozoic in Nova Scotia because of the evidence for exhumation of a thick cover of Cretaceous strata, the profound unconformity between Early Cretaceous and Quaternary sediments and the elevation of terrestrial outliers well below present sea-level.

Landscape evolution of Nova Scotia : a structural-exhumation hypothesis

The prevailing notion about landscape development in eastern Canada is that the topography is largely erosional, formed by selective removal of weaker rocks after a Tertiary regional uplift, and only slightly modified by glaciation (Goldthwait 1924; Lin 1970; Mathews, 1975; Roland, 1982, Grant, 1994). This erosional paradigm of landscape formation can be challenged, based on the new understanding of Cretaceous tectonics. The Elmsvale Basin records this sequence of events:

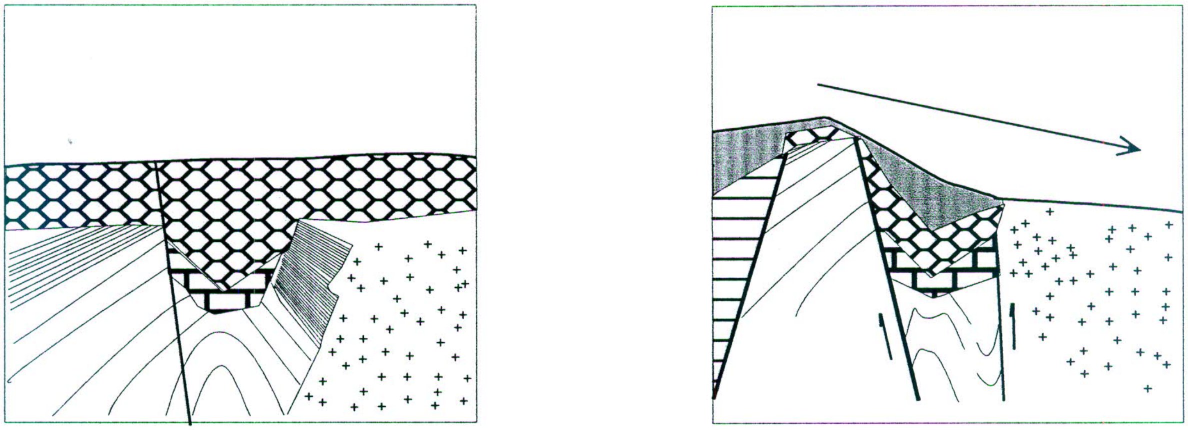
1. Early Cretaceous deposition of the Chaswood Formation ~140-110 Ma (age range).
2. Post-Early Cretaceous faulting-regional uplift and erosion ~110-80 Ma.
3. Mesozoic-Tertiary exhumation/erosion/non-deposition 80 Ma - 2 Ma.
4. Quaternary deposition.

Goldthwait (1924, p. 59) first recognized that the key to the erosional model is the age of the basin fill. If valley formation predates the oldest valley fill, it would imply a pre-Cretaceous age for many Nova Scotia valleys. The recognition of young faults (Mesozoic-Cenozoic) of basin margin tectonics was used by Stea and Pullan (2001) to develop the argument that most of the present topography is a Mesozoic structural remnant. Recent discoveries of fault-bounded Cretaceous outliers in Antigonish (Stea, et al., 1995) and Sussex, New Brunswick (R. Fensome, pers. comm. 2003) attest to the regional nature of this tectonic event. Another important observation is the elevation of the Diogenes Brook outlier in Cape Breton, between 100 and 130 m above sea level. The preservation of this elevated Cretaceous outlier for ~100 ma suggests a substantial cover



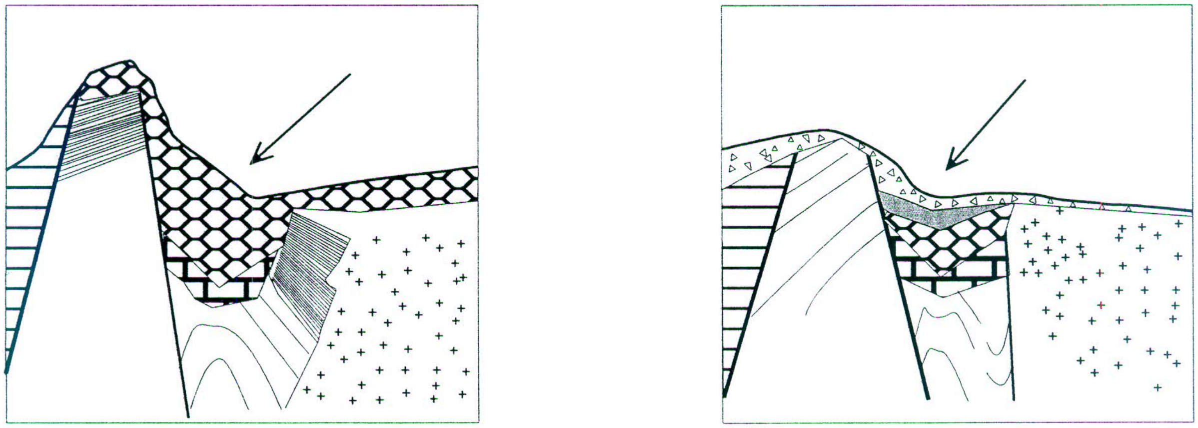
(A) Early Carboniferous

(D) Early -Mid Cretaceous



(B) Late Carboniferous

(E) Mid-Cretaceous-Tertiary



(C) Triassic-Jurassic

(F) Quaternary

Fig. 13. Evolution of landscapes in Nova Scotia from Carboniferous to Quaternary

of post-Early Cretaceous sediment and it is significant that the highest outlier is also apparently the oldest (Dickie, 1986). The inference drawn from this observation is that much more cover had been stripped from this region than at other localities. The lack of a marine or terrestrial Late-Cretaceous and Tertiary sedimentary record implies regional uplift and erosion throughout these time periods and is further evidence of exhumation of a substantial volume of Mesozoic sediment (Stea and Pullan, 2001). Evidence from thermal maturation studies of lignites (Hacquebard, 1984; Stea et al.,1996; Calder et al., 1998) suggests a cover of between 600m and 1 km, as does forward modelling of apatite fission track data (Arne et al., 1989). Wade et al. (1996) estimated a Mesozoic cover of about 2 km based on thermal maturation indices in the Fundy Basin. Alternatively, Grist and Zentilli (2000) explained Mesozoic thermal effects with an anomalous heat flow possibly related to tectonic events or greenhouse climates rather than burial. Another method of determining cover thickness is to use an average Appalachian denudation rate (10-20 m/ma; Denny, 1982; Stanford-Scott et al. 2002) and multiply that rate by the duration of the erosional hiatus (~100 ma). This admittedly crude estimate produces a cover thickness of 1-2 km, in line with that determined by the thermal maturation of lignites.

The structural-exhumation hypothesis infers that Carboniferous and Mesozoic sediment was eroded from the tops of Mesozoic horst blocks such as Wittenburg Mountain, made of resistant older rocks (Fig. 13). If it is correct then a flux of reworked Early-Cretaceous palynomorphs, should be recorded in the offshore basins in the thick pile of overlying recycled Mid-Late Cretaceous and perhaps Tertiary sediments. Early Cretaceous sediments were "hidden" or preserved in the structural valleys adjacent to the horsts, whereas Mesozoic and Cenozoic erosion largely exhumed the pre-Carboniferous accordant upland "peneplanes" across Nova Scotia (Giles 1981). In this way aligned cross valley "wind-gaps" in Nova Scotia may reflect consequent former north-south superposed stream drainage patterns according to the tenets of classical geomorphic cycle theory

Day 2: Stop 1: Clark Head Fault Zone

Leader: H. V. Donohoe

Purpose: To look at a classic exposure of faulted Triassic-Jurassic rocks along the Cobequid-Chedabucto Fault System.

Introduction

The Clarke Head area exposes the boundary between older rocks and the Mesozoic succession (Fig. 14). The Triassic–Jurassic rocks are located in a small graben bounded by east-northeast trending faults. From Clarke Head at the east end to the boundary fault, a distance of 2 km, the cliffs expose a magnificent example of a chaotic zone interpreted as a fault zone and a megabreccia boundary between the Avalon and Meguma terranes by Donohoe and Wallace (1985) and Gibbons et al. (1996). A note on safety. Stay away from the cliffs. The chaotic nature of this

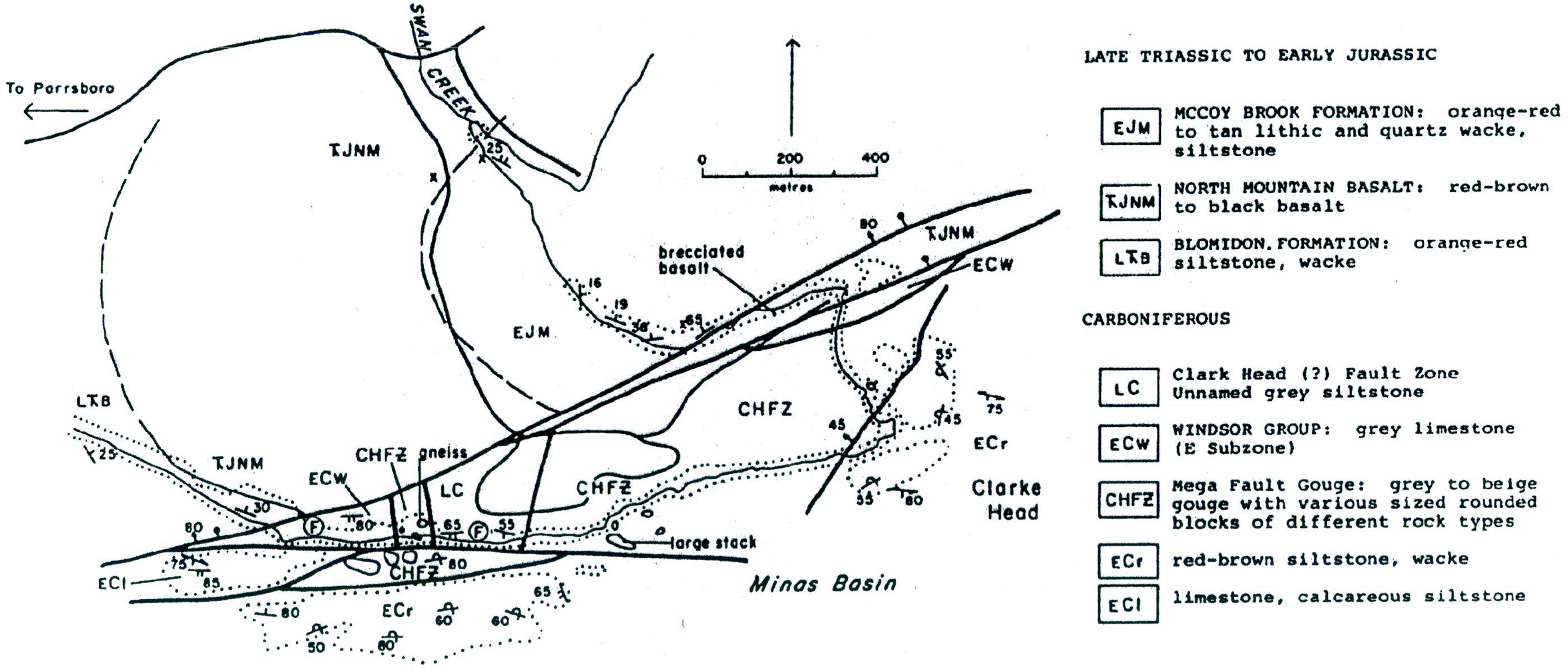


Fig. 14. Geological map of the Clark Head area, Nova Scotia.

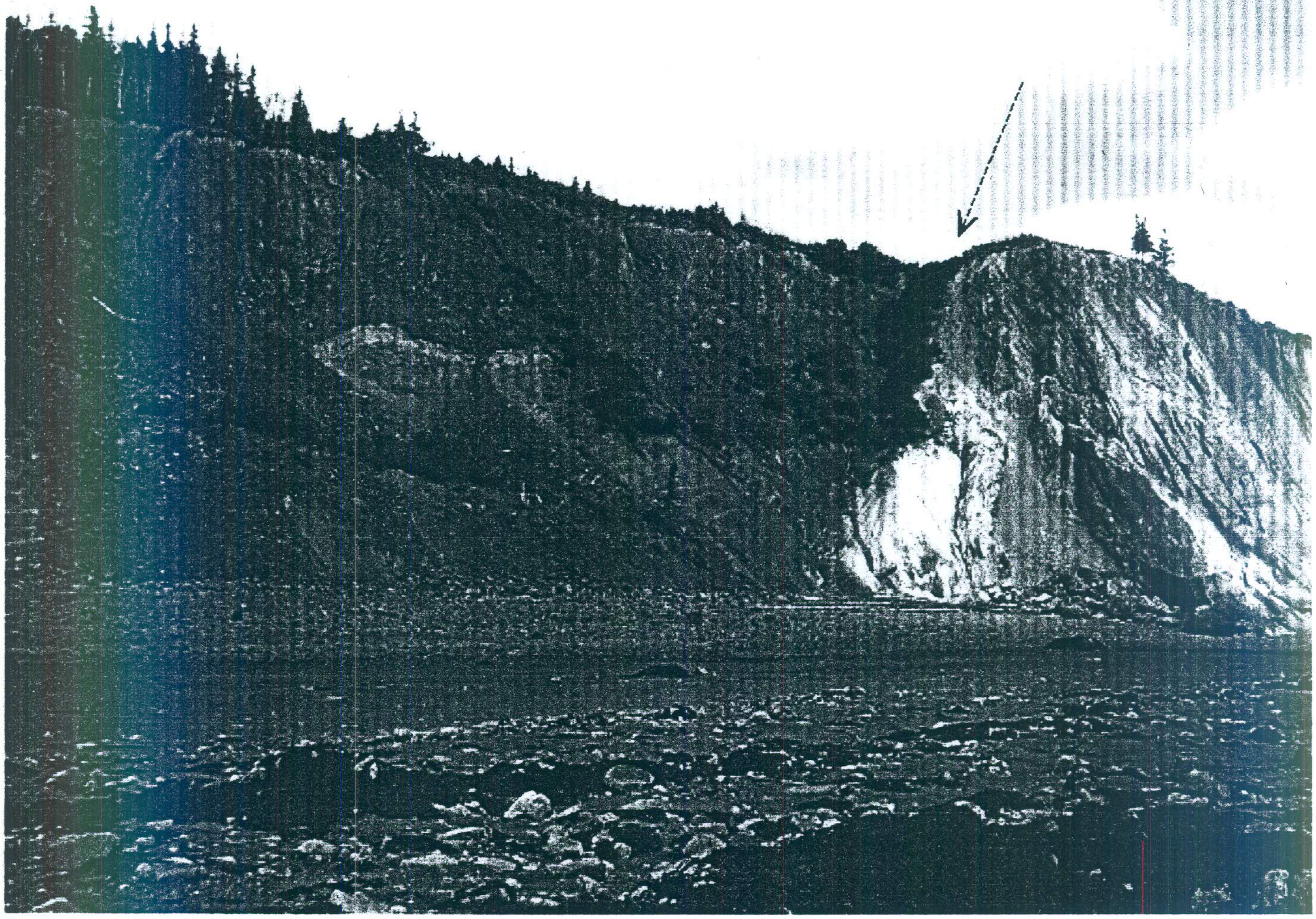


Fig. 15 a. Photograph of the Clark Head fault zone. Arrow points to the fault contact of Carboniferous and Mesozoic rocks.

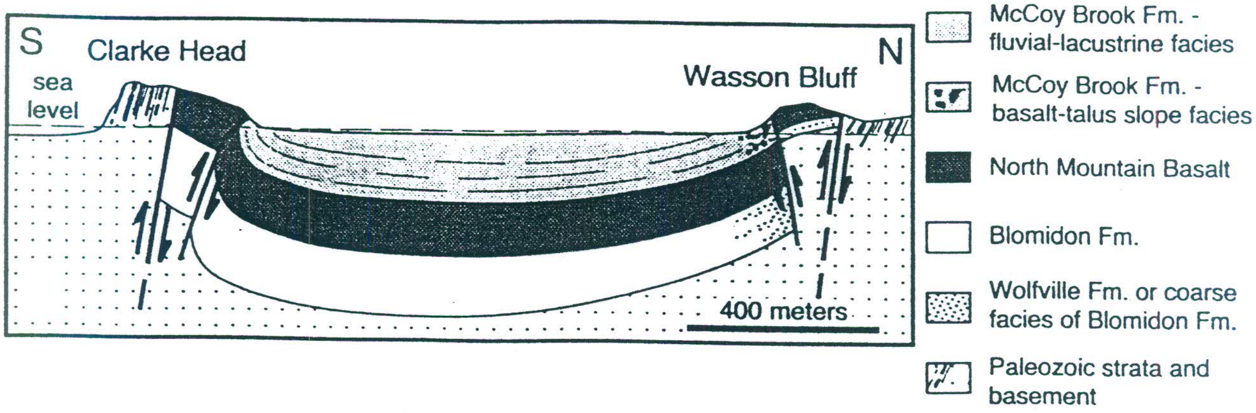


Fig. 15 b. Cross section of the Clark Head fault zone. (After Withjack et al. (1995)

fault zone means inherent instability. Loose material falls out of the exposure easily. Tide range in the Bay of Fundy – Minas Basin is extreme. Plan your walk to this outcrop on a falling tide and use care.

Description

The Clarke Head area exposes the boundary between older rocks and the Mesozoic succession (Fig. 14). The Triassic–Jurassic rocks are located in a small graben bounded by east-northeast trending faults. From Clarke Head at the east end to the boundary fault, a distance of 2 km, the cliffs expose a magnificent example of a chaotic zone interpreted as a fault zone and a megabreccia boundary between the Avalon and Meguma terranes by Donohoe and Wallace (1985) and Gibbons et al. (1996).

Three units are exposed in the area. The oldest stratified unit is the latest Early Carboniferous (Late Mississippian) West Bay Formation exposed on the beach in the area of the campground steps. An east-northeast trending fault (not exposed) is the north boundary of a small double sided graben enclosing the Mesozoic succession. The second fault juxtaposes the Mesozoic and the Clarke Head Fault Zone (Fig. 15a). The resistant tholeiitic basalts of the Jurassic age North Mountain Formation underlie Green Hill.

The West Bay Formation (part of the Mabou Group) comprises red and grey siltstones, lithic sandstones and channel based conglomerates. Spores and plants give the age as latest Early Carboniferous which is distinctly different than the unconformably overlying earliest Late Carboniferous Parrsboro Formation.

The Mesozoic Fundy Group is represented by Triassic aged Blomidon Formation and the Jurassic aged North Mountain and McCoy Brook formations (see Wade et al, 1996). These units are constrained in a local graben bounded not by the usual normal faults but high angle reverse faults according to Withjack et al (1995). Deformation was in part synchronous with deposition. They cited the basalt boulders and cobles in a talus like deposit as evidence for fault movement during deposition of the McCoy Brook Formation. The cross section in Figure 15b shows the interpretation of Withjack et al. (1995) of the small scale graben in the Clarke Head– Wassons Bluff area. At the south boundary fault, look for the white layers directly below the basalt. These layers are at the Triassic–Jurassic boundary and represent an important world-wide extinction event.

The Clarke Head Faut Zone (CHFZ) is a mega-fault gouge with rounded to sub-angular blocks of all sizes and compositions. Undeformed fossiliferous limestones of the Early Carboniferous Windsor Group are exposed at the west end. A several hundred metre wide block of Parrsboro Formation is enclosed in the matrix of finely commutated shaly material. A huge block of red shales and sandstones are exposed in the wave cut platform. At the top of the cliff near the centre of the fault zone exposure 2 m to 6 m boulders of almandine-pyroxene-plagioclase granulite are surrounded by the matrix. An entire anticlinal synform of probable Carboniferous age is located at the east end of the exposure. Other interesting rocks include marble and a sea-stack of meta-diabase both of indeterminate age.

The gneissic boulders raised a great deal of curiosity. Gibbons and Murphy (1995) reported that Sm-Nd data suggested the age of the protolith at c. 1 Ga. Gibbons et al (1996) found that zircons yielded a Devonian age (369 Ma) for the mylonitic granulite. Younger brittle deformation produced fractures filled with Visean amphibole (c. 335 Ma, Ar-Ar). The fractured mylonite was later mixed with mostly Carboniferous rocks during a late Namurian megabrecciation event (Gibbons et al, 1996).

Interpretation

The first recorded movements on the Cobequid-Chedabucto Fault Zone (CCFZ) (Minas Geofracture of Keppie 1982) began in the mid Devonian. Parts of the ancient granulitic basement complex of the Avalon Terrane (Gibbons and Murphy 1995) became embroiled in the movement zone as the Meguma Terrane began docking against the Avalon Terrane through lateral motion. Movement was episodic. During the latest part of the Early Carboniferous (Namurian) major movement commenced again which included fracture filling of the mylonitic granulite at depth and folding, erosion and deposition of the Parrsboro Formation on an unconformity at the surface. Later movements in the Carboniferous enclosed blocks of the Parrsboro Formation in the CHFZ .

The collision of the Meguma Terrane with Avalonia employed ramping faults dipping from the surface in New Brunswick under the Meguma block to juxtapose the two crustal blocks. Right lateral movement on the CCFZ assisted in the docking of the Meguma block. Later in the latter part of the Middle Triassic, the mega-thrusts became listric faults as extension began. The Minas Basin arm of the Fundy rift basin began as a down to the north movement on the Cobequid and other faults. The complex nature of the fault movement produced periods of trans-extension and trans-compression. The small graben in the Clarke Head area developed during trans-compression (Withjack et al, 1995) and was actively influencing deposition after the eruption of the basalt flows. Movement of faults and accompanying deformation after the Early Jurassic is not well understood. This small area of outcrop has allowed geologists to interpret part of the geological history of the Maritimes for a period of approximately 190 Ma.

References

Akande, S. O., and Zentilli, M., 1984. Geologic, fluid inclusion, and stable isotope studies of the Gays River lead-zinc deposit, Nova Scotia, Canada, Economic Geology, **79:** 1187-1211

Arne, D. C., Duddy, I. R. and Sangster, D. F. 1989. Thermochronologic constraints on ore formation at the Gays River deposit, Nova Scotia, Canada, from apatite fission track analysis. Canadian Journal of Earth Sciences, **27:** 1013-1022.

Boehner, R. C. 1977. The lower Carboniferous stratigraphy of the Musquodoboit Valley, central Nova Scotia, M. Sc. thesis, Acadia University, Wolfville, Nova Scotia.

Calder, J, H., 1998. The Carboniferous evolution of Nova Scotia *In* Lyell: The key past is key ot the present Edited by: D. J. Blundell and A. C. Scott, Geological society of London, Special Publications 143: pp. 261-302.

Calder, J. H., Dolby, G., Finck, P. W., Mukhopadhyay, P. K., Scott, A. C., and Stea, R. R., 1998. Cretaceous lignites of Nova Scotia: Observations on their petrography, geochemistry and palaeobotany. Abstract volume, 15th Annual Meeting for the Society of Organic Petrology, pp. 95-96.

Davies, E. H., Akande, S. O., and Zentilli, M. 1984. Early Cretaceous deposits in the Gays River lead-zinc mine, Nova Scotia; *In* Current Research, Part A, Geological survey of Canada, Paper 84-1A.

Denny, C. S., 1982. Geomorphology of New England, United States Geological Survey, Professional Paper 1208.

Dickie, G. B. and Murphy, R. 1992: Report on Shubenacadie clay pit drill program; Aggregate Division, L. E. Shaw Limited, 4 p.

Dickie, G. B. 1986. Cretaceous deposits of Nova Scotia, Nova Scotia Department of Mines and Energy, Paper 86-1.

Donohoe, H. V. Jr. and Wallace, P. I., 1985, Repeated Orogeny, Faulting, and Stratigraphy in the Cobequid Highlands, Avalon Terrain of Northern Nova Scotia, Excursion 3, GAC/MAC Annual Meeting, Fredericton, NB, 77 p.

Faribault, E.R., 1899. Upper Musquodoboit map sheet, Geological Survey of Canada, Map 49.

Finck, P. W., Stea, R. R., and Dwyer, D. F. 1994. Preliminary results of drilling Quaternary and Cretaceous sediments near Shubenacadie, Hants County, Nova Scotia, Nova Scotia Department of Natural Resources, Mines and Energy Branches Open File Report 94-026.

Finck, P. W., Stea, R. R., and Pullan, S. 1995. New discoveries of Cretaceous sediments near Shubenacadie, Nova Scotia, *In* Nova Scotia Department of Natural Resources Minerals and Energy Branch Report of Activities, Report 95 -1.

Fowler, J. H. 1972. Clay and sand deposit at Elmsvale, Halifax County, Nova Scotia Department of Mines, Miscellaneous Publication 72-03.

Gibbons, Wes and Murphy, J. Brendan, 1995, Mylonitic mafic granulite in fault megabreccia at Clarke Head, Nova Scotia: a sample of the Avalonian lower crust.

Gibbons, Wes, Doig, Ronald, Gordon, Terence, Murphy, Brendan, and White, Joseph Clancy, 1996, Mylonite to megabreccia: Tracking fault events within a transcurrent terrane boundary in Nova Scotia, Canada, Geology, v. 24, p. 411-414.

Giles, P. S., and Boehner, R. C. 1982. Geological map of the Shubenacadie and Musquodoboit Basins, central Nova Scotia. Nova Scotia Department of Mines and Energy, Map 82-4.

Giles, P. S. 1981. The Windsor Group of the Mahone Bay area, Nova Scotia; Nova Scotia Department of Mines and Energy, Paper 81-3.

Gillis, M. X. 1998. A report on the 1997-1998 exploration program for kaolin clays in the Musquodoboit, Stewiacke and Shubenacadie regions of Nova Scotia. Nova Scotia Department of Natural Resources, Assessment Report 98-041.

Gillis, M. X., and Stea, R. R. 2000. Mesozoic stratigraphy and kaolin exploration in the Sibley Road area, Nova Scotia. *In* Nova Scotia Department of Natural Resources, Minerals and Energy Branch, Report of Activities 1999, Report 2000-1.

Gobeil, J-P, 2002. Stratigraphy, sedimentology, and provenance of the Chaswood Formation, West Indian Road pit, Shubenacadie, Nova Scotia; unpublished M. Sc. thesis, Dalhousie University Halifax, 205 p.

Goldthwait, J.W. 1924. Physiography of Nova Scotia. Geological Survey of Canada, Memoir 140.

Grant, D. R. 1994. Quaternary Geology, Cape Breton Island, Geological Survey of Canada, Bulletin 482. 159 p.

Greenough, J. D., 1995. Mesozoic rocks, Chapter 6. *In* Geology of the Appalachian-Caledonian Orogen in Canada and Greenland, *edited by* H. Williams; Geological Survey of Canada, Memoir 6, pp. 567-600.

Grist, A. S. M., and Zentilli, M. 2000. Apatite fission track constraints on a widespread Early Cretaceous heating episode in the Canadian Atlantic margin: added effect of a climatically perturbed gradient? *In* 9th International Conference on Fission Track Dating and Thermochronology, Lorne, Australia, Feb. 6-11, Geological Society of Australia Abstract Series **58**: 135-137.

Guernsey, T. D., 1927. Quartz sand and clay deposits, Melford, Cape Breton, Canada Department of Mines, Geological Survey, Summary Report 1926, Part C, pp. 110-124.

Hacquebard, P.A. 1984. Composition, rank and depth of burial of two Nova Scotia lignite deposits, *In* Current Research, Part A, Geological Survey of Canada, Paper 84-1a.

Horne, R. J., King, M. S. and Young, P. 2000. Geology of the Wittenburg Mountain slate belt, Centre Musquodoboit area (NTS 11E03), Nova Scotia Department of Natural Resources, Report ME 2000-1 pages 67-74.

Jansa, L., and Pe-Piper, G. A., 1988. Middle Jurassic to early Cretaceous igneous rocks along eastern North American continental margin, The American Association of Petroleum Geologists Bulletin, v. 72: 347-366.

Keppie, J. D., 2000; Geological map of the province of Nova Scotia [1:500 000] Nova Scotia Department of Natural Resources; Map ME 2000-1.

King, L. H., MacLean, B., Bartlett, G. A., Jelestsky, J. A., and Hopkins, W. S. 1970. Cretaceous strata on the Scotian Shelf. Canadian Journal of Earth Sciences, **7:** 145-155.

King, M. A. 1997: Magnetic susceptibility mapping: applications for the Meguma Group, central Nova Scotia; Atlantic Geology, v. 33, p. 121-132.

Lin, C. L. 1971. Cretaceous deposits in the Musquodoboit river valley, Canadian Journal of Earth Sciences, v. 8: 1152-1154.

Mathews, W. H., 1975. Cenozoic erosion and erosion surfaces in eastern North America; American Journal of Science, v. 275, p. 818-824.

Pe-Piper, G., Jansa, L. F., and Palacz, Z., 1994. Geochemistry and regional significance of the Early Cretaceous bimodal basalt-felsic associations on grand banks, eastern Canada, Geological Society of America Bulletin, v. 106: 1319-1331.

Pullan, S. E., Stea, R. R., Finck, P. W., Burns, R. A., Douma, M., and Good, R. L. 1997. Seismic exploration for Cretaceous kaolin deposits in glaciated terrains: Example from Nova Scotia, Canada. *In* SAGEEP'97, Proceedings of the Symposium of the Application of Geophysics to Engineering and Environmental Problems, March 23-26 1997, Reno, NV, 1, pp. 133-142.

Ries, H. and Keele, J. 1911. The clay and shale deposits of Nova Scotia and portions of New Brunswick, Canada Department of Mines, Geological Survey Branch, Memoir 16-E.

Roden-Tice, M. K., Tice, S. J., Schofield, I. S., Michaud, D. P., 1998. Evidence for differential unroofing in the Adirondack Mountains, New York State, through apatite fission track thermochronology, Geological Association of America program with abstracts.

Roland, A. E. 1982. Geological background and physiography of Nova Scotia, Nova Scotia Institute of Science.

Scott, A. C., Collinson, M. E., Nichols, G. J. Cripps, J., and Calder, J. H. 1998. Fire ecology of Cretaceous vegetation in the Isle of Wight, England and Nova Scotia, Canada. Geological Society of America, Program with abstracts.

Stanford-Scott, D., Ashley, G. M., Russell, E.,W-B., Brenner G. J., 2002., Rates and patterns of late Cenozoic denudation in the northernmost Atlantic Coastal Plain and Piedmont. Geological Society of America Bulletin. v. 114; no. 11, p. 1422-1437.

Stea, R. R., Finck, P. W., Prime, G., and DeMont, G. J. 1995. New discoveries of silica sand and kaolinite near Brierly Brook, Antigonish County; *In* Minerals and Energy Branch, Report of Activities 1994, Report 95-1.

Stea, R. R., Finck, P. W., and Fensome, R. A. 1997. Lithostratigraphy of Early Cretaceous and Quaternary unconsolidated sediments in the Musquodoboit and Shubenacadie Valleys, Nova Scotia, Canada. *In* Nova Scotia Department of Natural Resources Mineral Resources Division, Report of Activities, 1996, Report 97-1, pp. 163-173.

Stea, R. R., Finck, P. W., Pullan, S. E., and Corey, M. C. 1996. Cretaceous deposits of kaolin clay and silica sand in the Shubenacadie and Musquodoboit Valleys, Nova Scotia, Canada, Nova Scotia Department of Natural Resources; Mines and Minerals Branch; Open File Report, 960003.

Stea, R. R. and Fowler, J. H. 1981. Petrology of Lower Cretaceous silica sands at Brazil Lake, Hants County, Nova Scotia. *In* Nova Scotia Department of Mines and Energy Mineral Resources Division Report of Activities. Report 81 - 1.

Stea, R. R., and Pullan, S. E. 1998. Post-Early Cretaceous faulting in the Musquodoboit Valley, Nova Scotia, *In* Nova Scotia Department of Natural Resources Mineral Resources Division, Report of Activities, 1997, Report 98-1, pp. 135-143.

Stea, R. R., and Pullan, S. E. 2001: Hidden Cretaceous Basins in Nova Scotia : Canadian Journal of Earth Sciences: v. 38, p. 1335-1354.

Swift, D. J. P., Jagodits, F. L., Ministre, B. L., and Paterson, N. R., 1967. Structure of the Minas Passage, Bay of Fundy: a preliminary report, Maritime Sediments, **3:** 112-118.

Stevenson, I. M. 1959. Shubenacadie and Kennetcook Map Areas, Colchester, Hants and Halifax Counties, Nova Scotia, Geological Survey of Canada, Memoir 302.

Wade, J. A., Brown, D. E., Traverse, A., and Fensome, R., A. 1996. The Triassic-Jurassic Fundy Basin, eastern Canada: regional setting, stratigraphy and hydrocarbon potential, Atlantic Geology, 32: 189-231.

White, T. S. Witzke B. J., Ludvigson G. A., 2000. Evidence for an Albian Hudson arm connection between the Cretaceous Western Interior Seaway of North America and the Labrador Sea: Geological Society of America, v. 112, p. 1134-1355.

Withjack, M. O., Olsen, P. E., and Schlische, R. W., 1995. Tectonic evolution of the Fundy Rift basin, Canada: Evidence of extension and shortening during passive margin development. Tectonics v 14, p. 390-405.