Hidden Cretaceous basins in Nova Scotia

Rudolph R. Stea and Susan E. Pullan

Abstract: Early Cretaceous unconsolidated quartz sand and kaolinitic clay deposits in the lowlands of Nova Scotia are preserved in narrow half-grabens obscured by glacial drift. The Chaswood Formation sediments can be subdivided into three members; upper and lower members dominated by cyclical sand–mud facies of fluvial origin and the middle member with lignitic clay of lacustrine origin. Ferruginous oxisols are common in the fine-grained facies of the upper and lower members. Seismic data indicate that Chaswood Formation strata in the Elmsvale Basin are deformed into steeply dipping faults and fault-related folds (Rutherford Road fault zone). An Aptian–Albian age for this tectonic event is inferred from synsedimentary deformation and from the angular unconformity spanning the Late Cretaceous and Tertiary that truncates the Chaswood Formation. Exhumation of a thick cover of Mesozoic sediment (1–2 km) is needed to account for the preservation of Chaswood Formation outliers after ~80 Ma of erosion. The half-grabens that host the Chaswood Formation were formed in the Mesozoic and were antecedent to the present-day structurally controlled lowlands.

Résumé : Des dépôts non consolidés de sable quartzeux et d'argile à kaolin (Crétacé précoce) dans les basses-terres de la Nouvelle-Écosse sont préservés dans d'étroits demi-grabens sous des dépôts glaciaires. Les sédiments de la Formation de Chaswood peuvent être subdivisés en trois membres : des faciès cycliques sable-boue d'origine fluviale dominent les membres inférieur et supérieur et de l'argile ligneuse d'origine lacustre domine le membre intermédiaire. Les faciès à grain fin des membres inférieur et supérieur comprennent fréquemment des oxisols ferrugineux. Des données sismiques indiquent que les strates de la Formation de Chaswook dans le bassin d'Elmsvale ont été déformées en failles à pendage abrupte et en plis reliés aux failles (zone de failles Rutherford Road). L'âge de cet événement tectonique (Aptien-Albien) est déduit de la déformation synsédimentaire et de la discordance angulaire couvrant le Crétacé tardif et le Tertiaire qui recoupe la Formation de Chaswood. Pour tenir compte de la préservation des lambeaux externes après ~80 Ma d'érosion, il faut l'enlèvement d'une épaisse couverture (1 à 2 km) de sédiments mésozoïques. Les demi-grabens hôtes de la Formation de Chaswood ont été formés au cours du Mésozoïque et ils précèdent les basses-terres actuelles qui sont contrôlées par la structure.

[Traduit par la Rédaction]

Introduction

Hidden under a thick blanket of glacial drift in the Carboniferous and Triassic basins of Nova Scotia are the preserved remnants of once 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; Fig. 1). Stevenson (1959) first established an Early Cretaceous age for these unique deposits, which have long been mined for valuable refractory clay, aggregate and glass-sand (Fowler 1972). This paper summarizes the results of a 3-dimensional surficial mapping program initiated in 1992 by the Nova Scotia Department of Natural Resources (NSDNR) and the Geological Survey of Canada (GSC) with the purpose of defining 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." Cretaceous basins from several to 10 km^2 were defined through drilling and reflection seismic techniques. Kaolin deposits with economic potential for use in the paper industry were identified in these basins (Finck et al. 1994, 1995; Stea et al. 1996; Pullan et al. 1997; Stea et al. 1997). This paper will provide fundamental geological data defining this body of sediment and introduce new evidence on the deformation of Cretaceous strata. The Mesozoic and Cenozoic deposits in these basins provide the last chapters in the evolution of landscapes in eastern Canada.

Geological and physiographic setting

The central Nova Scotia study area comprises the Shubenacadie and Musquodoboit river valleys, located in the Carboniferous lowlands of central Nova Scotia (Figs. 1, 2). The Shubenacadie valley is underlain by Lower to early Upper Carboniferous strata composed of marine evaporites, including gypsum, anhydrite, and salt, as well as carbonates, and grey and red siliclastic rocks. The Carboniferous rocks

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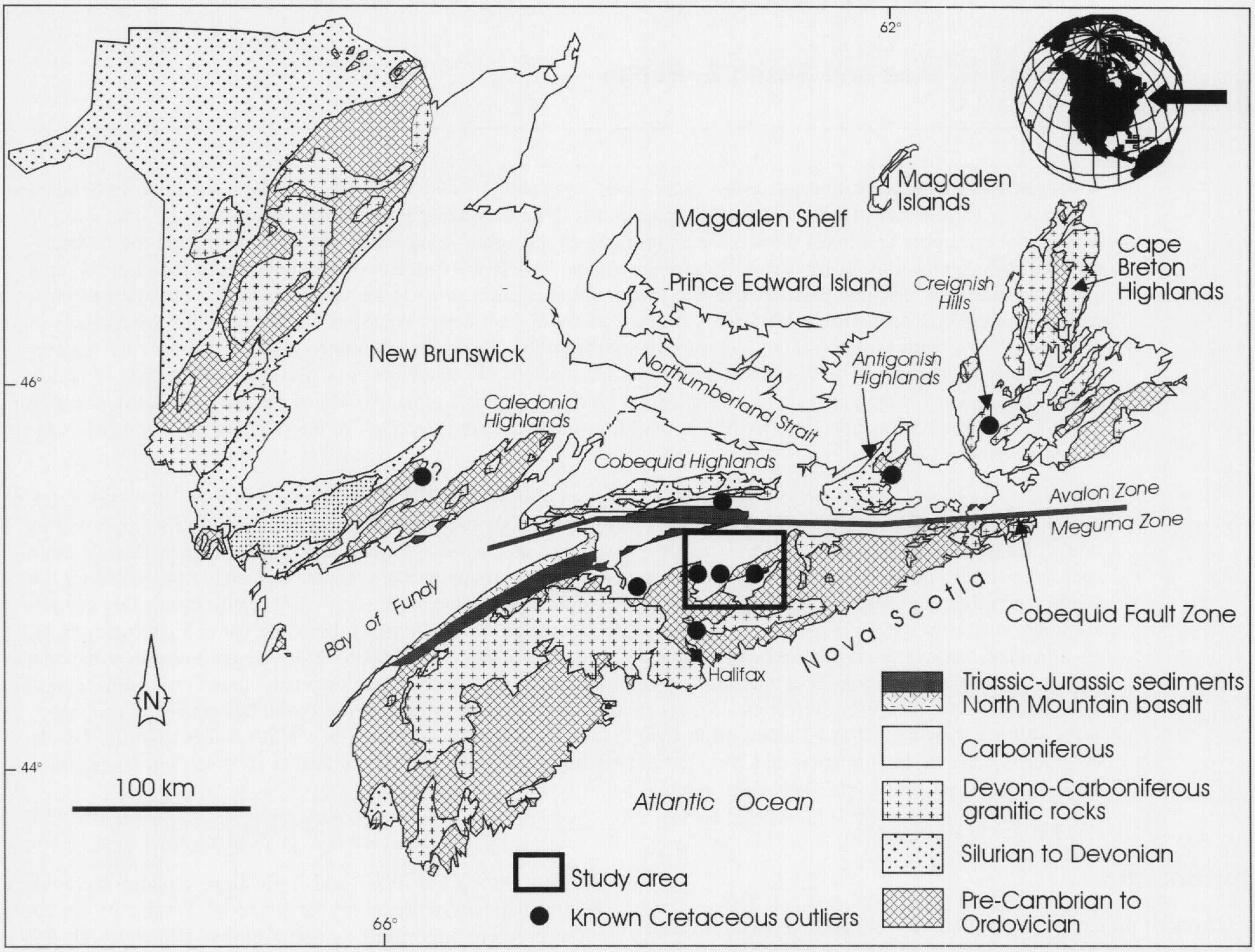
Fig. 1. Geology of Maritime Canada showing locations of Early Cretaceous outliers and the study area.



are divided into the Horton, Windsor, and Mabou groups of the Shubenacadie and Musquodoboit basins (Giles and Boehner 1982), part of a once interconnected series of depocentres collectively termed the Maritimes Basin (Calder 1998). The Musquodoboit Basin is separated from the Shubenacadie Basin by a horst of Cambro-Ordovician Meguma Group metasedimentary rocks known as Wittenburg Mountain (Horne et al. 2000).

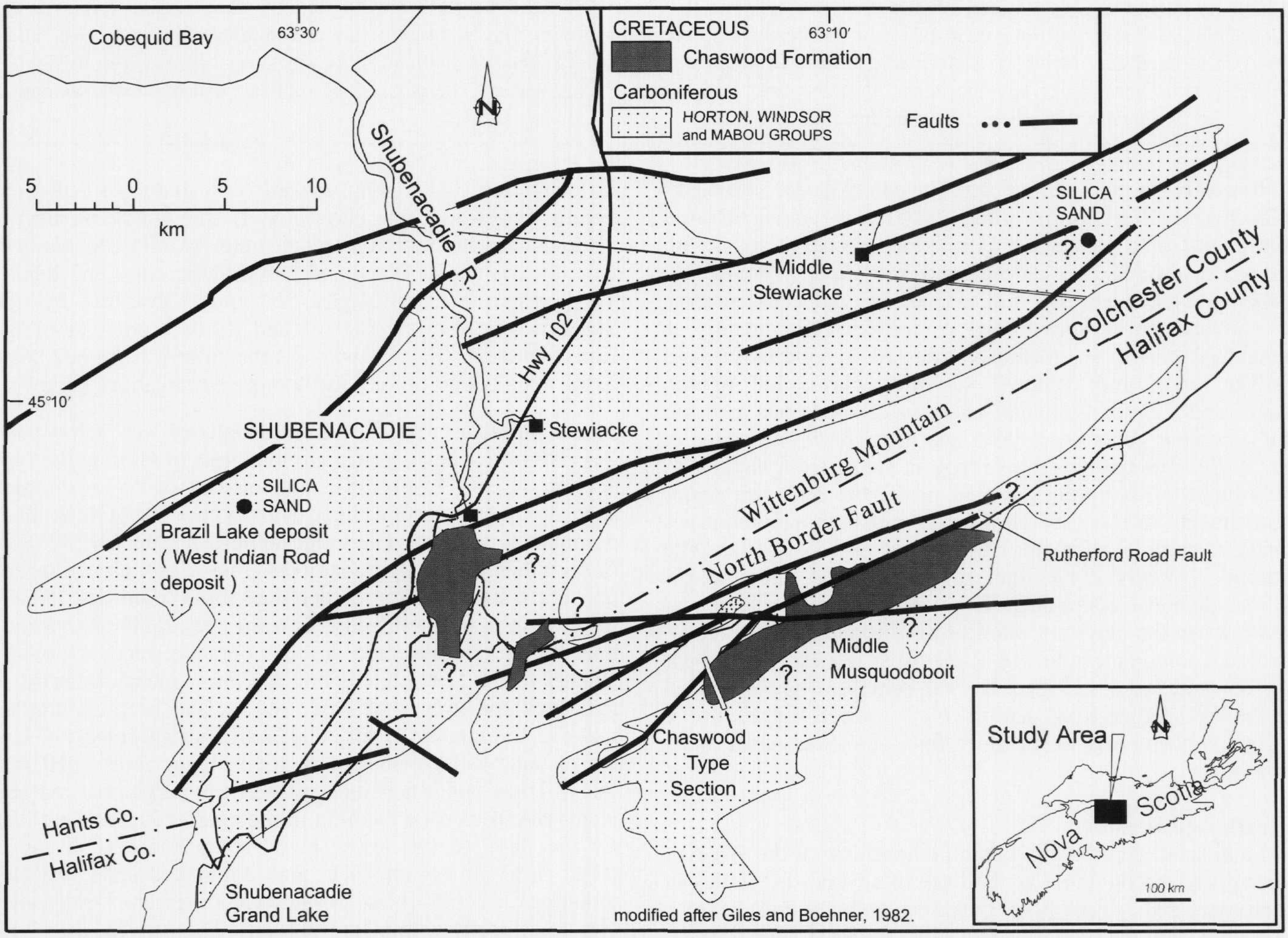
Cretaceous sediments have been found within some Windsor Group karst depressions, such as at the Gays River Pb–Zn Mine (Davies et al. 1984; Arne et al. 1989). The Brazil Lake outlier (West Indian Road quarry) in the Shubenacadie Basin is currently being mined for silica sand (Fig. 2). Additional outliers of kaolinitic clay and silica sand outcrop along the margins of the Musquodoboit Valley, in a clay quarry in the town of Shubenacadie, and in faulted Carboniferous basins adjacent to the Cobequid and Antigonish Highlands and the Creignish Hills in Cape Breton (Stea et al. 1995; Dickie 1986; Figs. 1, 3*a*). A silica sand occurrence in a similar tectonic setting near Sussex, New Brunswick, may be of Cretaceous age (V. Venugopal, personal communication, 1999; Fig. 1).

Methods

The subsurface Mesozoic–Cenozoic stratigraphy was initially examined through existing stratigraphic databases described in Stea et al. (1996). A program of 21 diamond-drill holes was undertaken at sites selected on the basis of mapping, seismic test-spread data, and stratigraphic database searches. Spurred by the government survey and interest in silica sand and kaolin, a newly formed company (Kaoclay Inc.) conducted a seismic and drilling exploration program in the study area (Gillis 1998). Finck et al. (1994) and Stea et al. (1996) described the rotary diamond drilling and wireline coring methods used in the government survey, and Gillis (1998) describes the industry survey in which substantial improvements were made in the core recovery of coarse sediments.

The Shubenacadie–Musquodoboit shallow seismic reflection survey involved both a testing and a production phase described in Pullan et al. (1997). The production phase of the seismic program involved recording continuous 12-fold common-midpoint (CMP) profiles, such as those presented

Fig. 2. Map of central Nova Scotia study area showing Cretaceous outliers and mapped Cretaceous basins.



in this paper. In total, 10 line-km of 12-fold data were collected in the Shubenacadie and Musquodoboit valleys. An additional 30 km of 12-fold seismic data were collected in the Musquodoboit and Stewiacke valleys by Kaoclay Resources Inc. (Gillis 1998). All data have been processed by applying standard CMP sequences of processing steps, including trace editing, static corrections, bandpass filtering, gain scaling, velocity analysis, normal move-out corrections and stacking of the corrected traces (e.g., Steeples and Miller 1990).

Downhole geophysical logs provide a remote means of identifying stratigraphic units based on variations in their physical properties. These were especially useful in this study to cover gaps in the stratigraphic record from lack of core recovery in coarse sediment. The logs discussed in this paper include natural gamma, conductivity, and magnetic susceptibility measurements acquired with a Geonics EM-39 portable logging system and downhole seismics. (Hunter et al. 1998).

Lithostratigraphy

Introduction

Cretaceous strata in Nova Scotia have been known and described for many years, but until now a formal stratigraphic nomenclature had not been introduced. The lithic and seismic stratigraphic data collected during this project have enabled the authors to formalize elements of the stratigraphy (Stea et al. 1996, 1997). In the study area, Cretaceous strata are confined to narrow, steep-sided basins within the Musquodoboit and Shubenacadie valleys (Fig. 2). The largest area of subcropping Cretaceous sediment is a northeast–southwest 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 (Fig. 4). The Elmsvale basin consists of two wide parts joined by a narrow neck near Middle Musquodoboit (Fig. 4). A smaller basin, termed the Shubenacadie outlier (3 × 6 km) is located near the village of Shubenacadie (Fig. 2).

Six diamond-drill holes linked with a seismic reflection profile across the southwest Elmsvale basin south of Chaswood in the Musquodoboit Valley constitute the type section of the Chaswood Formation (Stea et al. 1997; transect 1; Fig. 5). Five drill holes were used to define a cross-section of the Chaswood Formation in the Shubenacadie outlier (transect 2; Fig. 6). A southwest–northeast six drill-hole longitudinal profile along the Elmsvale basin is shown in transect 3 (Fig. 7). The drill hole transects encountered three main lithostratigraphic units: Carboniferous (Windsor Group)

Fig. 3. Photographs of the Chaswood Formation. (*a*) Brick clay quarry at Shubenacadie (tip of iceberg!). (*b*) Channel sand over purplish silty clay at the West Indian Road quarry. (*c*) Diamond-drill hole (DDH) MUSC-96-2 showing stratigraphic subdivisions. (*d*) MUSC 95-4 showing the typical facies of the Chaswood Formation, lignitic clay, light-grey clay and mottled clay oxisol. (*e*) "Drab halo" in mottled clay facies. (*f*) Deformed clay in drill hole (top to right). (*g*) Banded rhythmites? in the lower member (top to right). (*h*) Diagenetic liesegangen banding in the upper member (top to right); note: vertical alteration along rootlets? and horizontal alteration in primary sedimentary banding. (*i*) Basal breccia.

sedimentary rocks, Cretaceous unconsolidated sediments (Chaswood Formation), and Quaternary unconsolidated sediments. The Chaswood Formation reaches a maximum thickness of 90 m at diamond-drill hole MUSC95-4, subcropping beneath 20–35 m of Quaternary glacial deposits.

The Chaswood Formation is composed predominantly of terrestrial clastic sediments, dominated by quartzose sand (silica sand), multicoloured kaolinitic clays, and lignitic clays and lignite. Chemical analysis of the sands indicate SiO_2 content generally > 96% and as high as 99% (Stea et al. 1996). The quartz grains range in shape from angular to subrounded. Kaolinitic clay and muscovite mica are major constituents in the silty clay units, with minor amounts of anatase, goethite, hematite, pyrite and organic matter. The kaolin is poorly crystalline, submicron, and anhedral (V. Hurst, personal communication, 1998). Purple, yellow and red hues in the clays are due to ferric iron (Fig. 3; V. Hurst, personal communication, 1998). Feldspar is a rare constituent of the sand facies and gypsum was present in gravelly sand at the West Indian Road deposit (Fig. 2) as rod-shaped, brittle grains concentrated in the finer fractions (Stea and Fowler 1981).

Stratigraphic units

Laminated, grey-brown dolomitic limestone of the Windsor Group was encountered at the base of several drill holes in transects 1 and 2 (Figs. 5, 6). Limestone and mudstone bedrock encountered in transects 1 and 2 belong to the Middle to Upper Windsor Group, probably the Green Oaks Formation (R. C. Boehner, personal communication, 1996) although the Cretaceous may unconformably overlie Canso Group and Lower Windsor Group rocks in those basins (Giles and Boehner 1982).

Unnamed Breccia (age uncertain)

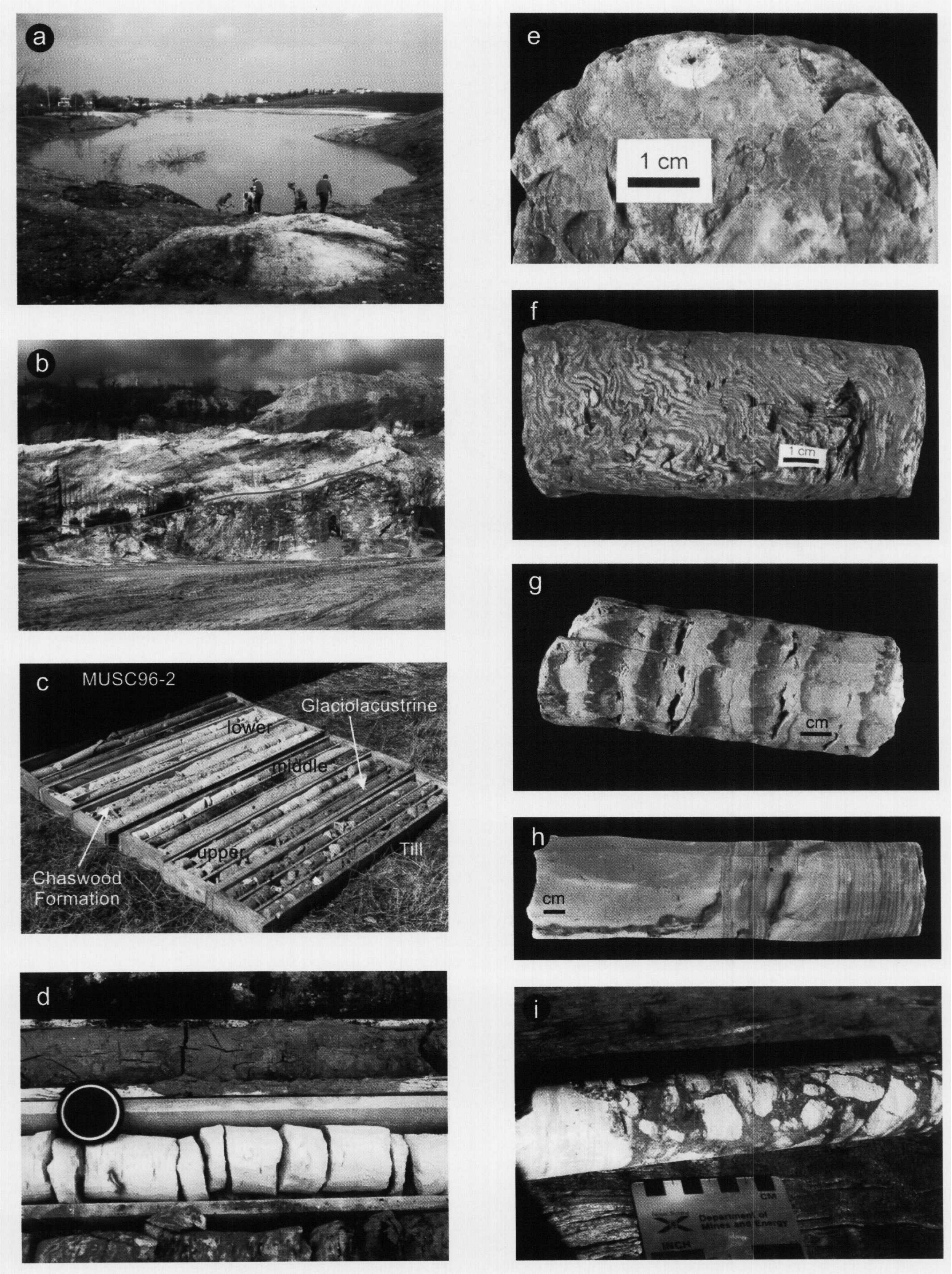
A greenish-grey, brecciated and faulted mud unit underlies the Chaswood Formation in drill holes within the Shubenacadie and Musquodoboit basins (Figs. 3, 5, 6, 7). The breccia varies in thickness from less than 0.5 m to 2 m or more and is mostly composed of angular, intraformational, pebble- to granule-sized clay fragments in a silty-clay matrix. It is interbedded with indurated dolostone, limestone, and mudstone. Slickenside surfaces were observed in some cores. In transect 1 (Fig. 5), pyrite and calcite veinlets are common within this unit, but do not appear to extend upward to the Chaswood Formation. The exact boundary between the Chaswood Formation clay and the breccia is sometimes not readily distinguishable.

Chaswood Formation

The Chaswood Formation in the Shubenacadie outlier and Elmsvale Basin can be subdivided into three informal units: the lower, middle, and upper members. The upper and lower members feature similar cycles of coarse to fine quartz (silica) sand and silt, grading upwards into multicoloured (mottled) and light-grey silty clays (Fig. 3). The middle member is distinguished from these inorganic units by thick sequences of laterally continuous black and grey lignitic clays and lignite. This tripartite stratigraphy is most evident in the Shubenacadie outlier (Fig. 6) and the western end of the Elmsvale basin (Fig. 5), whereas the eastern Elmsvale basin is seismically and lithologically more homogenous (Fig. 7).

Lower member: The lower member of the Chaswood Formation reaches a maximum thickness of 60 m at the type section (CH96-2; Fig. 5) and consists of 5–15 m thick sand-dominated sections alternating with 3–10 m thick mud-dominated packages. The lower member has thicker packages of sand than the younger members (Figs. 5, 6). Gravel makes up only a small portion of the sand units, confined largely to basal lags in thick fining-upward cycles, although gravel may be underrepresented due to poor core recovery of the coarser strata. Mud units within the lower member consist of light-grey and grey, pink, red, yellow, and purplish-mottled massive and laminated silty clay. Laminations consist of layers of sandy-silty-mud and mottled clayey mud 1–10 mm thick. These laminations are enhanced by purple and red titanium- and iron-oxide banding in the coarser layers (Fig. 3*h*). At the base of the lower member in transects 1 and 2 (Figs. 5, 6) are organic-rich, mud-dominated units, with alternating dark-grey and grey-brown, or greenish-grey silty clay and locally a thin lignite seam. The base of drill hole MUSC95-4 (Fig. 3*g*; 116 m, Fig. 5) reveals a rhythmically laminated, silty-clay facies.

Natural gamma and conductivity logs (Fig. 8) clearly demonstrate the cyclicity of the Chaswood Formation with quasi-periodic oscillations from coarse to fine sediment. The muscovite-bearing silty clay units of the Chaswood Formation are characterized by high gamma counts. Zones of count rates in excess of 100 counts/s (cps) represent the intersection of fine-grained units in the borehole (e.g., 87–93 m depth in MUSC95-4; 38–56 m depth in MUSC96-4). In contrast, well-sorted sands of the lower member of the Chaswood Formation show count rates as low as 30–50 cps, implying that these are very clean silica sand units (e.g., 93–96 and 97–102 m depth in MUSC95-4; 56–67 and 75–80 m depth in MUSC96-4). The natural gamma log can be used to identify the existence of thin fine-grained layers within these sands (e.g., 67–67.5 and 95.5–97 m depth in MUSC95-4; 62–63 and 81.5–84 m depth in MUSC96-4). The natural gamma and conductivity logs show a very close correspondence, suggesting that clay minerals are controlling the apparent electrical conductivity of the sediments. The lower member of the Chaswood Formation can be differentiated from the upper member by lower frequency and thicker sand-clay oscillations, with more abrupt contacts between the two facies. Lignite layers in the lower and middle members are associated with fine-grained units (i.e., high gamma counts


a
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c
MUSC96-2
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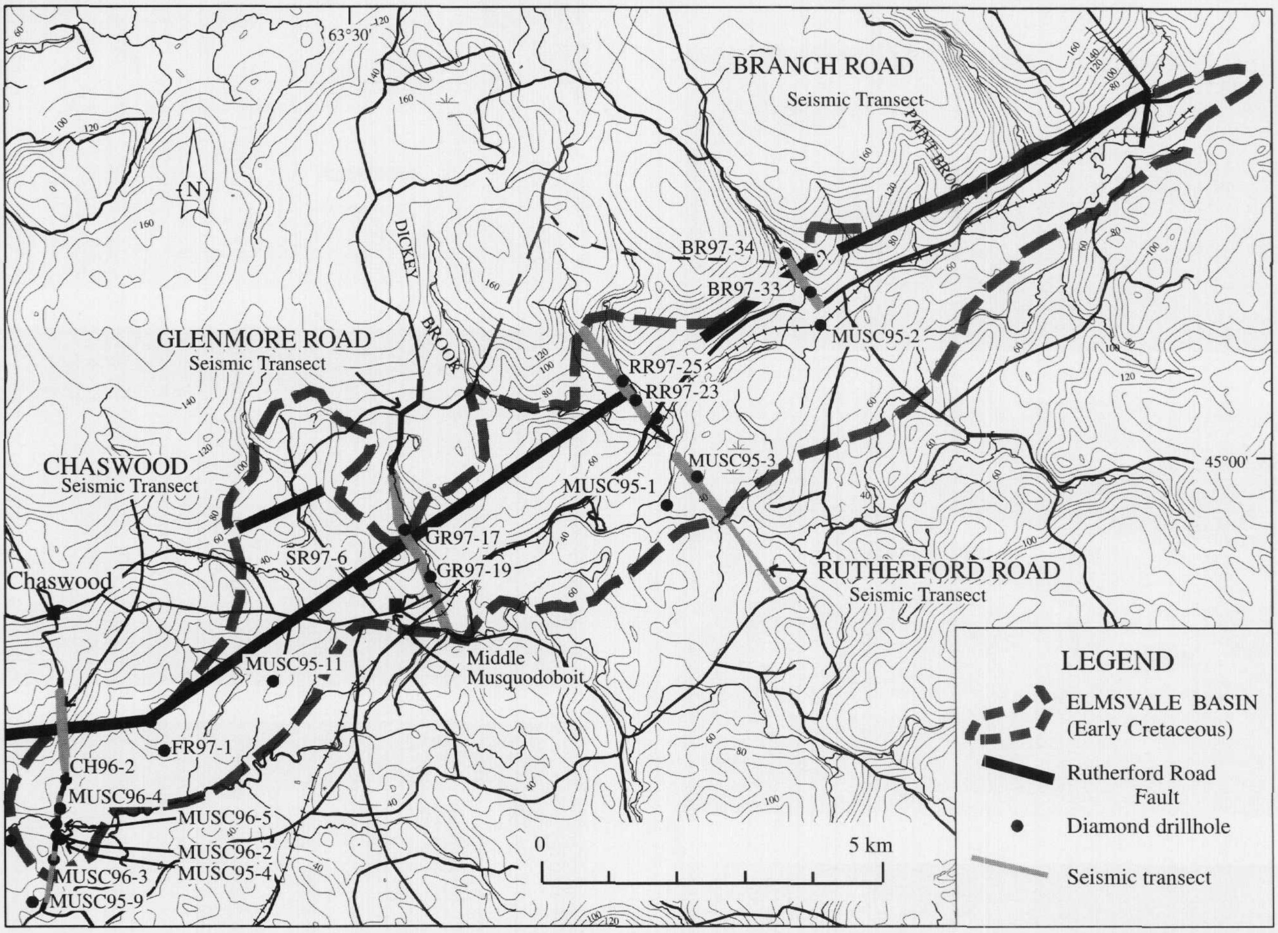
Fig. 4. Expanded map of the Elmsvale Basin showing the location of the Rutherford Road fault zone, diamond-drill hole locations and seismic transects. Only a portion of the seismic transects are depicted in the figure. For the others see Gillis (1998).



and conductivities), though the lignite layer itself is sometimes characterized by a local lowering in the gamma count rate (lignite layers may be more clearly observed in the seismic records).

Middle member: The base and top of the middle member of the Chaswood Formation is defined by a sharp or gradational (over 1–5 m) transition into organic-rich sediment, including massive grey to dark-grey to black lignitic clay, lignite and laminated silty-clays (Figs. 5, 6, 7). Lignite horizons vary in thickness from a few centimetres to 1.5 m and are traceable between drill holes and in seismic sections. The lignite beds of drill holes MUSC95-1, MUSC95-2, and MUSC95-3 (Fig. 4) are dominated macroscopically by two broad lithofacies: charred plant stems (fusain) with quartz and kaolin and homogenous, massive dull lignite. The fusain-rich lithotype predominates (Calder et al. 1998). Lignite beds can cap fining-upward cycles of silica sand overlain by light-grey, grey or dark grey-black, lignitic mud (Fig. 5). The lignitic or organic mud facies tend to be massive, but are locally finely laminated with alternating coarser grey silty clay and finer dark-grey clay. Pyrite and marcasite are common in the lignitic clay and lignite, both as rounded grains and as diagenetic, dendritic growths along fracture planes. A light-grey, calcium carbonate-cemented silica sand is found within the middle member associated with organic-rich clay and sand in the type section and other drill holes in the Elmsvale basin.

Upper member: The upper member of the Chaswood Formation consists largely of inorganic mud- and sand-dominated facies in sharp or gradational contact with the middle member (Figs. 5, 6). At transect 1 (DDHs MUSC95-4 and MUSC96-5) the upper member has a maximum thickness of 40 m and consists of 0.5–10 m-thick fining-upward cycles of white to light-grey, coarse to fine silica gravel–sand capped by 0.5–2 m of light-grey, silty clay and red, yellow, and purplish mottled silty clay (Fig. 5). Locally, one of these cycles is capped by a grey to black, lignitic silty clay, usually less than 50 cm thick. Sand units within the upper member are enriched in clay compared to the lower member, accounting for fair to good core recovery in the initial drilling program. Light-grey kaolin within the sand units is present in the following three forms: (1) interstitial matrix, (2) pseudomorphs after feldspar grains, and (3) intraformational clasts ("clay balls"). In the geophysical logs, the upper member is characterized by more frequent sand-clay oscillations, higher background gamma counts in many of the sand facies (indicating interstitial clay), and distinct fining-upward successions (38–35 m depth in MUSC95-4, 37–32 m depth in MUSC96-4; Fig. 8).

Eastward across the Elmsvale basin, the upper member facies change from sand-dominated to mud-dominated

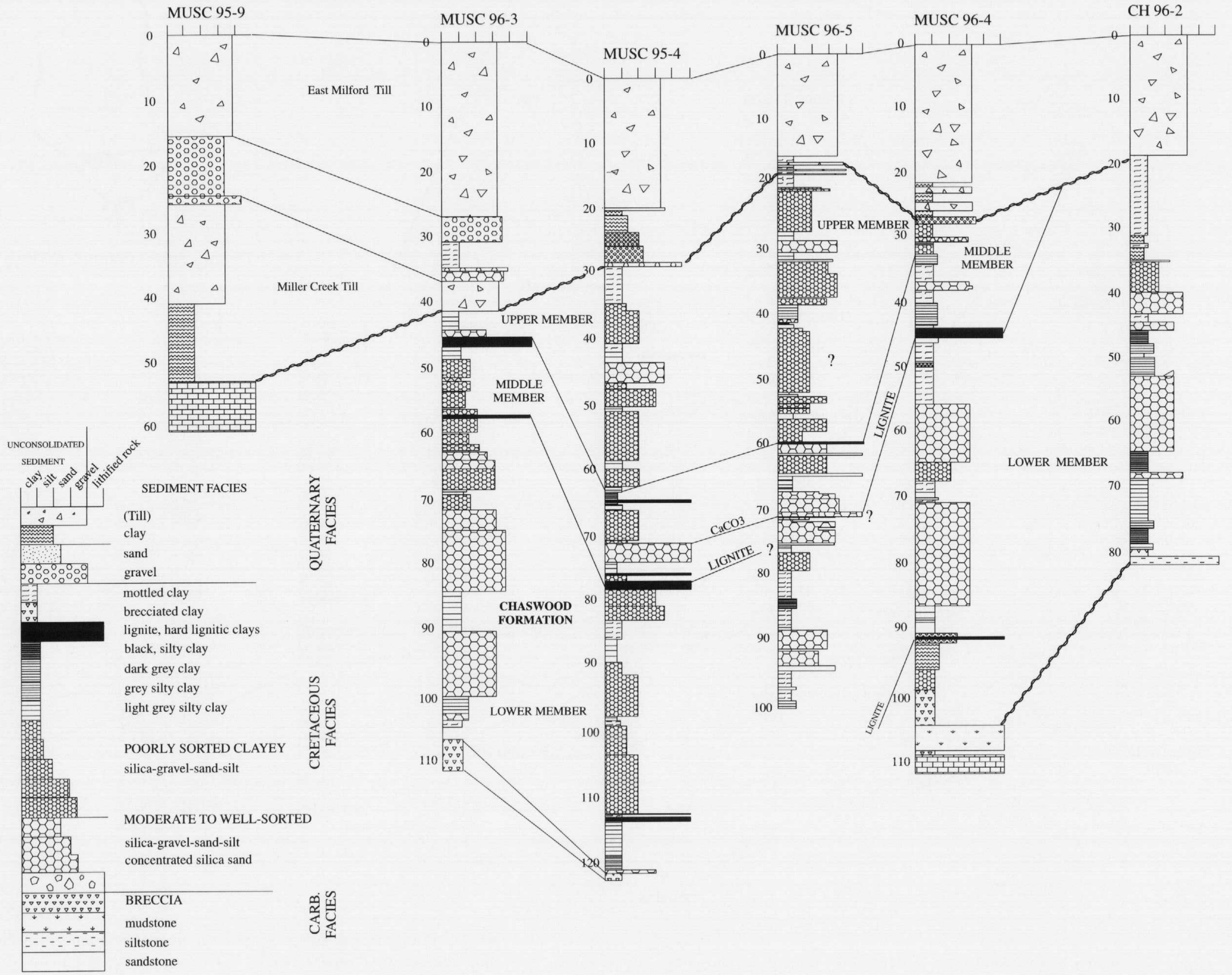


Fig. 5. Diamond-drill hole transect 1, Chaswood, Nova Scotia; type section of the Chaswood Formation and pattern legend (see Fig. 4 for DDH locations). Note: Because of the importance of lithified horizons to seismic interpretation, the facies log has been modified from convention to depict all rock horizons, regardless of grain size, to the far right of the grain size code, differentiating them from the unconsolidated strata. CARB., Carboniferous.

Fig. 6. Diamond-drill hole transect 2, Shubenacadie, Nova Scotia; reference section of the Chaswood Formation. Inset map of the Shubenacadie Cretaceous outlier showing drill hole and seismic transect locations referred to in the text.

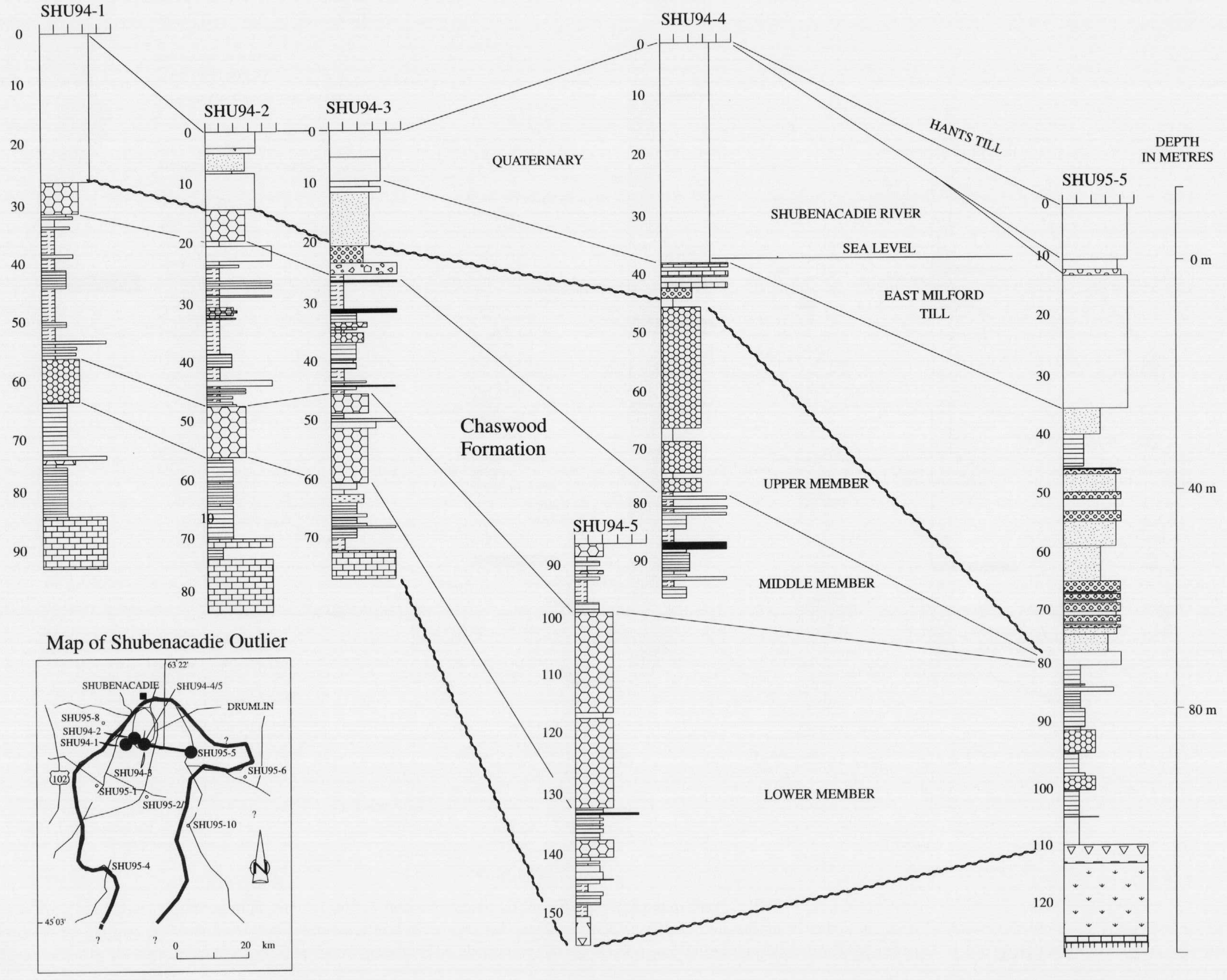


Fig. 7. Longitudinal diamond-drill hole transect across the Elmsvale Basin (see Fig. 4 for DDH locations). 1 indicates a good example of a fining-upward sequence within the upper member of the Chaswood Formation capped by red ochre oxisol.

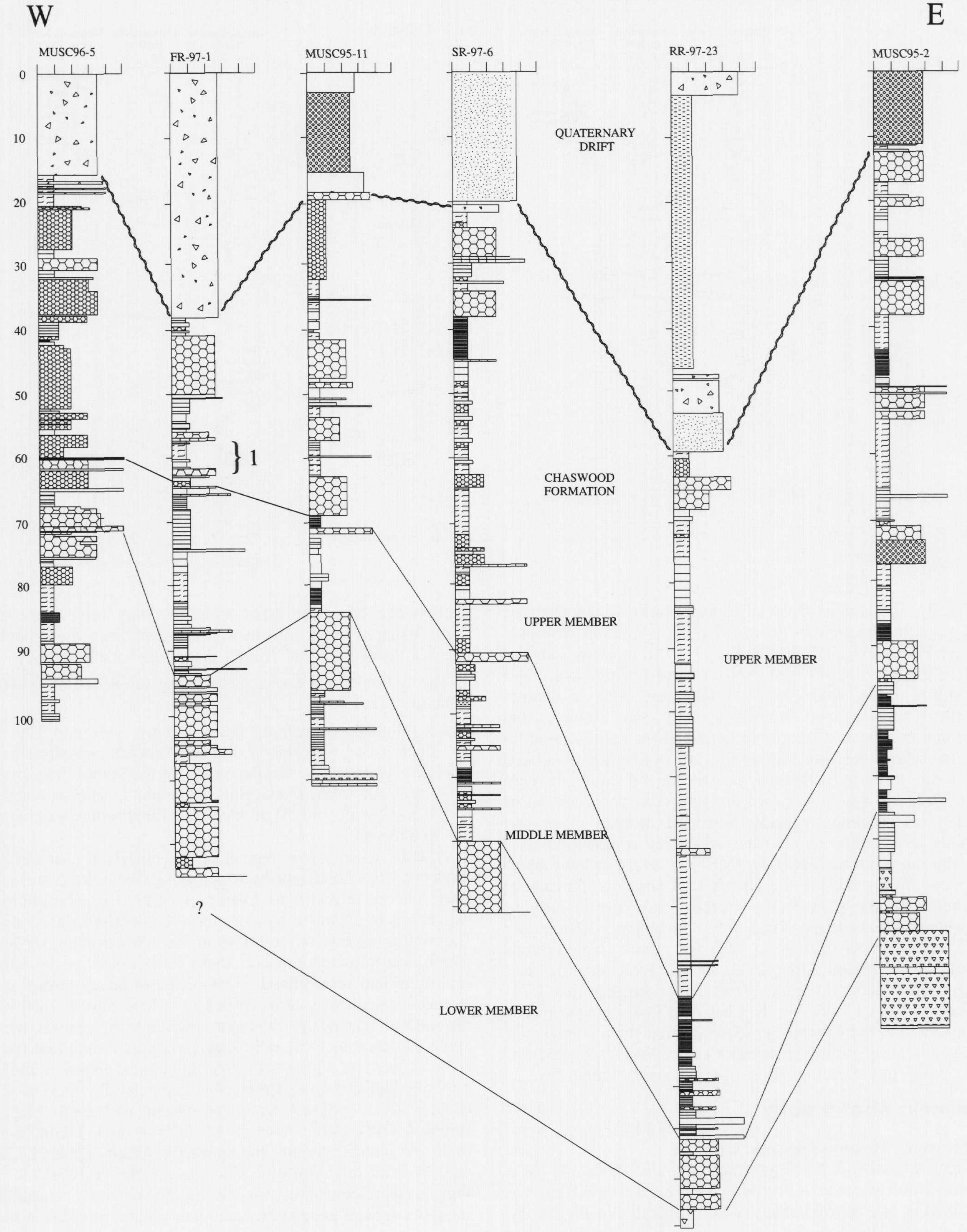
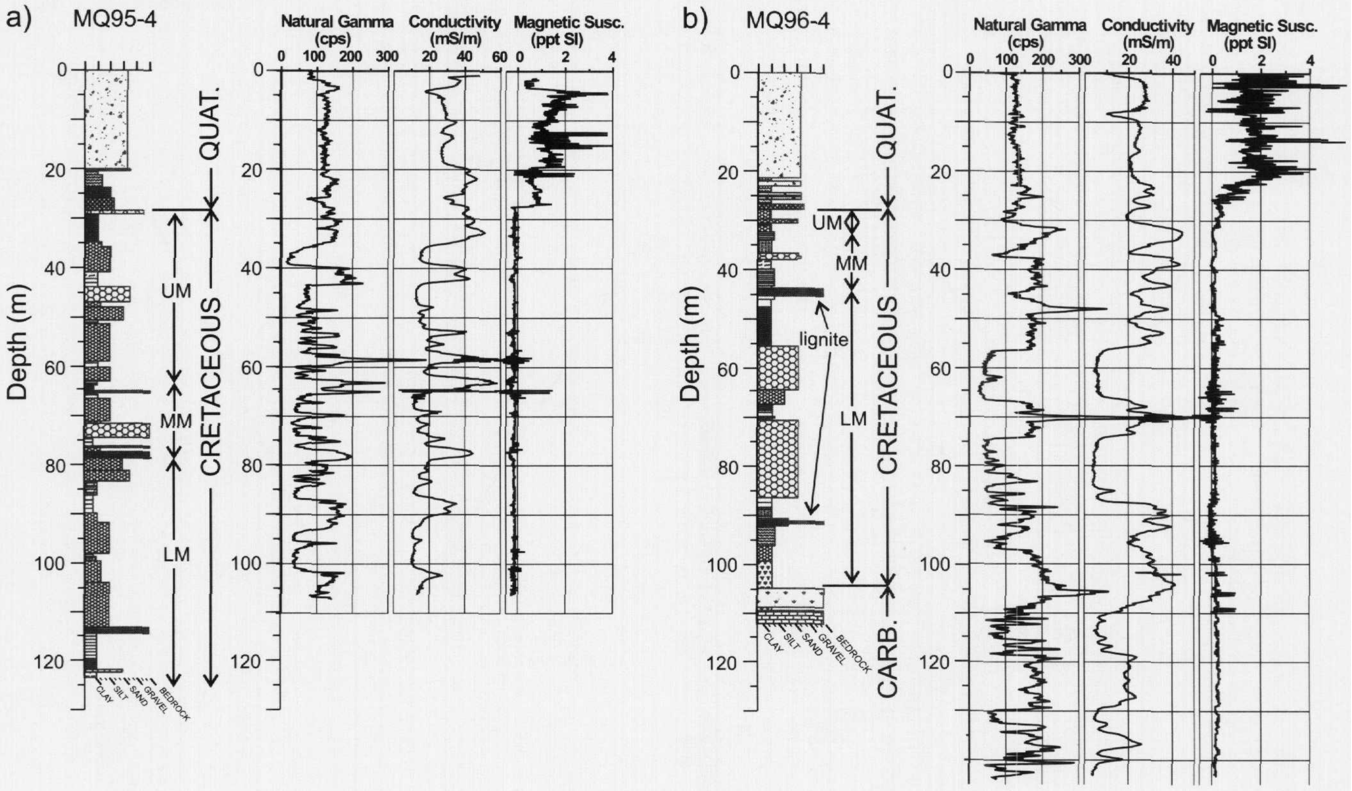


Fig. 8. Natural gamma, conductivity and magnetic susceptibility logs for boreholes (*a*) MUSC95-4 and (*b*) MUSC96-4. UM, MM and LM refer to the upper, middle and lower members of the Chaswood Formation, respectively. CARB., Carboniferous; QUAT., Quaternary, cps, counts per second; ppt, × 10^{-3}, Susc., susceptibility.



(Fig. 7). The northeast part of Elmvale basin is characterized by great thicknesses (> 30 m) of reddish mottled silty clay (e.g., Fig. 3*d*, 3*e*; RR-97-23, Fig. 7). The mottling consists of brightly coloured, red, yellow, and purple, iron- and titanium-oxide segregations, sometimes with a distinct vertical zonation and orientation (Fig. 3*h*). Some of the coloration can be attributed to hard, red (hematite–limonite) grains within the clay. Fining-upward cycles are associated in some cores by a distinct, up-section reddening. In core FR-97-1, for example, a typical cycle consists of 45 cm of white silt grading vertically into red mottled clays and finally into a thin, massive red ochre clay (Fig. 7).

The magnetic susceptibility (MS) log (Fig. 8) shows a precipitous drop reflecting the almost total absence of magnetic minerals in the Cretaceous sediments and the underlying Carboniferous bedrock. King (1997) documented similar low MS levels (mean 0.17 × 10^{-3} SI) for clastic Carboniferous rocks in the region. High levels of MS for magnetite- and pyrrhotite-bearing Meguma Zone rocks suggest that local uplands are not a source for the Chaswood Formation sediments. Zones within the Cretaceous sequence that show some small magnetic susceptibility responses correspond with zones of secondary pyrite precipitation in organic-rich sequences.

Seismic stratigraphy

Chaswood Meadows seismic transect

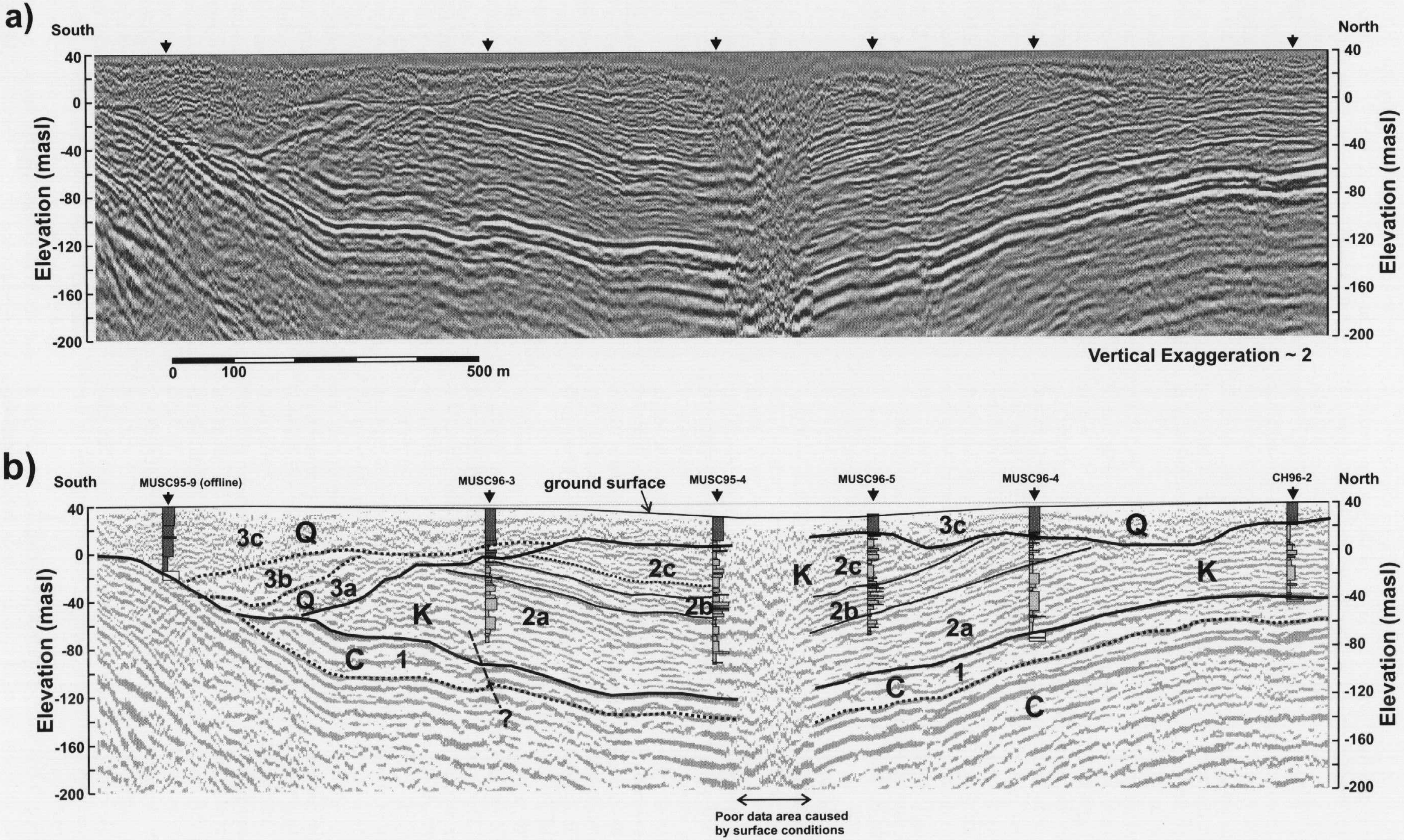
The Chaswood Meadows seismic line (Fig. 9) is a north–south transverse profile across the western Elmsvale basin (Fig. 4), approximately 2 km in length. In Fig. 9, the section has been converted from two-way travel time to depth using velocity information obtained from the seismic records themselves and from a downhole seismic survey.

The section clearly shows many strong subsurface reflections which outline

(1) a roughly symmetrical basin, 2 km+ wide and 130 m deep, filled with unconsolidated Cretaceous sediments.
(2) an asymmetrical, smaller valley at the south end of the line, cut into Cretaceous sediments, approximately 0.5 km wide and 50 m deep, and filled with Quaternary sediments.

A series of continuous, high amplitude reflections characterize sequence 1 (Carboniferous bedrock), though the bedrock surface itself can be difficult to identify clearly. Large-amplitude reflections to depths of tens of metres below the Cretaceous–Carboniferous contact result from impedance contrasts between low-velocity breccia zones interbedded with hard limestone and mineralized (pyrite–calcite) layers within sequence 1. Sequence 2a is a thick (> 50 m) unit defined by discontinuous, low- to 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 MUSC96-5, there are indications that the contact between sequences 2a and 2b is an unconformity. Though not clearly revealed in Fig. 9, an unconformity in the middle of the Cretaceous sequence is well documented on other seismic profiles in the

Fig. 9. Chaswood-type seismic transect (*a*) and interpretation (*b*) displayed in depth. Two-way travel times have been converted to depth and are displayed as actual elevations (masl, m above sea level). The upper profile is an amplitude display, where the dark areas are positive amplitude, the same as the dark lines on the variable area display below. Schematic representations of the lithological logs of six boreholes drilled on or close to this seismic line are superimposed on the lower panel (see Fig. 4 for location and Fig. 5 for detailed lithologies). Sequences 1–3 correspond to Carboniferous bedrock (C), Cretaceous sediments (K), and Quaternary strata (Q).



Elmsvale basin (e.g., Figs. 10, 11). These reflections are from lignite and (or) lignitic clay layers of the middle member, which are characterized by large reflection coefficients. A distinctive calcareous-cemented sand also produces a high-amplitude reflection within sequence 3 (Figs. 5, 9). The contrast between higher amplitude reflections in sequence 2b and the more transparent sequence 2c may correspond to the Cretaceous sediments become sandier and less organic higher in the section. The upper member of the Chaswood Formation defined in drill holes (Fig. 5) is correlative with sequence 2c in the seismic section (Fig. 9).

Northward-dipping reflections of sequences 1 and 2 are clearly truncated by an asymmetric valley at the south end of the section filled with Quaternary deposits (Fig. 9). Within the valley two seismic sequences are observed; a lower sequence with hummocky facies (3*a*, likely coarse-grained sediments) and an upper sequence, largely reflection-free (3*b*, likely fine-grained deposits). The valley fill is truncated by sequence 3*c*. The resolution of these data is not high enough to differentiate lithological variations within sequence 3*c*, though some borehole logs suggest that there are glaciolacustrine sediments underlying the surface till sheets that make up most of the sequence (Fig. 5).

Rutherford Road transect

The Rutherford Road transect runs northwest–southeast across the north side of the central Elmsvale basin (Gillis 1998; Fig. 4); only a 1-km section of this transect is shown in Fig. 10. 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 (Fig. 10, RR-97-25). The bedrock surface has an apparent vertical offset of more than 100 m across a horizontal distance of 200 m (350–550 m, Fig. 10). This fault zone is herein termed the Rutherford Road fault zone (RRFZ).

The deepest part of the Cretaceous basin is just south of the RRFZ (at 350 m), where it reaches a maximum depth of ~200 m. Three major seismic sequences can be differentiated. Sequence 1 consists of continuous northward-dipping reflections below a large-amplitude reflection that corresponds to the bedrock surface in RR-97-23. Thus, the uppermost reflection of sequence 1 is interpreted as the contact between Carboniferous bedrock (C) and the overlying Mesozoic–Cenozoic unconsolidated sediments (K). North of the RRFZ, the sequence 1 – sequence 2 boundary is evident on the seismic line (Fig. 10) as a slightly hummocky reflection at –20 m (with respect to sea level). Continuous reflections within sequence 1 are interpreted as contacts between different bedrock types (mudstone, siltstone, dolostone, limestone) or between soft breccia zones and bedrock. High-amplitude reflections observed just below the bedrock surface at both drill-hole locations may represent a more competent bedrock material, such as limestone. (It should be noted that the depth scale below the sequence 1 – sequence 2 boundary may be inaccurate because of the lack of velocity control in this depth range.)

Sequence 2 is a thick sequence observed to the south of the RRFZ with low- to moderate-amplitude reflections, corresponding to a drill-hole record (RR-97-23) of Cretaceous sediments consisting mainly of thick clay-dominated beds and thin sand layers. The lower part (30–40 m thick) of this sequence (2*a*) is conformable with the bedrock surface; above this (sequence 2*b*), there is apparent onlap where sediments appear to have in-filled a developing basin. Truncating sequence 2*b* is a hummocky, channelized? erosional surface (base of sequence 2*c*) which may be Cretaceous or may represent a Quaternary event. Lack of drill-hole control makes an age interpretation tenuous.

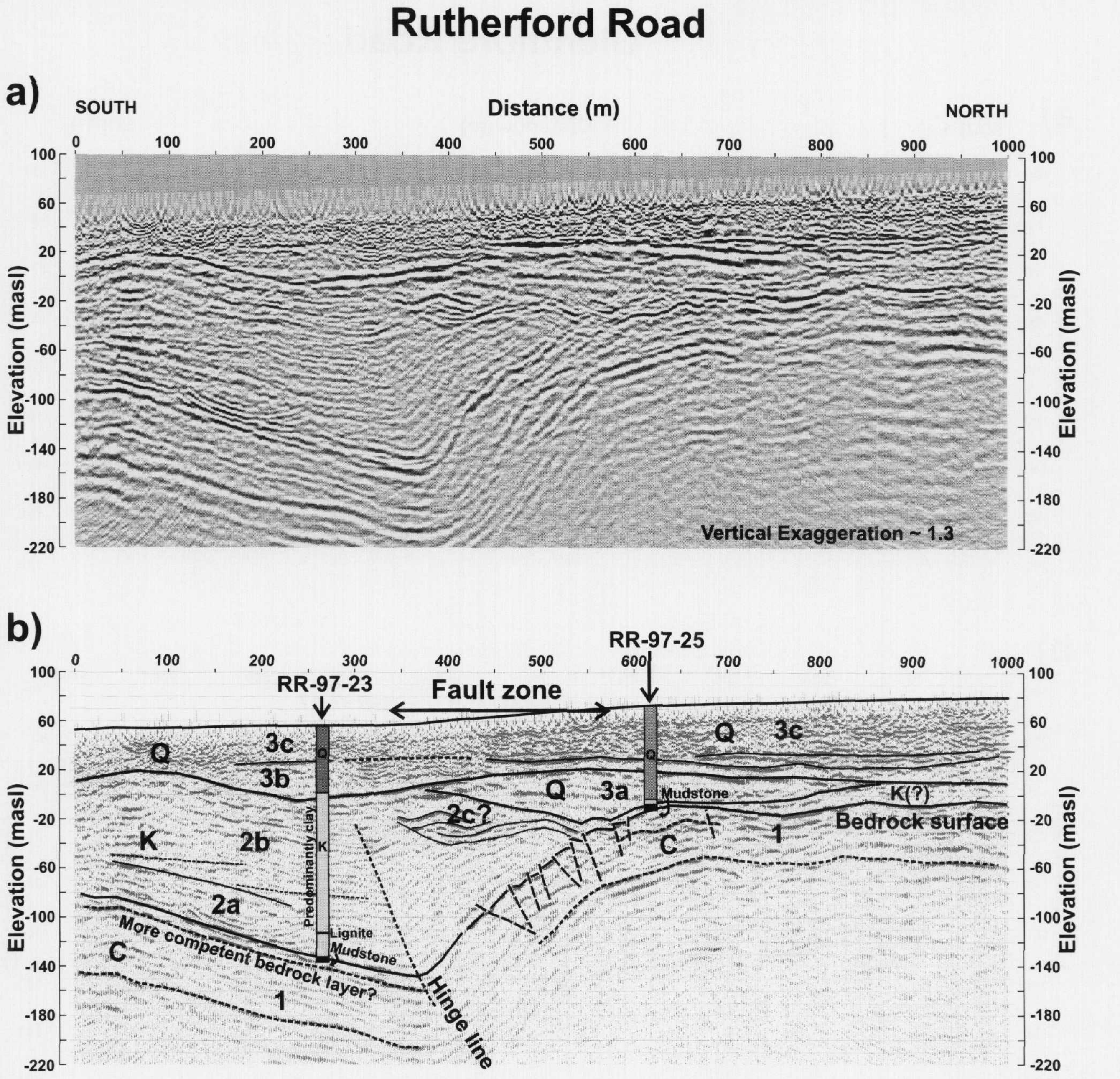
Sequence 3 corresponds to glacio-lacustrine(?) muddy sediment and till in the drill-hole records (Quaternary deposits). Along this profile, it is a complex sequence that can be divided into three distinct units: 3a exists only in the vicinity of RR-97-25, with internal reflections that dip slightly to the north; 3b is underlain by an undulating, large-amplitude reflection that may represent an erosional surface; 3c is the near-surface layer with internal reflections that appear to mirror the surface topography (shallow unit is poorly defined on seismic profile). Sequence 3*a* and 3*b* may be successive channel infills with glaciofluvial and glaciolacustrine sediments, as seen in the Chaswood Meadows profile. The Quaternary sediments were not cored in drillhole RR-27-23 to verify this conclusion.

Glenmore Road transect

The Glenmore Road seismic transect runs approximately north–south through the village of Middle Musquodoboit a few kilometres southwest of Rutherford Road (Fig. 4); a 1-km section of this transect is shown in Fig. 11. This seismic section also clearly indicates the presence of a major subsurface fault zone (Fig. 11).

South of the RRFZ coherent reflections dip northward to –140 m (i.e., metres below 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. North of the RRFZ, GR-97-17 intersected Carboniferous siltstone at a depth of 65 m (–5 m), Cretaceous Chaswood Formation strata (predominantly sand) between 23 and 65 m depth (~37 m to –5 m), and 23 m of surficial glacial drift. As along the Rutherford Road section (Fig. 10), the deepest part of the Cretaceous basin on Glenmore Road is just south of the RRFZ (at 400 m; Fig. 11), where the basin reaches a maximum depth of 170 m. Defining the basin are three seismic sequences (1–3). Sequence 1 consists of northward-dipping, high-amplitude reflections (Fig. 11), 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 (2*a* and 2*b*). The lower sequence (2*a*) 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 layers, 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 sequence 2a – sequence 2b boundary (Fig. 11). These high-amplitude

Fig. 10. Seismic profile (*a*) and interpretation (*b*) of part of the Rutherford Road transect displayed in elevation. Sequences 1–3 correspond to Carboniferous bedrock (C), Cretaceous sediments (K), and Quaternary strata (Q). masl, m above sea level.



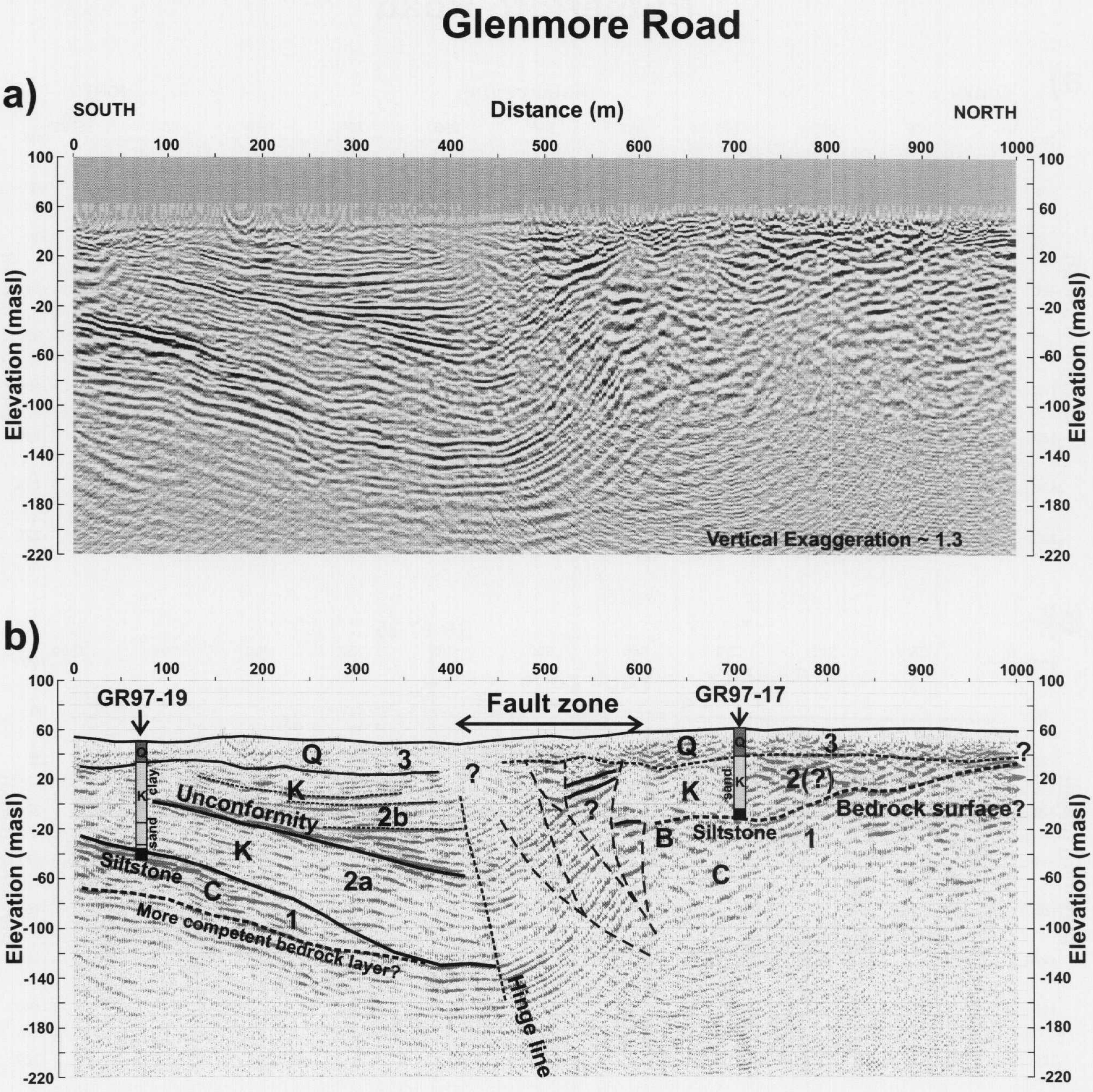
reflections may indicate lignite horizons, which are common in the middle member of the Chaswood Formation. Sequence 3 corresponds to glacial drift cover, but because of the shallow depths involved, it is not well resolved on these reflection profiles.

Acoustic basement (sequence 1 – sequence 2 boundary) north of the RRFZ has an apparent vertical offset of more than 100 m across a horizontal distance of 200 m (Fig. 11). Within the RRFZ, this profile also shows two distinct, laterally offset, high-amplitude "bright spots" (10–20 m depth at 520–580 m, and –10 m at 570–600 m). These reflections could possibly be rafted bedrock, overconsolidated Cretaceous segments, or perhaps accumulations of gas (released upwards through the fault?).

Branch Road transect

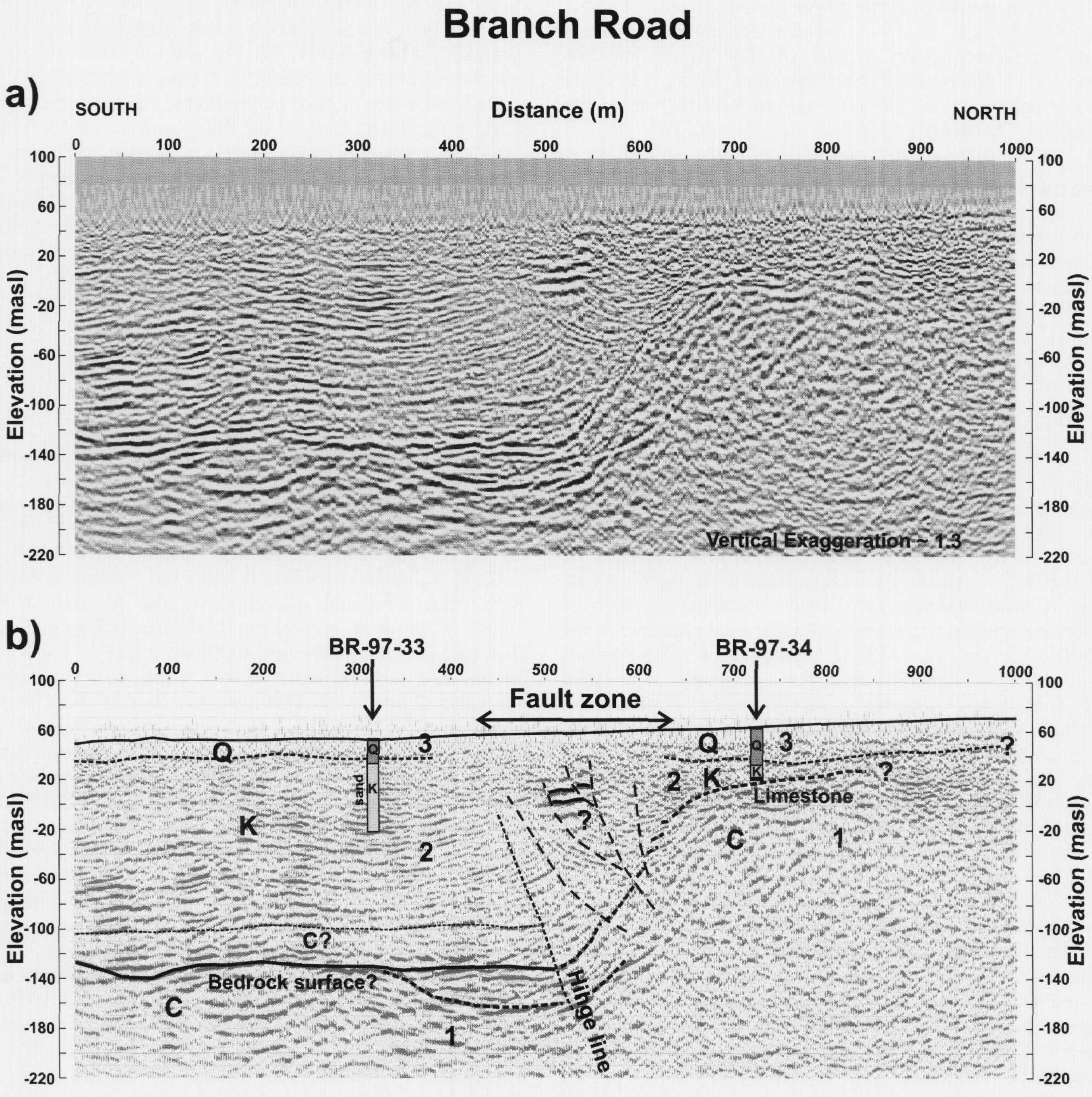
The Branch Road transect (Fig. 12) is located at the eastern end of the Elmsvale Basin (Fig. 4). In this seismic reflection profile, the RRFZ separates a deep basin to the south from relatively shallow bedrock to the north. The relatively flat-lying, thick basin sediments south of the RRFZ are upwarped then truncated at the "hinge line" (~450 m), and at least 100 m north-side up vertical offset in the sequence 1 – sequence 2 boundary is observed.

Fig. 11. Seismic profiles (*a*) and interpretation (*b*) of part of the Glenmore Road transect displayed in elevation. Sequences 1–3 correspond to Carboniferous bedrock (C), Cretaceous sediments (K), and Quaternary strata (Q). B represents the edge of competent rock.



Drill hole BR-97-33, approximately 100 m south of the RRFZ (Fig. 12), encountered 20 m of glacial drift overlying 55 m of Chaswood Formation sand and silty clay (35 m to –20 m). Little of the Cretaceous core was recovered (assumed to be predominantly sand) and the hole was abandoned before reaching bedrock. However, MUSC95-2, just south of the Branch Road transect (Fig. 4), penetrated to the Cretaceous–Carboniferous bedrock (interbedded siltstone and limestone) contact at 135 m depth (Stea et al. 1997; Fig. 7). BR-97-34, approximately 100 m north of the RRFZ, encountered limestone at an elevation of ~15 m, under 8 m of brecciated clay and 30 m of glacial drift. Refraction analysis of data acquired just north of this transect indicates a high-velocity layer (4100 m/s), interpreted to be Cambro-Ordovician metasedimentary bedrock, at a depth of less than 25 m below surface. The total thickness of the Cretaceous deposits (sequence 2) is about 170 m, if the large-amplitude, continuous reflection at –130 m is the bedrock contact (top of sequence 1), rather than part of a package of interlayered brecciated zones and bedrock. Sequence 3 is interpreted as Quaternary cover, based on the drill hole data. The seismic profile shows high-amplitude "bright spots"

Fig. 12. Seismic profile (*a*) and interpretation (*b*) of part of the Branch Road transect displayed in elevation. Sequences 1–3 correspond to Carboniferous bedrock (C), Cretaceous sediments (K), and Quaternary strata (Q).



(0 m at 500–550 m) near the RRFZ similar to that observed on the Glenmore Road profile. A borehole would be needed to identify the cause of these anomalous reflections.

Age of the Chaswood Formation

Palynological studies were carried out by Robert Fensome (personal communication, 1997) on lignitic sediments and clays recovered from the middle member of the Chaswood Formation in the Shubenacadie outlier (drill hole SHU94-3; Fig. 6). The following key species were identified: *Appendicisporites, Cicatricosisporites purbeckensis, Concavissimisporites apiverrucosus, Concavissimisporites granulosus, Concavissimisporites montuosus, Nodosisporites, Pilosisporites trichpapillosus, Rugubivesiculites,* and *Saxetia elongata.*

The presence of forms of *Appendicisporites* firmly places this suite above the Jurassic–Cretaceous boundary, and the lack of angiosperm pollen indicates a pre-Albian age. The richness in variety of cicatrose forms may indicate that the strata are Early Cretaceous, Barremian to Aptian in age (124–113 Ma), but an older age cannot be ruled out (R. Fensome, personal communication, 1997). Dickie (1986) reported a range of Valanginian to early Albian ages for Cretaceous sediments in Cape Breton (Diogenes Brook). The middle member in cores (MUSC95-1, MUSC95-11, and MUSC95-2; Fig. 4) from the western part of the Elmsvale

Basin, however, contained some angiosperm pollen indicative of an Albian age (G. Dolby, personal communication, 1998).

Clay from the base of the lower member from drill hole SHU94-3 (Finck et al. 1994) was also sampled and produced poorly preserved spores typical of the Viséan Windsor Group (G. Dolby, personal communication, 1995). Additional regional palynological data are required to further refine the age of the Chaswood Formation.

Discussion

Depositional environments of the Chaswood Formation

Cretaceous unconsolidated sediments were originally interpreted as fluvial (Ries and Keele 1911; Stevenson 1959; Lin 1971; Benteau 1973; Stea and Fowler 1981) or fluvial-deltaic (Dickie 1986). The upper and lower members of the Chaswood Formation consist of distinct fining-upward sequences characteristic of fluvial systems (Miall 1992). Erosional channel geometries are apparent in both field (Brazil Lake, Fig. 3*b*) and in seismic sections (Fig. 11; Stea et al. 1996; Pullan et al. 1997). The gamma logs with asymmetrical, serrated bell-shaped patterns are characteristic of fluvial facies (Fig. 8; Serra 1986). In cores and field sections (e.g., Fig. 3*b*) coarse, gravelly sand, traction-load deposits are overlain by sandy channel fills, lateral accretion beds, or crevasse splay deposits, and fine-grained overbank facies. There is little evidence for deltaic sedimentation, such as coarsening-upward facies and progradational clinoform sand bodies. Try et al. (1984) favoured a low-gradient anastomosing channel system for temporally correlative Early Cretaceous sediments of the Mattagami Formation in the Hudson's Bay Lowlands, which also exhibit many of the sedimentological characteristics of the Chaswood Formation. They suggested that the inherent stability of the anastomosing system inhibits channel migration, and as a result, thick sequences of fine-grained (bar-overbank) facies are preserved in the sedimentary record. The relatively sharp upper and lower boundaries of most of the channelized sand units best depicted on the gamma logs (Fig. 8) suggest that they formed by abrupt channel switching (avulsion) rather than lateral migration characteristic of a high sinuosity system.

The middle member, in contrast, is dominated by organic-rich fine-grained sediment indicative of lacustrine or estuarine systems. Lignite beds and lignitic clays defining the middle member of the Chaswood Formation are laterally extensive in the parts of the basins not affected by faulting (Fig. 5). Freshwater algae (e.g., *Tetraporina)* suggests terrestrial swamp and shallow lake environments, with fluctuating water levels (G. Dolby, personal communication, 1998). Fusain-bearing clays are interpreted as para-autochthonous deposits washed into topographic lows (floodplains) or lakes (Calder et al. 1998). Abundant charcoal within the middle member indicates forest fires, with rapid sedimentation as a result of fire-caused soil erosion (Scott et al. 1998). Seasonality, with alternating dry and wet periods, is also suggested (Scott et al. 1998). The genesis of a calcareous-cemented sandstone within the middle member (Fig. 5) is unknown, but a short-lived marine incursion cannot be ruled out.

Near the base of the lower member are rhythmically laminated, organic muds suggestive of tidal depositional systems (Dalrymple 1992). A preliminary study by Warringer 1996 has identified some marine foraminifera of indeterminate age (e.g., *Trochammina* sp.) in the organic clay facies of the lower member (SHU94-3, 94 m; SHU94-4, 140 m; Fig. 6), but reworked marine Carboniferous palynomorphs are also abundant in these facies. Notably, she found that the middle member lignites were barren of marine microfauna.

Red and white mottled clays and red massive clays appear towards the top of many of the fining-upward cycles (Fig. 5). Similar facies are interpreted as zoned paleosols by Pickering and Hurst (1989) in Georgia Cretaceous kaolin deposits and by Stewart (1983) for the Early Cretaceous Wealdon beds of southwest England. This interpretation is based on the following: (1) consistent stratigraphic position, intensifying toward the top of fining-upward cycles; (2) organic tubules with "drab haloes" (Retallack 1988) found in mottled clay zones (Fig. 3*e*); and (3) vertically oriented iron-oxide zones. These paleosols can be classified as oxisols, based on extensive alteration to Fe-oxides (Retallack 1988).

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). The seismic transects described in this study delineate a major subsurface structural discontinuity, the Rutherford Road fault, on the northern side of the Elmsvale Basin (Fig. 4). The RRFZ at the Rutherford Road section (Fig. 10) is interpreted as a fault-related fold with north-side-up movement (see also Horne et al. 1999). At the Branch and Glenmore Road sections (Figs. 11, 12), a steep reverse fault is indicated, although determining the sense of movement is tenuous at best. 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 occurred after the 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 (i.e., growth fault), as much sediment has been removed from the upthrown side of the fault. A pronounced unconformity within the Chaswood Formation (sequence 2a – sequence 2*b* boundary; Fig. 11; see also lines 3 and 4; Stea et al. 1996), however, may indicate the start of regional uplift, a precursor to more intense tectonism later manifested in faulting and folding of the Cretaceous sediments. A mid-Cretaceous age of deformation can be indirectly established by the unconformity that truncates the Chaswood Formation and the RRFZ (e.g., base of sequence 3; Figs. 10, 11), which spans the Late Cretaceous to the Tertiary.

Boehner (1977) proposed a northeast-trending fault (North Border Fault; Fig. 1) along the northern boundary of the Musquodoboit Valley separating the Carboniferous basin strata from a horst-block of Cambro-Ordovician basement rocks. It is not certain whether the North Border Fault and the Rutherford Road fault are temporally or spatially related. Breccia layers interbedded with the underlying Upper Windsor Carboniferous strata are an interesting problem. They appear to be tectonic and may relate to bedding-plane shear movement coeval with the deformation of the Chaswood Formation. The enigmatic Pembroke Breccia

(Clifton 1963), which hosts the Walton barite deposit, is a possible correlative.

This study helps to refine the timing and extent of the most recent major deformation event to affect eastern Canada. Post-Jurassic reverse faulting and folding of Triassic rocks in the Bay of Fundy is well described, but the 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, an eastward 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 preexisting northeast-trending subsidiary faults of the Cobequid–Chedabucto Fault, such as the Rutherford Road fault. According to Roden-Tice et al. (2000) fission-track analysis indicates that mid-Cretaceous fault-related uplift and exhumation occurred as far south as the Adirondacks. White et al. (2000) proposed that mid-Cretaceous uplift in eastern North America was caused by migration over the Great Meteor hotspot. Whatever the cause, Cretaceous uplift and deformation is the key to interpreting our present landscape.

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 1971; Roland 1982; Grant 1994). This erosional paradigm of landscape formation can be challenged, based on the findings of this study. The Elmsvale basin records this sequence of events (Fig. 13):

1. Early Cretaceous deposition of the Chaswood Formation ca. 140–110 Ma (age range).
2. Post-Early Cretaceous faulting; regional uplift and erosion ca. 110–80 Ma.
3. Mesozoic–Tertiary exhumation, erosion, and nondeposition ca. 80–2 Ma.
4. Quaternary deposition.

Goldthwait (1924, p. 59) first recognized that the key to the erosional model is the age of the basin fill. Valley formation predates the oldest valley fill, which would imply a pre-Cretaceous age for many Nova Scotia valleys. Using established rates of denudation (Denny 1982), however, the present topography can be no older than the late Cenozoic. This paradox can be resolved if we consider the present topography as structural and older, rather than erosional and younger.

This hypothesis requires a thick cover of Mesozoic sediment (1–2 km) to account for ~80 million years of exhumation or erosion occurring since the mid-Cretaceous, the inferred timing of the tectonic event, and the last record of deposition before the Quaternary. Cretaceous outliers in northern Nova Scotia, such as Diogenes Brook, Belmont, and Brierly Brook (Fig. 1), range in elevation from 20–100 m above sea level. It is unlikely that these outliers would have survived erosion throughout the late Mesozoic and Cenozoic without substantial cover. Freshwater deposits (Chaswood Formation) in the lowlands far below present sea level imply regional uplift to account for the lack of marine incursion during Mesozoic and Cenozoic periods of higher eustatic sea levels (Haq et al. 1987). Tertiary sediments are absent in Maritime terrestrial basins, so Cenozoic cover was probably minimal, but a large Tertiary basin offshore implies considerable Cenozoic erosion (Grant 1994). A rough estimate of the 1.6 km of Mesozoic cover can be derived by simply multiplying a conservative estimate of the denudation rate for the Appalachians (20 m/Ma; Denny 1982) by the elapsed time of erosion (80 million years).

Thermal maturation studies lend support to the idea of substantial Mesozoic cover. The depth of burial of lignite beds within the Chaswood Formation has been inferred to be 1 km based on vitrinite reflectance values between 0.31 and 0.48% (Hacquebard 1984; Stea et al. 1996) and forward modelling of apatite fission-track data (Arne et al. 1989), assuming an average geothermal gradient of 30°C/km. 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.

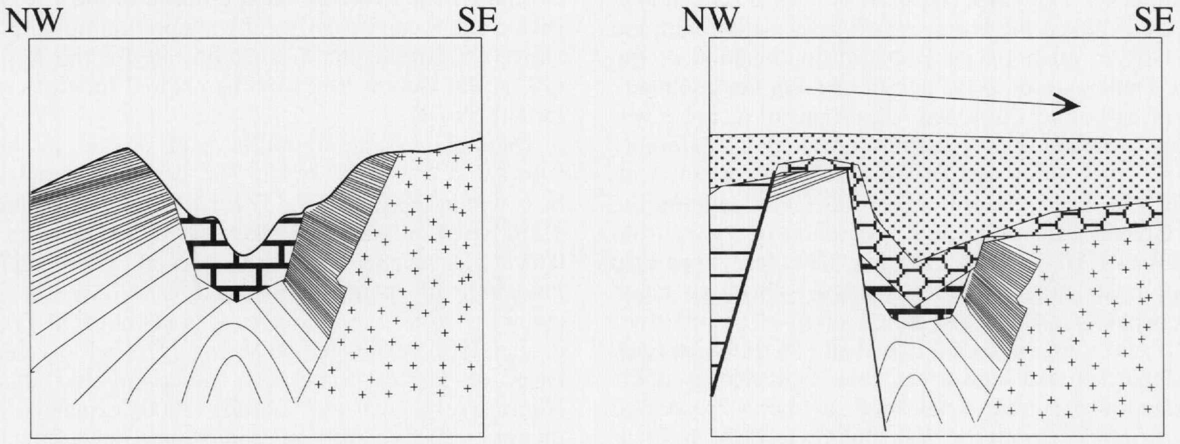
The structural-exhumation hypothesis infers that Carboniferous and Mesozoic sediment was eroded from the tops of Mesozoic horst blocks, such as Wittenburg Mountain, made of resistant older rocks (Fig. 13). If it is correct then a flux of reworked Early Cretaceous palynomorphs should be recorded in the 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.

Conclusions

The Early Cretaceous Chaswood Formation consists of economically important deposits of unconsolidated quartz sand and kaolinitic clays. The Chaswood Formation sediments can be subdivided into three members, with upper and lower members dominated by fluvial facies and the middle member of lacustrine origin. Small fault-bounded basins filled with up to 150 m of these sediments were formed by a mid-Cretaceous tectonic event that faulted and folded the sediments. Based on these data the topography of Nova Scotia is interpreted as structural, rather than erosional in origin, and over 1 km of Mesozoic cover is inferred.

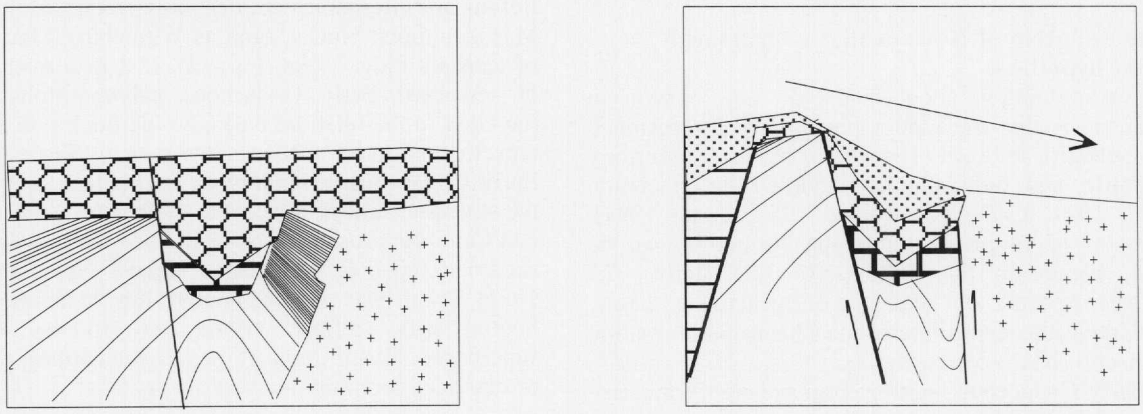
The sedimentologic and structural models presented in this paper have an important bearing on exploration strategies for industrial minerals in the Chaswood Formation. These deposits are undoubtedly more widespread throughout the drift-covered Carboniferous and Triassic basins of Nova Scotia. Many undiscovered buried grabens and half-grabens (some of which can be quite narrow < 500 m) may harbour

Fig. 13. Structural-exhumation hypothesis for the evolution of Nova Scotia landscapes. (*a*) Carboniferous sediments deposited in continental-epeiric basins, with (*b*) Pediplain formation in the Late Carboniferous. (*c*) Triassic rifting and landscape rejuvenation. Deposition of Triassic–Jurassic sediments in the Fundy Basin. (*d*) Deposition of 1–2 km^2 Early Cretaceous sediments in a low-relief coastal plain fluvial environment. North–south regional consequent drainage. Residuum in upland areas feeds the deltas and provides kaolin and quartz. (*e*) Mid-Cretaceous diastrophism creates or reactivates basin faults forming structural valleys (e.g., Elmsvale basin) followed by further Tertiary uplift and denudation. Subsequent valleys formed. Regional subsidence? (*f*) Quaternary modification, valley incision. Note: Arrows denote drainage directions.



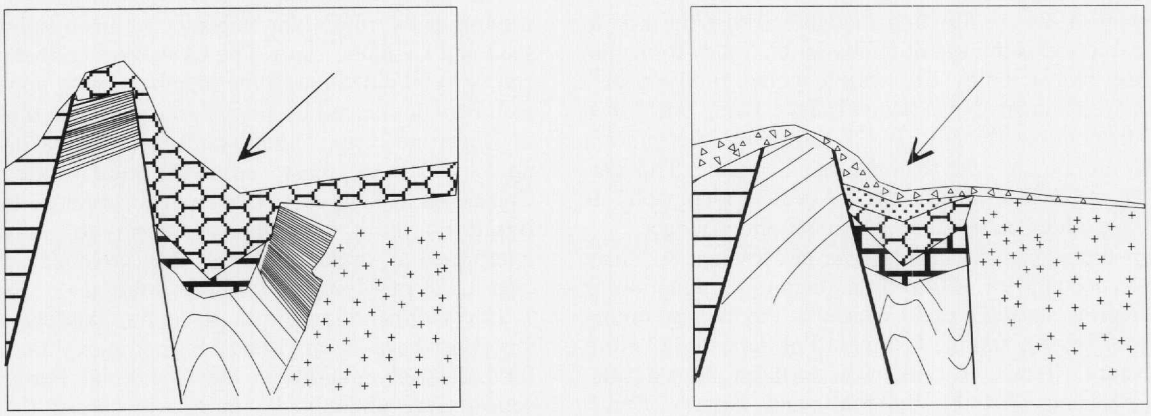
(A) Early Carboniferous

(D) Early-Mid Cretaceous



(B) Late Carboniferous

(E) Mid-Cretaceous – Tertiary



(C) Triassic–Jurassic

(F) Quaternary

the remnants of these sediments. The best potential for preservation from glacial erosion, however, may be in basins on the southeast or down-glacier side of horst blocks, such as Wittenburg Mountain (Fig. 4).

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