Post-Early Cretaceous Faulting in the Musquodoboit Valley, Nova Scotia[1]

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Introduction

Early Cretaceous outliers of unconsolidated, quartz-rich sand, kaolin and lignite have been known to exist in the Carboniferous and Triassic basins of Nova Scotia and New Brunswick (Ries and Keele, 1911; Stevenson, 1959; Lin, 1971; Fowler, 1972; Dickie, 1986). Some of these deposits are presently mined for industrial clay, brick, aggregate and glass-sand. A mapping, drilling and seismic program, conducted jointly by the Nova Scotia Department of Natural Resources and the Geological Survey of Canada, has led to the discovery of large hidden valleys of Mesozoic age, buried under thick glacial deposits. Finck *et al.* (1995), Pullan *et al.* (1997), and Stea *et al.* (1996, 1997) have described the stratigraphy and geometry of these valleys as the project progressed, and have demonstrated the potential for economic quantities of kaolin suitable for use in the paper industry. A company was formed (Kaoclay Resources, Inc.) to further evaluate the economic potential of these Cretaceous sediments and they are currently exploring for kaolin deposits (cf. Gillis, 1997). In this report we will document the evidence for a hitherto unknown post-Early Cretaceous fault system in the Musquodoboit Valley (NTS 11E/03) and discuss the implications for regional tectonic history and landscape evolution. Some of the seismic and drillhole data used in this report have been provided courtesy of Kaoclay Resources, Inc.

Seismic Reflection Survey Methods

High resolution reflection seismic profiles have proven to be very effective in delineating the architecture of unconsolidated Mesozoic and Cenozoic deposits (Pullan *et al.*, 1997). The seismic profiles used in this study were collected in 1996 by the Geological Survey of Canada (Pullan *et al.*, 1997) and in follow-up exploration of the Musquodoboit Valley (Gillis, 1997).

Both seismic programs involved the recording of continuous 12- and 24-fold common midpoint (CMP) data. The CMP technique, outlined in Steeples and Miller (1990), involves recording multiple traces with the same midpoint between source and receiver positions, and "fold" refers to the number of traces stacked or summed to produce a single trace on the final section after normal move-out corrections. This stacking procedure is designed to improve the signal to noise ratio. 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. Details on the data acquisition and processing parameters used in the seismic reflection surveys are given in Stea *et al.* (1996), Pullan *et al.* (1997) and Gillis (1997).

Seismic Stratigraphy and Lithostratigraphy

The Early Cretaceous Chaswood Formation (Stea *et al.*, 1997) is confined to narrow, steep-sided basins in the Musquodoboit and Shubenacadie valleys (Figs. 1, 2). The largest area of subcropping Cretaceous sediment is a northeast-southwest basin confined to the Musquodoboit Valley, herein termed the Elmsvale Basin. The Elmsvale Basin extends for 15 km along the valley and has a maximum width of 4 km. The basin consists of two wide parts, joined by a narrow neck near Middle Musquodoboit (Fig. 2).

Seismic stratigraphic profiles were collected across an inferred fault at the northern edge of the Elmsvale Basin by the Geological Survey of Canada and Kaoclay Resources Inc. (Fig. 2). Drillholes on the north and south side of the fault on each of these profiles provide lithostratigraphic control.

Glenmore Road Transect

The Glenmore Road seismic transect shown in Figure 3 runs northeast-southwest through the Village of Middle Musquodoboit in the middle of the Elmsvale Basin (Figs. 2, 3). A major discontinuity disrupts the basin fill

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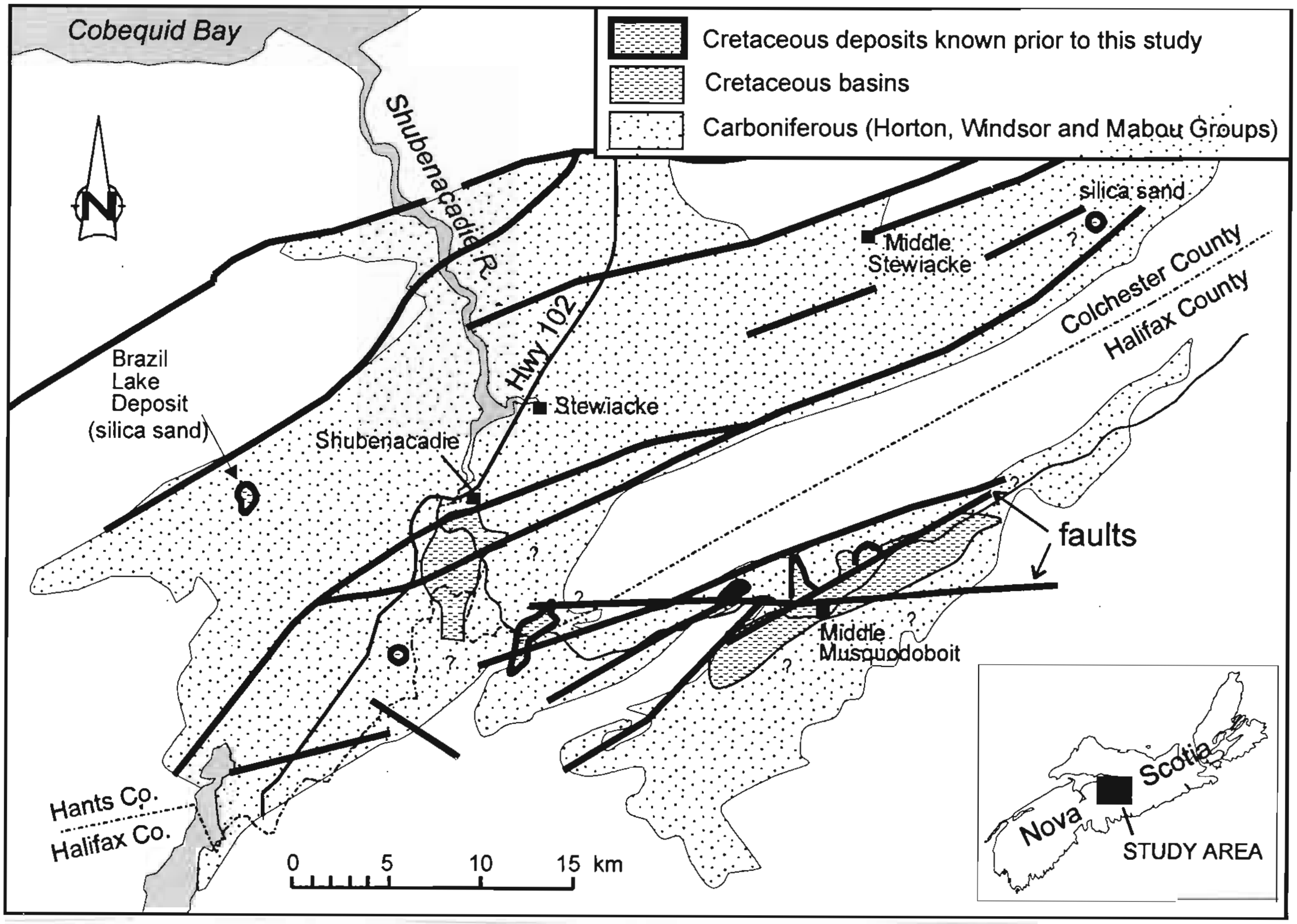

Figure 1. Map of central Nova Scotia study area showing previous occurrences and mapped Cretaceous basins. The fault defining the northern boundary of Carboniferous rocks north of Middle Musquodoboit is called the North Border Fault (after Giles and Boehner, 1982).

on the north side of the Elmsvale Basin. South of the discontinuity coherent reflections descend to -140 masl (i.e. metres above sea level; sea level is approximately 30 m below the ground surface in the area, see Fig. 3), whereas north of the discontinuity acoustic basement lies at -20 to -40 m. Diamond-drill hole GR-97-19, south of the discontinuity, intersected Carboniferous mudstone bedrock at -35 m, indicated by a series of gently northward-dipping reflections at the base of the acoustic section (Fig. 3). Above bedrock, the core consists of unconsolidated sand and clay between -35 m and +20 m (Chaswood Formation) and glacial drift above 20 m.

South of the discontinuity, four seismic sequences can be differentiated within the basin fill, with the fourth, uppermost sequence represented by the overlying Quaternary glacial sediments. Sequence 1 consists of northward-dipping, high amplitude reflections (Fig. 3) that terminate at the discontinuity. The uppermost reflection of sequence 1 represents the contact between Carboniferous bedrock and Mesozoic/Cenozoic unconsolidated sediments. The basin fill attains a maximum thickness of 170 m next to the zone of chaotic reflections which marks the discontinuity.

Sequence 2 has relatively few coherent reflections and consists of thick sections of silica sand, interbedded with thin silty-clay horizons, prevalent near the base of DDH GR-97-19 and characteristic of the lower member of the Chaswood Formation (Stea *et al.*, 1997). Sequence 3 consists of high amplitude reflections, that lap out against the 2/3 sequence boundary marked by the dashed line on Figure 3. These high amplitude reflections may indicate lignite horizons, which are common in the middle member of the Chaswood Formation. Stea *et al.* (1996) noted a similar unconformity in Cretaceous basin fill at Shubenacadie, which may indicate a base-level fluctuation or erosion concomitant with major sedimentary facies

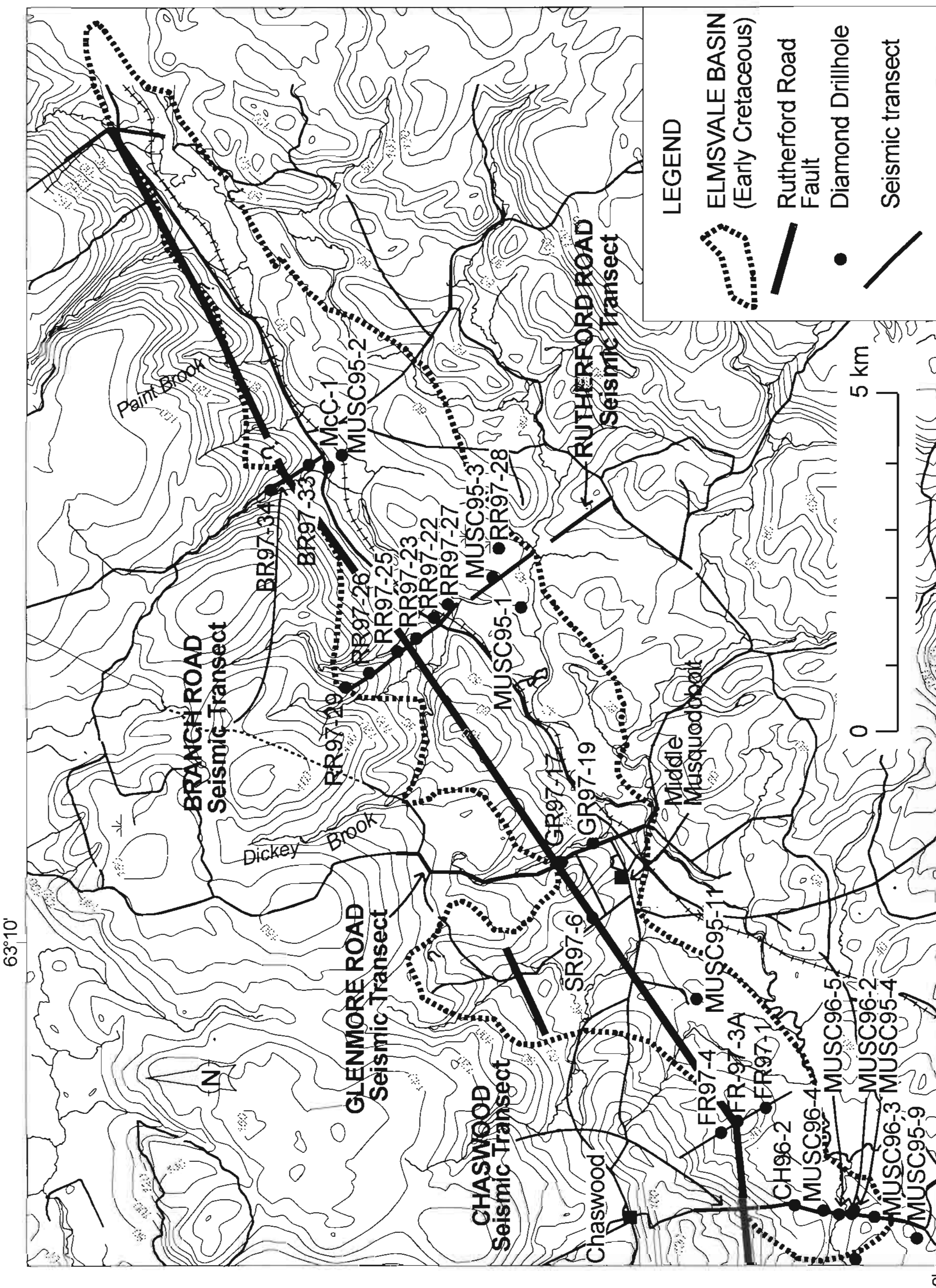

Figure 2. Map of the Elmsvale Basin showing the location of the Rutherford Road Fault, drillhole locations and seismic transects.

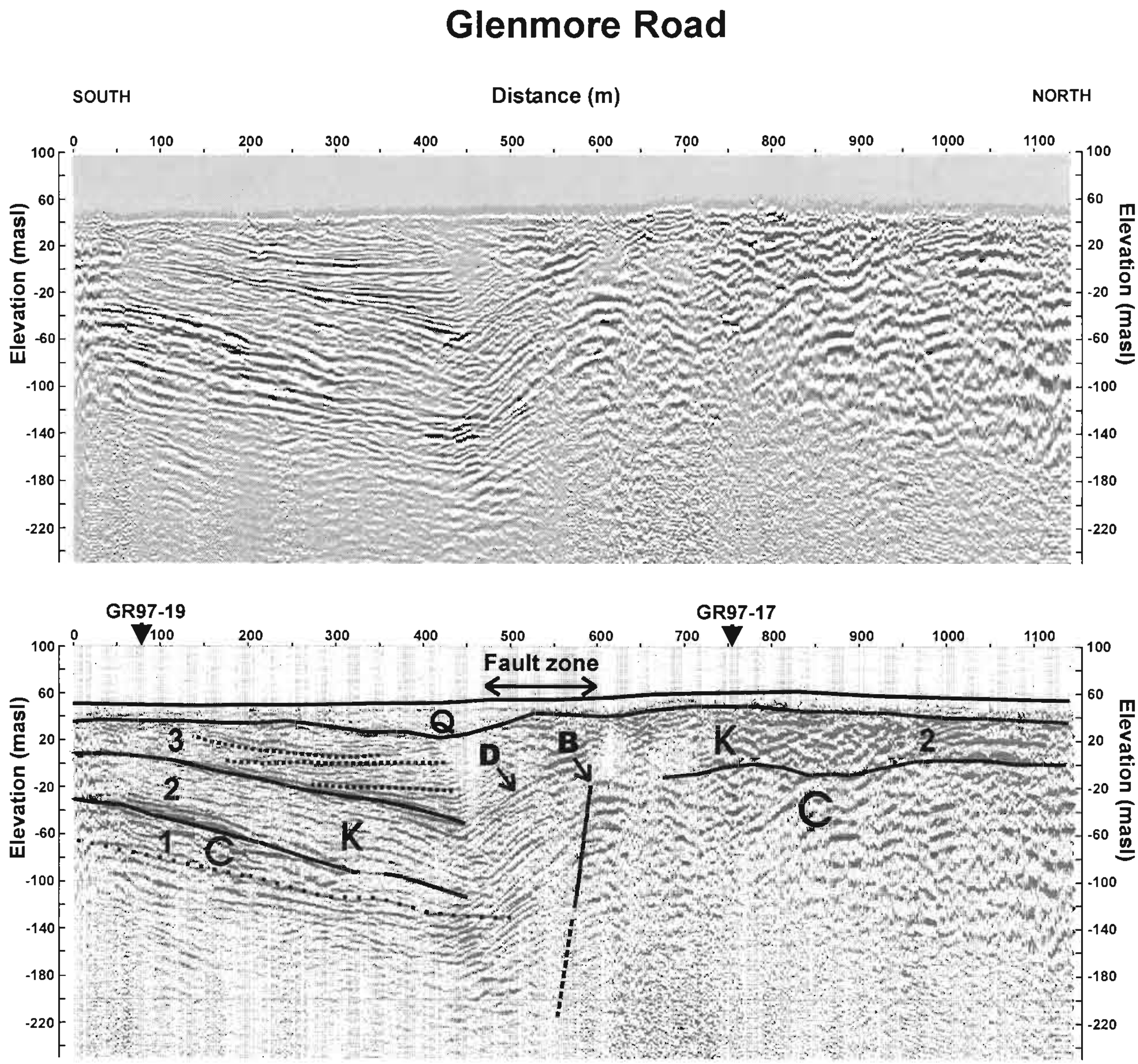

Figure 3. Seismic profiles and interpretation of part of the Glenmore Road transect. Time sections have been converted to depths in the profiles (masl = metres above sea level). The upper profile is an amplitude display where the dark areas are positive amplitude, the same as the dark lines on the variable area display below. C-Carboniferous bedrock, K-Cretaceous sediment, Q-Quaternary glacial deposits, D- diffractions, B-edge of competent rock. Seismic sequences numbered 1-3.

changes. Sequence 4 corresponds to glacial drift cover, not well resolved on the reflection profiles.

North of the discontinuity, the seismic profile is less coherent. A diamond-drill hole (GR-97-17) north of the discontinuity intersected Carboniferous mudstone at -10 m, Cretaceous Chaswood Formation strata between -15 and 20 m, and glacial drift above 20 m. The sediment/bedrock interface is marked by a poorly defined basal reflection zone, shown on Figure 3. Acoustic basement north and south of the seismic discontinuity is offset by what is intepreted to be a high-angle fault, with an apparent throw of greater than 100 m.

Rutherford Road Transect

The Rutherford Road transect (Fig. 4), northeast of Glenmore Road, also exhibits a distinct seismic break with deep, continuous, coherent reflections to the south, and shallow reflections to the north. Diamond-drill hole RR-97-25, north of the seismic discontinuity, encountered 75 m of till and mud (Quaternary) and only 5 m of mottled clay of probable Cretaceous age, overlying Carboniferous mudstone bedrock at -20 m. This bedrock/clay boundary is evident on the seismic line by a hummocky reflection at -20 m separating sequences 1 and 2 (Fig. 4). South of the discontinuity drillhole RR-97-23 intersected 50 m of glacial drift, and 130 m of Chaswood Formation strata, before bottoming in Carboniferous bedrock at -150 m. Sequence 2 has few continuous high amplitude reflections, corresponding to a drillhole record consisting mainly of thick clay-dominated beds and thin sand layers. Sequences 3 and 4 correspond to glacio-lacustrine(?) muddy sediment and till in the drillhole records.

The bedrock/clay high amplitude reflecting horizon (sequence 1/2 boundary) can be traced from south to north to an inferred fault where it is offset by a high-angle fault with a throw of nearly 100 m (Fig. 4; K. McNulty, pers. comm., 1997). High-angle patterns that crosscut interpreted stratal boundaries represent diffraction from point sources. The dip of the inferred fault surfaee may be significantly overestimated because of the attenuation of the (assumed) footwall acoustic signal under the hanging wall of the inferred fault. Shallowing of the highest point of the Carboniferous/Cretaceous contact along the fault, diffraction from steep rock surfaces, and signal attenuation make the precise location of the fault difficult to interpret.

Branch Road Transect

The Branch Road transect is located at the western end of the Elmsvale Basin (Fig. 2). A break in this seismic record occurs along an extrapolated straight line from the Rutherford Road transect to the Branch Road (Figs. 2, 5). The Cretaceous unconsolidated basin fill is thickest on the south side of an inferred fault, and thins rapidly on the north side (Fig. 5). Drillhole BR-97-34 encountered limestone at an elevation of 20 m (asl), directly under glacial drift. Refraction analysis of data acquired just north of this transect indicates a zone of high velocity (4100 m/s) <25 m below surface, which may be Cambro-Ordovician metasedimentary bedrock. Drillhole BR-97-33 encountered Chaswood Formation sand and silty clay at a depth of 30 m to -20 m, but the hole was abandoned at that depth. Drillhole MUSC95-2, just south of the Branch Road transect (Stea *et al.*, 1997; Fig. 2), penetrated to the Cretaceous/Carboniferous bedrock eontact at 140 m depth. On the south side of the Branch Road transect, the base of the seismic profile, at an elevation of -120 m, consists of high amplitude, continuous reflections (Sequence 1). The complex nature of this reflection package may result from interfaces between bedrock and low velocity, brecciated zones, seen in the MUSC95-2 drillhole record. Sequence 2 is a series of discontinuous, high amplitude reflections that may correspond to clay/sand boundaries or lignite lenses. A high amplitude reflection that separates sequences 2 and 3 may be a lignite horizon, characteristic of the middle member of the Chaswood Formation (Stea *et al.*, 1997). Sequenee 4 is an incoherent, reflection-free zone, interpreted as a cover of massive glacial till(s).

Sequence 1 reflections are truncated in the northern end of the profile, giving way to a reflection-free area near the inferred fault (Fig. 5). Bedding appears to be steeply tilted in this region. Isolated high amplitude reflections above the fault zone may be boulder pavements in till or gas pockets (Fig. 5).

Discussion

The fault zone documented on the seismic profiles has strikingly similar characteristics in all profiles and can be traced in a nearly straight line from the eastern end of the Elmsvale Basin, from the Branch Road, the Rutherford Road and the Glenmore Road in Middle Musquodoboit (Gillis, 1997), to Chaswood at the western end of the Elmsvale Basin (Stea *et al.*, 1996). The term Rutherford Road Fault, after the type seismic transect, will be heneeforth applied to these fault traces.

Stea and Fowler (1981), Davies *et al.* (1984) and Akande and Zentilli (1984) observed that the unconsolidated Cretaceous sediments close to suspected faults are deformed and tilted, and suggested post-Cretaceous tectonism. Stea *et al.* (1996) gave further seismic evidence to bolster a late-faulting hypothesis, and proposed that the "hidden valleys" were formed during that faulting event. Dickie (1986), on the other hand, postulated that the Cretaceous sediments in the Elmsvale Basin were deposited in pre-existing fault-bounded basins of Carboniferous age.

Seismic stratigraphy and lithostratigraphy indicate an abrupt break on the northern edge of the Elmsvale Basin separating a basin filled with more than 100 m of Cretaceous sediments from Carboniferous bedrock or thin Cretaeeous outliers. This break or discontinuity is probably a steeply-dipping fault, as reflections indicating the Chaswood Formation/Windsor Group (Carboniferous)

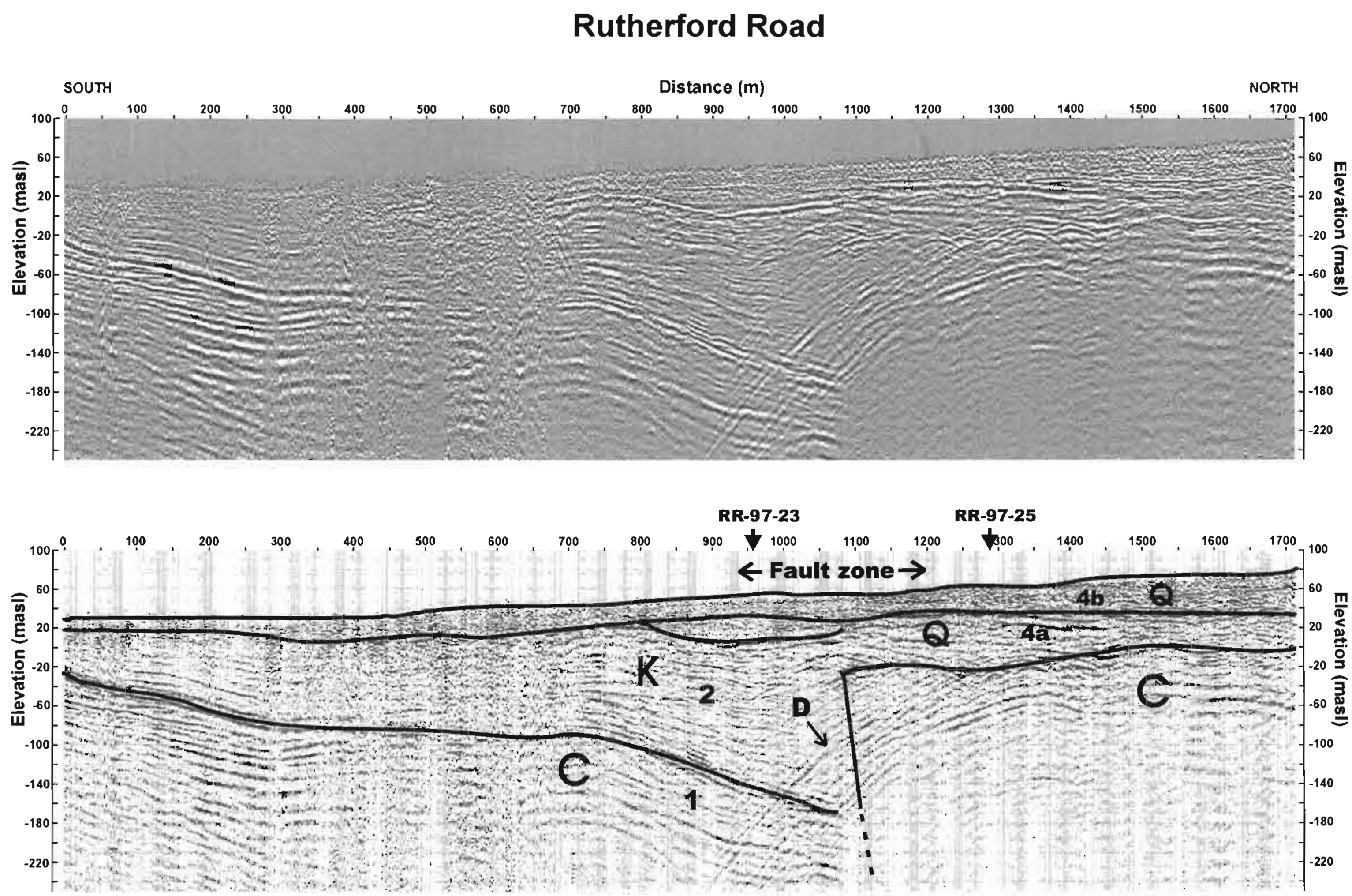

Figure 4. Seismic profile and interpretation of part of the Rutherford Road transect. Time sections have been converted to depths in the profiles (masl = metres above sea level). The upper profile is an amplitude display where the dark areas are positive amplitude, the same as the dark lines on the variable area display below. C-Carboniferous bedrock, K-Cretaceous sediment, Q-Quaternary glacial deposits, D- diffractions. Seismic sequences numbered 1-4. 4a - Quaternary glaciolacustrine mud, 4b - Quaternary glacial till.

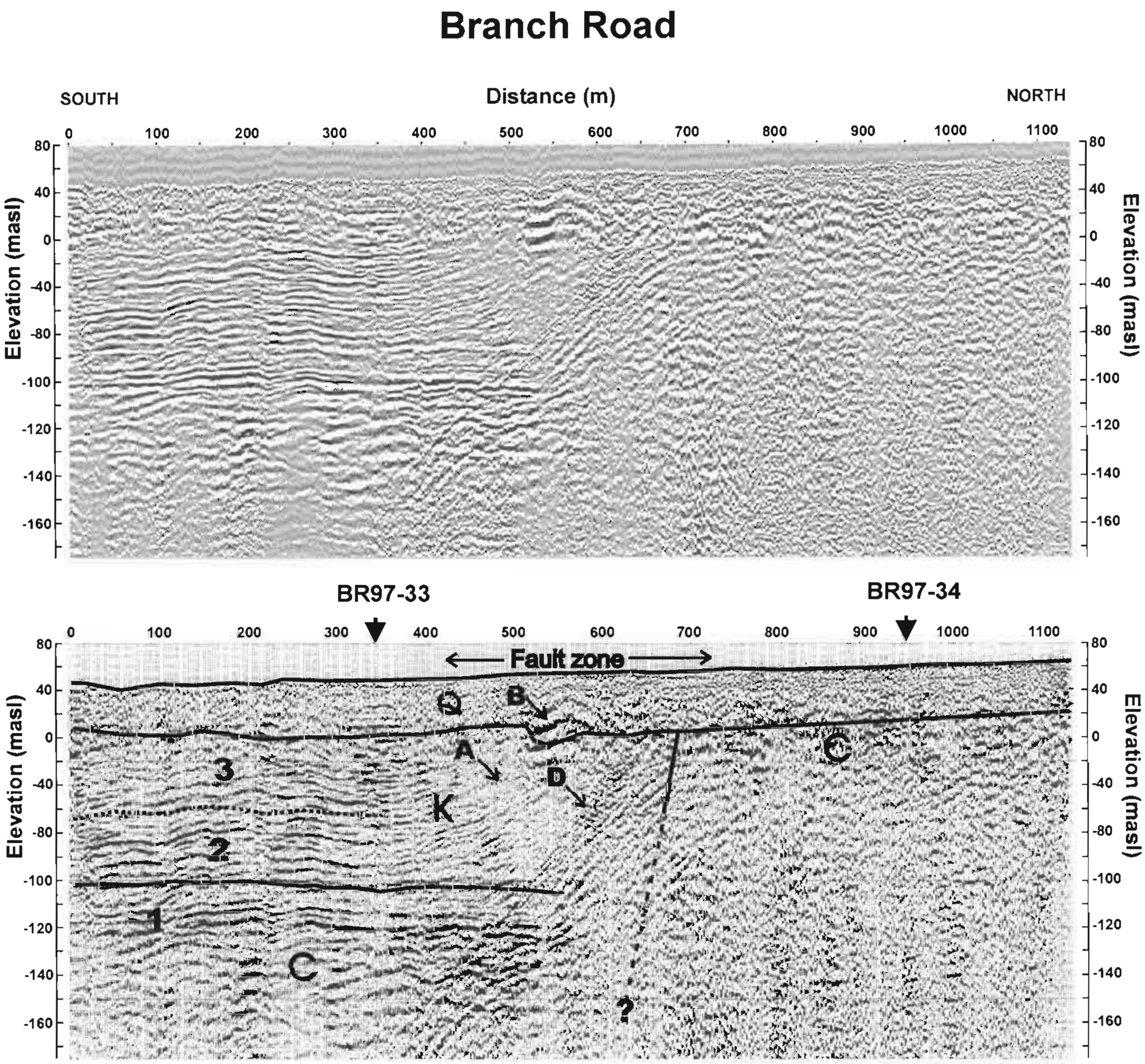

Figure 5. Seismic profile and interpretation of part of the Branch Road transect. Time sections have been converted to depths in the profiles (masl = metres above sea level). The upper profile is an amplitude display where the dark areas are positive amplitude, the same as the dark lines on the variable area display below. C-Carboniferous bedrock, K-Cretaceous sediment, Q-Quaternary glacial deposits, A- steep bedding, tilted, B-gas(?) or boulder layer above fault zone, D- diffractions. Seismic sequences numbered 1-3.

contact can be traced from cored sites to an offset zone indicating up to 100 m of dip-slip movement. On the Rutherford Road transect, seismic evidence suggests that the hanging wall is on the north side of the fault, and has moved upwards relative to the footwall to the south, hence the fault at this locality is reverse. Dip-slip displacement of the Chaswood Formation by this movement indicates that the Rutherford Road Fault is post-Early Cretaceous, the inferred age of the Chaswood Formation (Stea *et al.*, 1997).

Kaoclay Resources geologists have observed deformation and apparent repetition of beds in core from drillholes near the Rutherford Road Fault (T. Coughlan, Jr., pers. comm., 1997). Stea *et al.* (1996) noted brecciated zones, ductile deformation and slickenside planes at the base of many cores from drillholes near the fault, along the Chaswood seismic transect (Fig. 2), but the deformation seems most intense near the contact with Carboniferous bedrock, and in the bedrock itself. Anomalous dips were observed in laminated silt-clay beds of the Chaswood Formation at the base of core MUSC96-2 (Fig. 2) at the southwestern edge of the Elmvale Basin.

Faults are suspected to form the northern boundary of the Musquodoboit Valley (North Border Fault, Fig. 1), separating the Carboniferous basin fill from horst-blocks of Cambro-Ordovician basement rocks (Boehner, 1974). Northeast-trending faults along the Meguma-Carboniferous contact along the northern border of the Musquodoboit Basin were identified by Boehner (1974). They were originally inferred from mineral exploration diamond-drill cores that intersected anomalously thick Carboniferous strata near the concealed contact with basement rocks of the Meguma Group. It is not certain whether the North Border Fault (Fig. 1) and the Rutherford Road Fault are temporally or spatially related.

It is interesting to note that reverse faulting and folding of Triassic strata may be associated with movement of the Cobequid Fault (Swift *et al.*, 1967; Greenough, 1995). This deformation is post-Jurassic, and Greenough (1995, p. 586) links it with the Early Cretaceous diastrophism observed offshore in the Orpheus Graben (King and MacLean, 1976) and the Grand Banks (Jansa and Pe-Piper, 1988). Wade *et al.* (1996) also describe compressional structures associated with dextral strike-slip motion along the Cobequid Fault. Pe-Piper *et al.* (1994) invoked reactivation of transform faults along the Orpheus Graben to explain mid-Cretaceous volcanism and a major mid-Cretaceous (Avalon) unconformity. This tectonic event may have been propagated throughout pre-existing northeast-trending subsidiary faults (e.g. North Border Fault?) of the Cobequid Fault system. Reverse as well as normal faults may be expected in this transform-fault setting.

It has long been assumed that Cretaceous sediments were deposited in pre-existing valleys and sinkholes formed through stream erosion and solution (cf. Goldthwait, 1924). Sediment maturity and exotic heavy mineral content (Stea and Fowler, 1981), however, indicate long distance transport and non-local sources for this material. This paradox can be resolved with a structural solution, in which the valleys were created after deposition of the Cretaceous sediments rather than before. Substantial Mesozoic vertical movement along faults may have initiated an exhumation cycle which eventually resulted in the present topography. Resistant older rocks were exhumed first from the horst blocks, buried under a thick Carboniferous and Cretaceous sediment pile. Depth of burial of lignite beds within Chaswood Formation has been inferred to be 1 km based on vitrinite reflectance values between 0.31 and 0.48% (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. Fission track resetting may have occurred as a result of higher heat flow during this tectonic event, rather than burial. If the exhumation hypothesis is correct then a flux of reworked Early Cretaceous palynomorphs should be recorded in the offshore basins within Middle to Late Cretaceous and perhaps Tertiary sediments.

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