SEDIMENTOLOGY, STRATIGRAPHY, AND DEPOSITIONAL HISTORY OF THE COAL MEASURES NEAR COTTAM SETTLEMENT, DEBERT-KEMPTOWN BASIN, NOVA SCOTIA

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Abstract

This study utilizes detailed core descriptions of two closely-spaced drill holes and a measured section of continuous outcrop along the Debert River to assess the sedimentology, stratigraphy, and depositional history of Westphalian C coal measures within the Debert-Kemptown Basin near Cottam Settlement, Nova Scotia. Five facies assemblages are recognized based on lithology, sedimentary structures, and fossilized plant and faunal remains. They include: open lacustrine deposits comprising organic-rich mudstone; lacustrine delta deposits comprising planar-bedded to cross-laminated sandstone, laminated siltstone, and mudstone successions; distributary channel deposits comprising massive to trough cross-bedded sandstone; overbank deposits comprising rooted mudstone, siltstone and sandstone; mire deposits comprising coaly shale and high volatile A bituminous coal. The coal seams are economically significant, with low sulfur (<1%) and variable ash (10-30%) contents, although structural complications may hamper any future coal mining.

The relatively restricted study interval records a five-stage depositional history characterized by alternating periods of delta plain, mire, and freshwater lake/lacustrine delta development. The Cobequid fault produced subsidence generating accommodation space, and might have provided a means for regionally sourced drainage systems to be diverted into the Debert-Kemptown Basin. Changes in the availability of sediment from regionally sourced rivers may have produced periods of high and low sediment supply, although climatic and eustatically driven factors may have exerted a significant control on sediment supply, as well as mire development. Coals could have formed during low stands and lakes/lacustrine deltas during high stands. Mires may have been nourished by groundwater discharge from alluvial fan deposits sourced from the paleo-Cobequid Highlands. Orographic climate change and differential subsidence may have also played a role in basin-fill development, although more evidence is required to prove or disprove either of these controls.

Key Words: Carboniferous, Maritimes Basin, Debert-Kemptown Basin, coal measures, fluvial-lacustrine

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CHAPTER 1: INTRODUCTION

1.1 Introduction

The Debert-Kemptown Basin is one of the smallest and least studied Carboniferous coal basins in Nova Scotia (Figure 1.1). Located north of the town of Truro in central Nova Scotia, the basin extends across Colchester and western Pictou counties from near Londonderry in the west to West River Station in the east (Figure 1.2). The coalfield comprises strata previously ascribed to the Pictou and Cumberland Groups or the informal Delaney formation. A recently published geologic map of the area with updated stratigraphic nomenclature subdivides the basin-fill into several formations, including the Late Carboniferous Chiganois River formation, which includes the coal measures near Cottam Settlement.

1.2 Coal mining history

The study area is located near Cottam Settlement, in the western part of the basin north of the town of Debert (Figure 1.2), and is in close proximity to the former Debert River and Berichan Resources mine sites (Figure 1.3). Stevenson (1958) summarized the history of coal mining in the basin, which commenced after coal seams were discovered cropping out along several Debert-Kemptown area rivers in 1836. A few short slopes, shafts, and levels were collectively driven near Coal Mine Brook and the Chiganois River (Belmont). However, little if any production ever occurred from these deposits. Development work on a deposit near Kemptown throughout the middle to late nineteenth century and intermittently from 1919 to 1947 resulted in roughly 7500 tons of coal production.

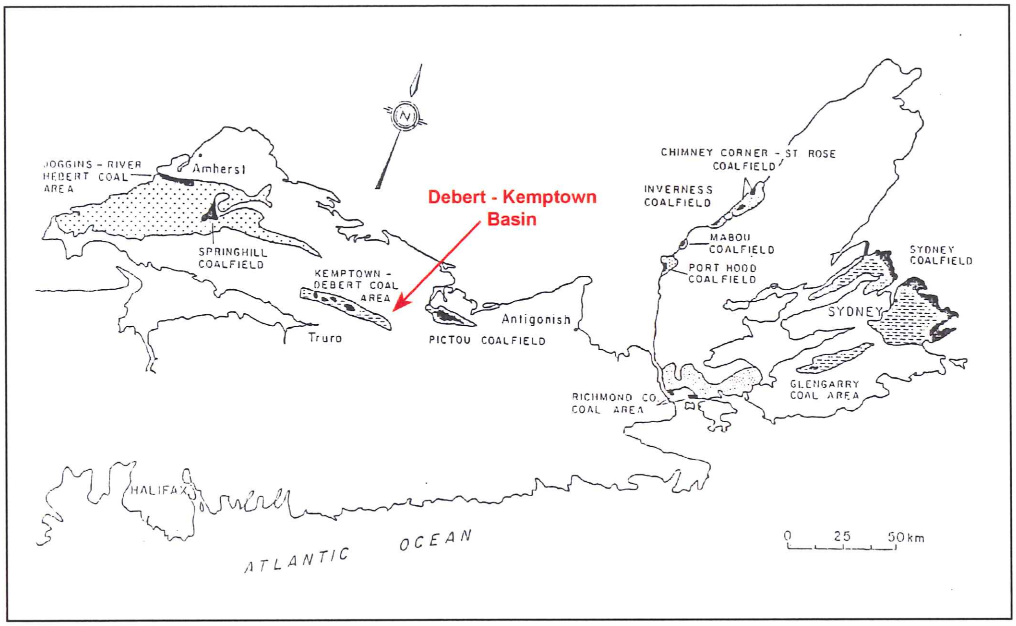


Figure 1.1. Location and size of the Debert-Kemptown Basin with respect to other major coal basins of Nova Scotia (modified Nova Scotia Department of Mines map).

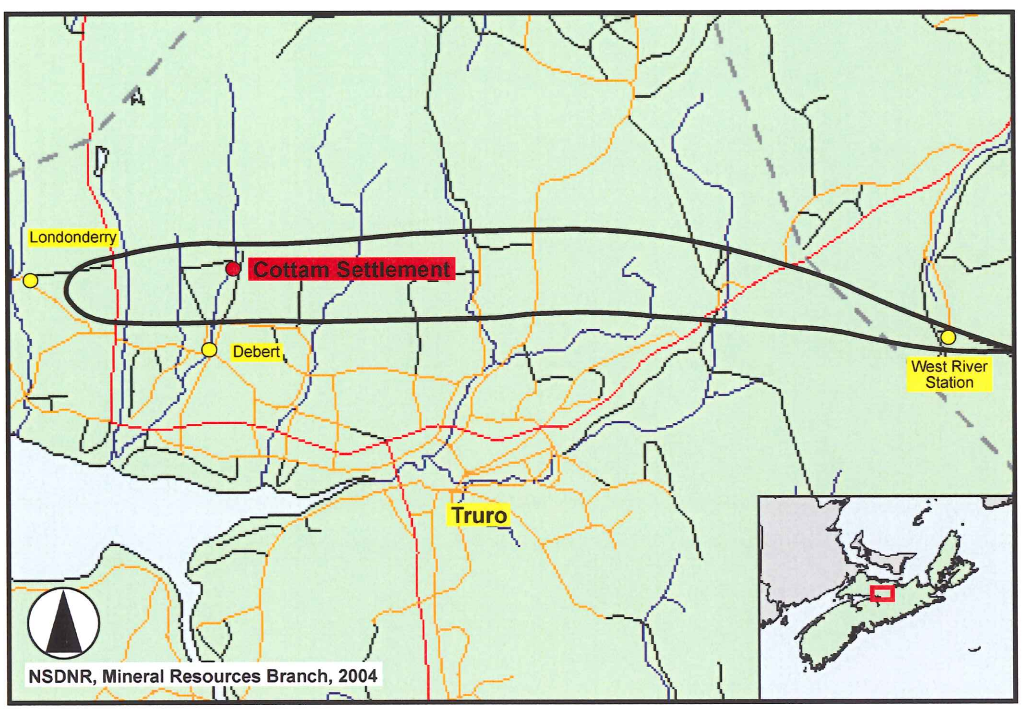


Figure 1.2. Geographic position of the Debert-Kemptown Basin (outlined by solid black line). Note the location of Cottam Settlement and the area of this study (modified Nova Scotia Department of Natural Resources online map).

The former Debert River Mine, which produced coal from the study area near Cottam Settlement, deserves special mention. Development of the deposit by the Colchester Coal and Railway Company began in 1903, and a 360-foot slope was driven along a 4.5 to 5-foot coal seam soon thereafter. The main slope was increased to 550 feet in 1905 after two additional coal seams 2.5 and 3.5 feet in thickness were identified by diamond drilling. A second coal seam was intersected and opened by a drift in 1907. A branch rail line was constructed joining the mine site with the Intercolonial Railway, and the first coal was shipped on July 9, 1907. Production peaked at 10 to 30 tons per day before the mine closed in 1908. After unsuccessful attempts to reopen in 1909, 1936, and 1951, the mine was finally abandoned in 1951.

Berichan Resources Ltd. operated a small surface coal mine several hundred metres east of the old Debert River Mine workings during 1999. The mine produced nearly 20,000 tons of coal over four months before groundwater inflow and coal seam displacement problems forced its closure in September 1999. The site was reclaimed later that year (MacDonald, 2001).

1.3 Previous work

Several nineteenth century geologists, including Abraham Gesner, Charles Lyell, and J.W. Dawson, studied strata within the Debert-Kemptown Basin. Gesner was the first to document several coal seams within Debert area strata (Gunn et al., 1987), which were later assigned a Carboniferous age by Lyell before being sub-divided into non coal-bearing and coal-bearing stratigraphic units by Dawson (Stevenson, 1958). Hugh Fletcher and W.A. Bell mapped Carboniferous rocks throughout the Debert-Kemptown area during the late 1800s and early 1900s (Naylor and Molyneaux, 1988), which supplemented additional mapping by I.M. Stevenson (1958) in the 1950s.

Focus within the basin shifted to identifying and outlining the extent of coal seams during the 1970s. The Nova Scotia Department of Mines (now Nova Scotia Department of Natural Resources) conducted a diamond drilling program from 1975-1977, which resulted in the completion of 21 cored drill holes mostly in the vicinity of Cottam Settlement, but also several near Belmont and Kemptown (Covert, 1975). D.P Lortie (1979) focused on regional structure and sedimentology during re-mapping of the north-western portion of the basin in 1979, aimed at outlining new coal occurrences in outcrop and establishing the stratigraphy of the area.

Numerous mapping projects and coal resource assessments of the basin were completed throughout the 1980s and early 1990s. Regional mapping of Colchester and Pictou County by Donohoe and Wallace (1982) supplemented detailed mapping of the Debert-Kemptown area by Naylor and Molyneaux (1988), who published a new map of the basin in 1992. Calder (1986) evaluated the sedimentology of five sites within the Debert-Kemptown Basin, which to date, represents the most detailed sedimentological work performed within the basin. Suncor Resources conducted a regional evaluation of the coalfield in 1986, which included renewed geological mapping, coal analyses, and new coal resource estimates (Gunn et al., 1987). Curragh Resources Inc. completed additional surface mapping and high-resolution reflection seismic surveys during 1991 in a new effort to evaluate the coal resource potential of the basin (Craven, 1991).

The most recent work within the Debert-Kemptown Basin has occurred near Cottam Settlement, for Berichan Resources Ltd. Work during 1995 focused on defining coal resources east of the old Debert River Mine workings near Cottam Settlement. The work consisted of a compilation study of all available data, followed by geological mapping, ground geophysical surveys (magnetic and EM), as well as diamond and auger drilling. The coal resource potential results from this assessment were favourable, and a small open pit coal mine opened in 1999 (Cullen, 1996).

1.4 Purpose and scope

To date, most work within the Debert-Kemptown Basin has focused on regional mapping of the strata and evaluating the resource potential of the coals. Previous geologists have provided regional descriptions of the sedimentology and stratigraphy of the strata, but only Calder (1986) has published detailed information on the sedimentology and depositional history of the coal measures. This study addresses the lack of detailed sedimentological information on the coal measures by providing detailed descriptions of the facies and facies assemblages that occur near Cottam Settlement, and interpreting the depositional history of the area.

1.5 Methodology

Sedimentological data from two Nova Scotia Department of Natural Resources drill cores and field observations from an outcrop section along the Debert River (Figure 1.3), provide a complete record of the sedimentology of the coal measures near Cottam Settlement, and enable an accurate interpretation of the depositional history to be made.

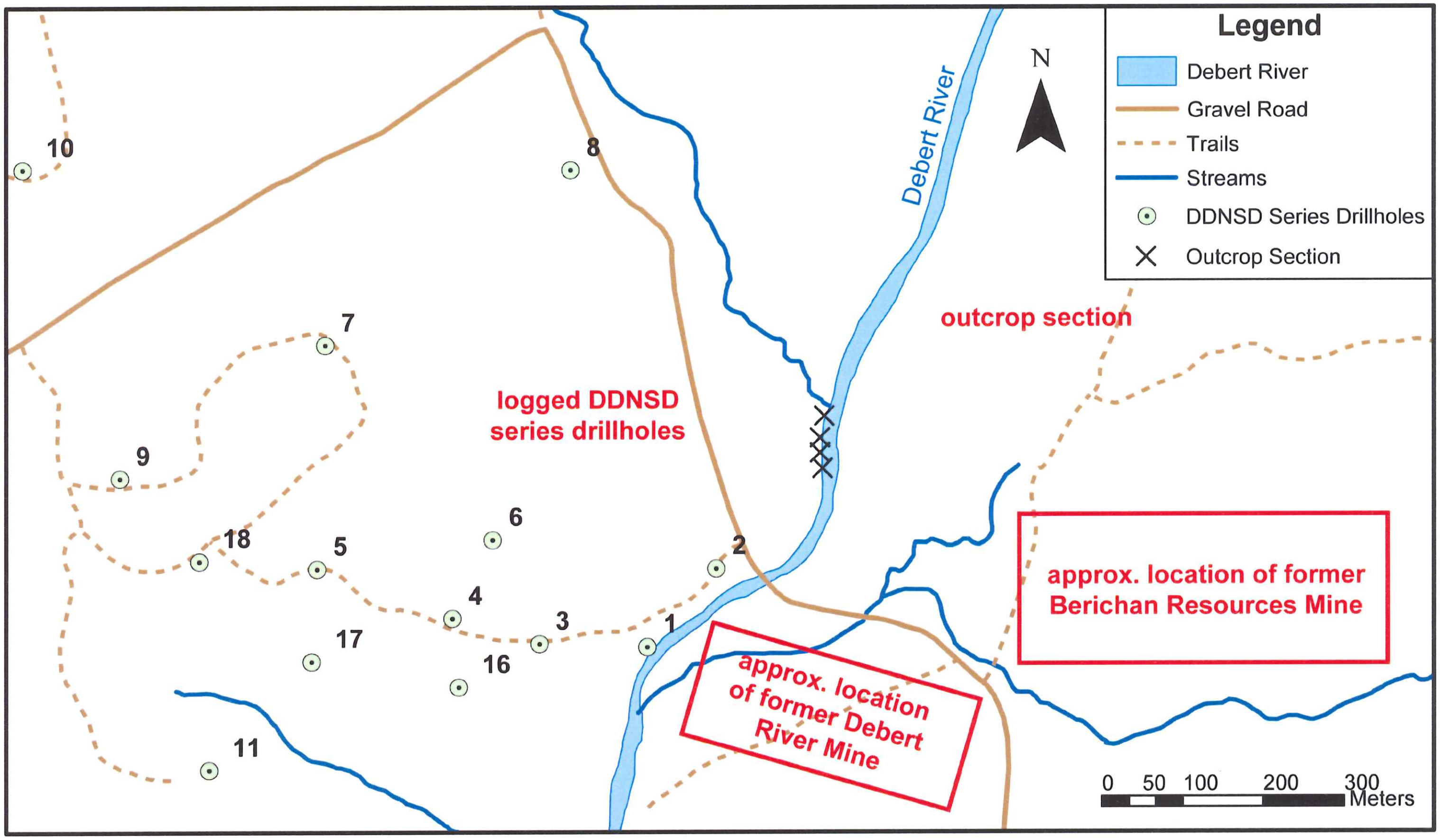


Figure 1.3. Map of the study area (Cottam Settlement) showing locations of the DDNSD-series drill holes, outcrop section, and former Debert River and Berichan Resources mine sites.

A common stratigraphic interval in two closely-spaced drill cores (DDNSD-2 and DDNSD-6) from the Nova Scotia Department of Mines drilling program near Cottam Settlement was logged centimetre by centimetre over the summer of 2004 at the Nova Scotia Department of Natural Resources Core Library in Stellarton, Nova Scotia. The total thickness measured in each drill core above a prominent red-bed succession, chosen as the base of the interval, was approximately 100 m. Strata within each drill core were relatively shallow dipping, with an average dip of 20 – 30°, and appeared less affected by faulting than strata in other drill cores of the DDNSD series.

Fieldwork along the Debert River near Cottam Settlement was performed over one day in late summer 2004. Detailed descriptions of the lithology, large-scale sedimentary structures, and facies relationships were noted. A 70 m segment of continuous outcrop identified during initial mapping was measured in detail using a 60-metre tape laid out perpendicular to strike. A total true-dip thickness of roughly 25 m was calculated for the measured section.

CHAPTER 2: GEOLOGICAL SETTING

2.1 Maritimes Basin

The Maritimes Basin is a large, nearly 150,000 km^2 basin that underlies a significant area of Atlantic Canada, including a portion of the Gulf of St. Lawrence and offshore regions of Nova Scotia and Newfoundland (McCutcheon and Robinson, 1987; St. Peter, 1993) (Figure 2.1). In a more narrow sense, the Maritimes Basin represents a basin complex that comprises numerous component sub-basins that were once partially connected intermontane basins separated by uplands or structural remnants of formerly distinct depocentres (Gibling et al., 1992; Gibling, 1995).

Many conflicting interpretations exist in the literature regarding the tectonic evolution of the Maritimes Basin (Bradley, 1982; McCutcheon and Robinson, 1987; St. Peter, 1993), although most interpretations still suggest a two-stage model (Ryan et al., 1987). The first stage is widely viewed as extensional (Bradley, 1982), involving reactivation of Acadian basement faults (St. Peter, 1993) and strike-slip movement along the Cobequid-Chedabucto and Hollow fault systems in the late Devonian to middle Westphalian (Ryan et al., 1987; Calder, 1998). A second stage of thermal sag (Bradley, 1982) is widely thought to have occurred from the middle Westphalian to early Permian (Ryan et al., 1987). This two-stage model is likely only a partial representation of a more complex basinal history (Gibling, 1995) that also includes a major transpression and transtension phase during the middle Carboniferous, and inversion during the Permian and Triassic (Calder, 1998).

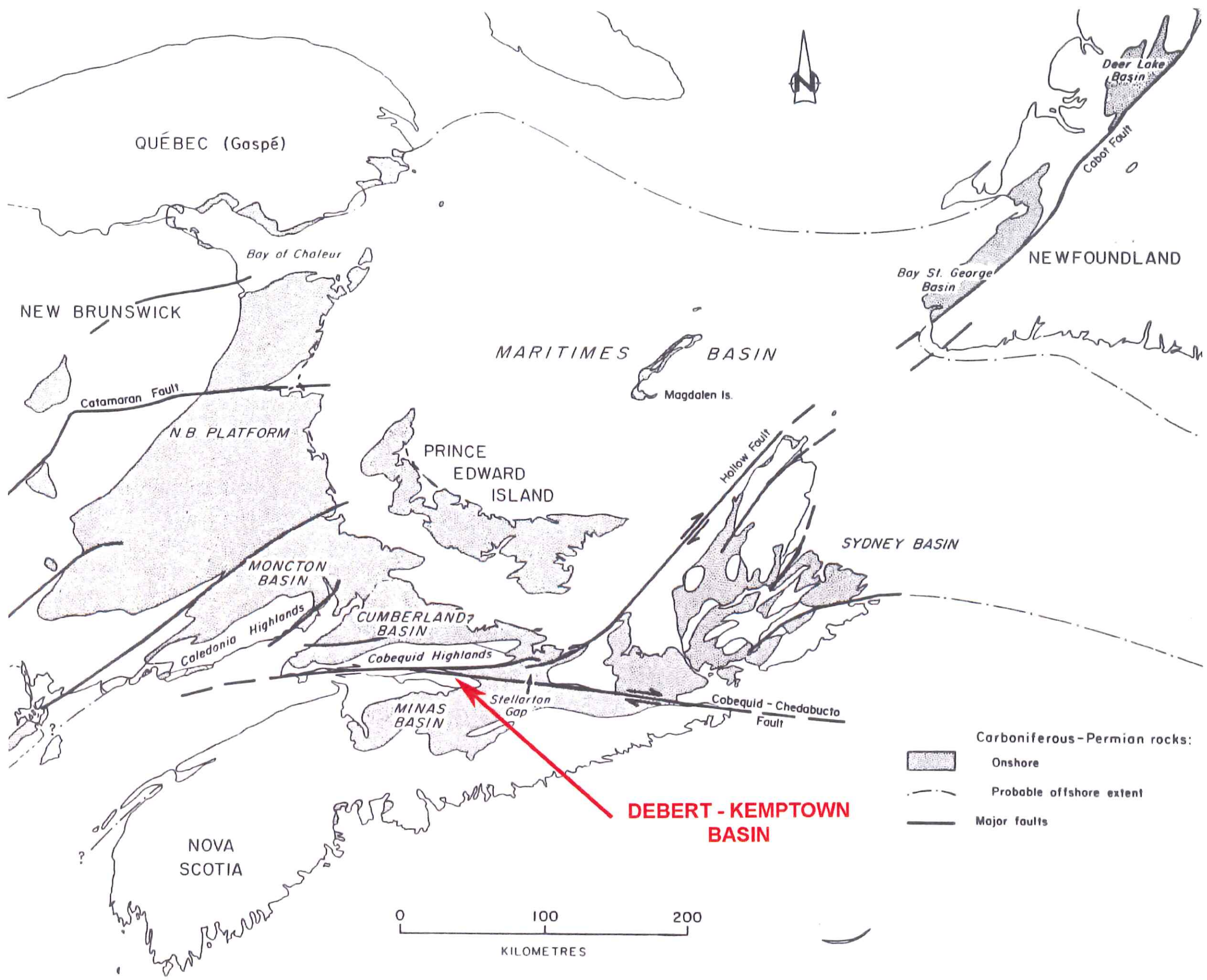


Figure 2.1. The onshore distribution and offshore extent of Upper Paleozoic rocks in the Maritimes Basin. Note the location of the Debert-Kemptown Basin in relation to other major sub-basins and faults (modified after Gibling et al., 1992).

2.2 Paleogeographic setting of the Maritimes Basin

Sedimentation began across the Maritimes Basin (positioned within Euramerica) shortly after the closure of the Iapetus Ocean during the middle Devonian, and continued throughout the Carboniferous as Euramerica drifted northward across the equator and collided with Gondwana to form Pangea (Calder, 1998; Rygel et al., in press) (Figure 2.2a). Euramerica drifted into the paleoequatorial humid belt and coal window by the Late Carboniferous (Figure 2.2b), where seasonally wet to continually wet conditions persisted (Calder and Gibling, 1994). The Appalachian orogen to the southwest contributed drainage and sediment to the partially connected depocentres of the Maritimes Basin, and additionally acted as a climate barrier (Calder and Gibling, 1994; Calder, 1998). The development of rainshadows along the Appalachian mountain belt promoted sporadic dry periods amid otherwise rainy conditions, and together with the continued northward drift of the continent, ultimately promoted the passage of the Maritimes Basin through the coal window (Calder and Gibling, 1994; Rygel et al., in press).

2.3 Stratigraphy of the Maritimes Basin

The Maritimes Basin originated in the Devonian following the Acadian Orogeny, and comprises Grenville, Avalon, and Meguma basement, overlain by Upper Paleozoic basin-fill deposited during episodic periods of subsidence and uplift (Calder, 1998; Rygel et al., in press). Although strata crop out as isolated or partially connected belts separated by unconformities and disconformities, major Late Paleozoic rock groups have been identified in many component sub-basins of the

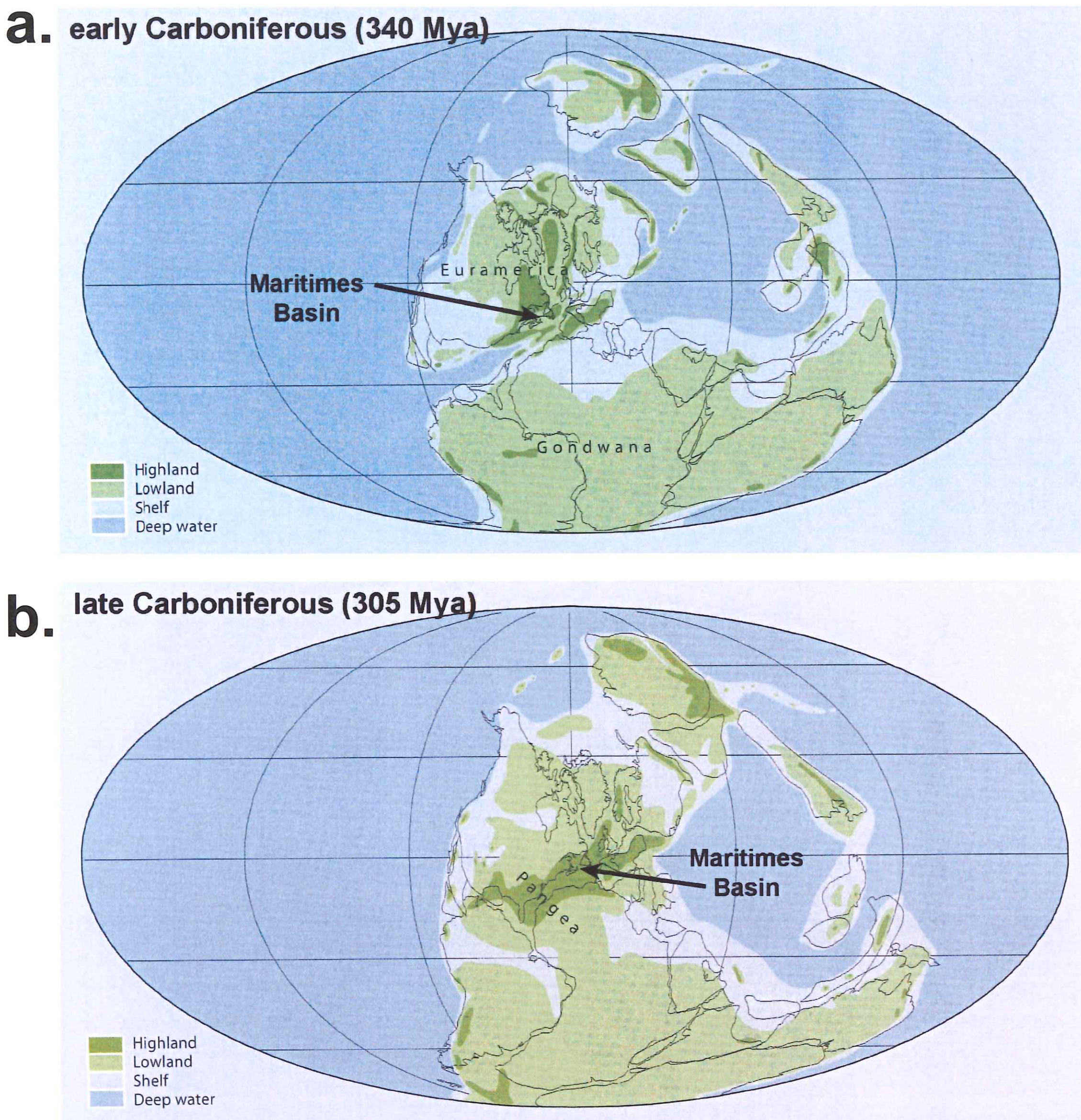


Figure 2.2 a-b. Paleogeographic reconstruction of the (a) Early and (b) Late Carboniferous. Note the position of the Maritimes Basin relative to the equator in each diagram (modified after Atlantic Geoscience Society, 2001).

regional Maritimes Basin (Gibling et al., 1992). A short summary of the six major stratigraphic packages of the Maritimes Basin follows below.

2.3.1 Fountain Lake and Horton Groups (Late Devonian-Tournaisian)

Fountain Lake and Horton strata record the earliest phase of deposition within the Maritimes Basin in a series of rift basins or half-grabens developed adjacent to major fault systems (Calder, 1998). The Fountain Lake Group is a unit of locally deformed bimodal volcanics and continental sedimentary rocks conformably or unconformably underlying the Horton Group (Gibling et al., 1992). Horton Group rocks are largely continental, consisting mainly of alluvial and lacustrine rocks that conformably to unconformably overlie Fountain Lake rocks (Gibling, 1995).

The continental sedimentary rocks, which include basin-margin conglomerates and basinal lacustrine deposits, together with the bimodal volcanics of the Fountain Lake Group, constitute a continental rift facies (Calder, 1998). Horton strata suggest deposition by alluvial fans, rivers, deltas, and perennial lakes or brackish bays within a series of rift basins (Martel and Gibling, 1996). Sub-aerial, bimodal volcanism occurred in response to movement along major Acadian fault zones (Boehner et al., 1986), while fault-bounded margins (Hamblin and Rust, 1989) shed large volumes of detritus that fine upwards through alluvial and lacustrine facies as local subsidence and uplift changed over time (Boehner et al., 1986).

2.3.2 Windsor and Mabou Groups (Viséan-Early Namurian)

Windsor Group strata record the transgression of the Windsor Sea across the Maritimes Basin, ending predominantly continental sedimentation (Rygel et al., in press). The Windsor Group comprises a sequence of marine evaporites (gypsum, anhydrite, halite, and potash), limestone, and intercalcated red-beds that conformably to unconformably overlie the Horton Group (Gibling et al., 1992).

Increasingly arid conditions and restricted inflow of the Windsor Sea, combined with declining subsidence and a transition to thermal subsidence (Rygel et al., in press), resulted in the deposition of cycles of evaporites, red-beds, and marine carbonates (Boehner et. al, 1986). The Windsor Sea retreated during the late Viséan, effectively ending Windsor Group deposition, although maximum transgressions continued to influence deposition of the Mabou Group (Calder, 1998).

The Mabou Group represents a transition to continental sedimentation from the marine conditions that dominated throughout the deposition of the Windsor Group (Boehner et al., 1986). Mabou Group strata conformably and disconformably overlie the Windsor Group, and consist of grey fine-grained calcareous facies and carbonate, along with minor gypsum and salt, that grades upwards into a grey and red facies with less carbonate (Crawford, 1995).

The Maritimes Basin underwent a fundamental change from a marine and evaporitic environment to a continental environment during the late Viséan (Crawford, 1995). Sub-aqueous sedimentation within a lacustrine environment characterizes lower Mabou sedimentation before giving way to fluvial sedimentation typical of the upper Mabou Group (Crawford, 1995). The climate became increasingly less arid and more sub-humid during this time, with the first appearance of coal near the top of the Mabou Group (van de Poll et al., 1995).

2.3.3 Cumberland and Pictou Groups (Middle Namurian-Westphalian D)

The deposition of Cumberland and Pictou Group strata represents a fundamental change in the evolution of the Maritimes Basin from an extensional to transpressional and transtensional tectonic setting (Gibling, 1995). The Cumberland Group consists of grey coal-bearing strata deposited in braided, meandering, and anastomosing river systems, along with local alluvial fans, although lacustrine deposits occur within some sub-basins (Gibling et al., 1992). The Pictou Group comprises mostly red sandstones and mudstones and, unlike the Cumberland Group, contains few coals (Gibling et al., 1992).

Sedimentation within the Maritimes Basin was increasingly fluvial (Calder, 1998) during the deposition of the Pictou and Cumberland Groups. Thick sandstone successions suggest seasonal rainfall and erosion of inverted and uplifted source areas (Calder, 1998). Waldron et al. (1989) attributed this change in sedimentation to convergence of the Avalon and Meguma terranes along the Cobequid-Chedabucto fault zone. The Pictou Group represents a period of thermal sag, during which alluvial sedimentation expanded to cover much of the region outside smaller fault-bounded depocentres (Calder, 1998).

2.4 Debert-Kemptown Basin

The Debert-Kemptown Basin is a small, approximately 200 km^2 elongate sub-basin of the regional Maritimes Basin or possibly a structural remnant of a much larger basin that may have included the Minas Sub-basin (Craven, 1991) (Figure 2.3). Bounded on the north and south by the Cobequid and North River-Portapique faults, the basin comprises fine- to coarse-grained coal-bearing strata folded into

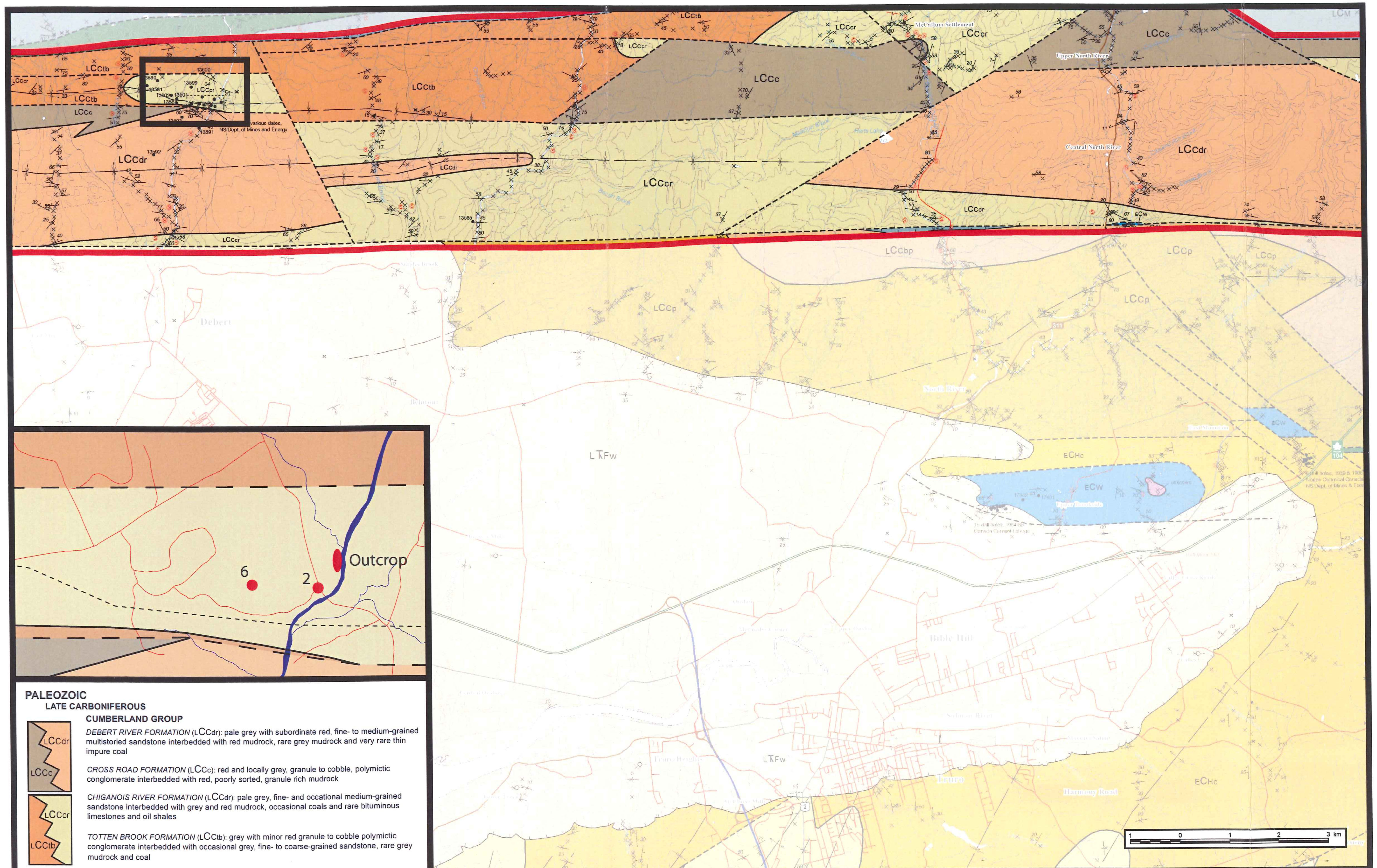


Figure 2.3. Geological map of the Truro area showing the distribution of Late Carboniferous strata in the Debert-Kemptown Basin (modified after Naylor et al., 2005). The approximate locations of the northern (Cobequid Fault) and southern (North River-Portapique Fault) limits of the basin are indicated by solid red lines. A close-up view of the geology of the Cottam Settlement area and a stratigraphic column of the basin-fill with unit descriptions are illustrated in the lower left hand corner of the map.

east-west trending synclines, and offset by numerous faults (Lortie, 1979; Naylor et al., 2005). Palynological studies by Dolby (1989) and those ages (based on palynology) reported by Calder (1986, citing Donohoe and Wallace, 1982), indicate the basin-fill youngs from early Westphalian B in the south and east to Westphalian C in the west. Strata near Cottam Settlement, in the north-western portion of the basin, are considered Westphalian C in age.

The Debert-Kemptown Basin appears to be more structurally complex than most other coal basins in Nova Scotia. Strata are characterized by rather abrupt changes in bedding attitude due to small-scale folding (limited) and extensive mesoscale faulting, including listric, high-angle reverse, normal, dip-slip, and sinistral and dextral strike-slip fault styles (Naylor and Molyneaux, 1988). Coal seams appear laterally discontinuous and displaced, and are thought to be uncorrelatable across the basin (Naylor, pers. comm., 2005). Lortie (1979) attributes the complex structural history of the basin to events along the Cobequid Fault.

2.5 Stratigraphy of the Debert-Kemptown Basin

The coal-bearing strata of the Debert-Kemptown Basin have been historically ascribed (undifferentiated) to the Cumberland and Pictou Groups (e.g. Stevenson, 1958), although the name Delaney formation, informally applied to all strata within the basin by Lortie (1979), has received the most recent widespread use. Lortie (1979) subdivided the Delaney formation into the lower McCallum member (conglomerate unit), middle West Branch member (major coal-bearing unit), and upper Debert member (red-bed unit). The extra-basinal conglomerates of the McCallum member and interbedded sandstone, siltstone, mudstone, and coal successions of the West Branch member were interpreted as the deposits of alluvial fans and fluvial, lacustrine, and coal-swamp environments by Calder (1986).

The informal use of the Delaney formation is abandoned on the most recently published geological map of the Debert-Kemptown area (Figure 2.3). Naylor et al. (2005) assigns the basin-fill to the Late Carboniferous Cumberland Group and further sub-divides the strata into the informal Totten Brook, Chiganois River, Cross Road, and Debert River formations, which almost certainly overlie the Parrsboro and Boss Point Formations (Naylor, pers. comm., 2005). For more detailed descriptions of each member, see Figure 2.3. Coal-bearing strata of the Chiganois River formation (comparable with the West Branch Member), which crop out near Cottam Settlement, are the focus of this study.

CHAPTER 3: FACIES

3.1 Introduction

Coal-bearing strata of the Chiganois River formation near Cottam Settlement comprise four rock types (coal, mudstone, siltstone, and sandstone). Rock types are divided into facies based on lithology, sedimentary structures, and fossils, which were classified as abundant, common, occasional, or rare. This chapter outlines the major lithological, sedimentological, and fossil characteristics of every facies, and provides an interpretation for each.

3.2 Coal

3.2.1 Coal & coaly shale facies (1a)

Description

Numerous coal seams, including those mined intermittently in the past and described in Section 1.2, are recognized in drill core and outcrop (Figure 3.1a, b). The coals are bright and generally range from 0.30-1.25 m in thickness, although the thinnest seams are dull and impure. Three high volatile A bituminous coal seams described by Cullen (1996) are low sulphur (0.5-1.1 %), with variable ash contents (8.8-31.1 %). The coal seams commonly grade into 0.05-0.45 m thick coaly shale with abundant plant fragments and coaly laminae. Thin coaly shale horizons occur frequently within dark grey and rarely within grey mudstone sequences, and commonly appear rooted.

Interpretation

This facies is interpreted as the organic deposits of peat swamps or mires. Scott (1987) summarized many of the fundamental aspects of peat formation (mire

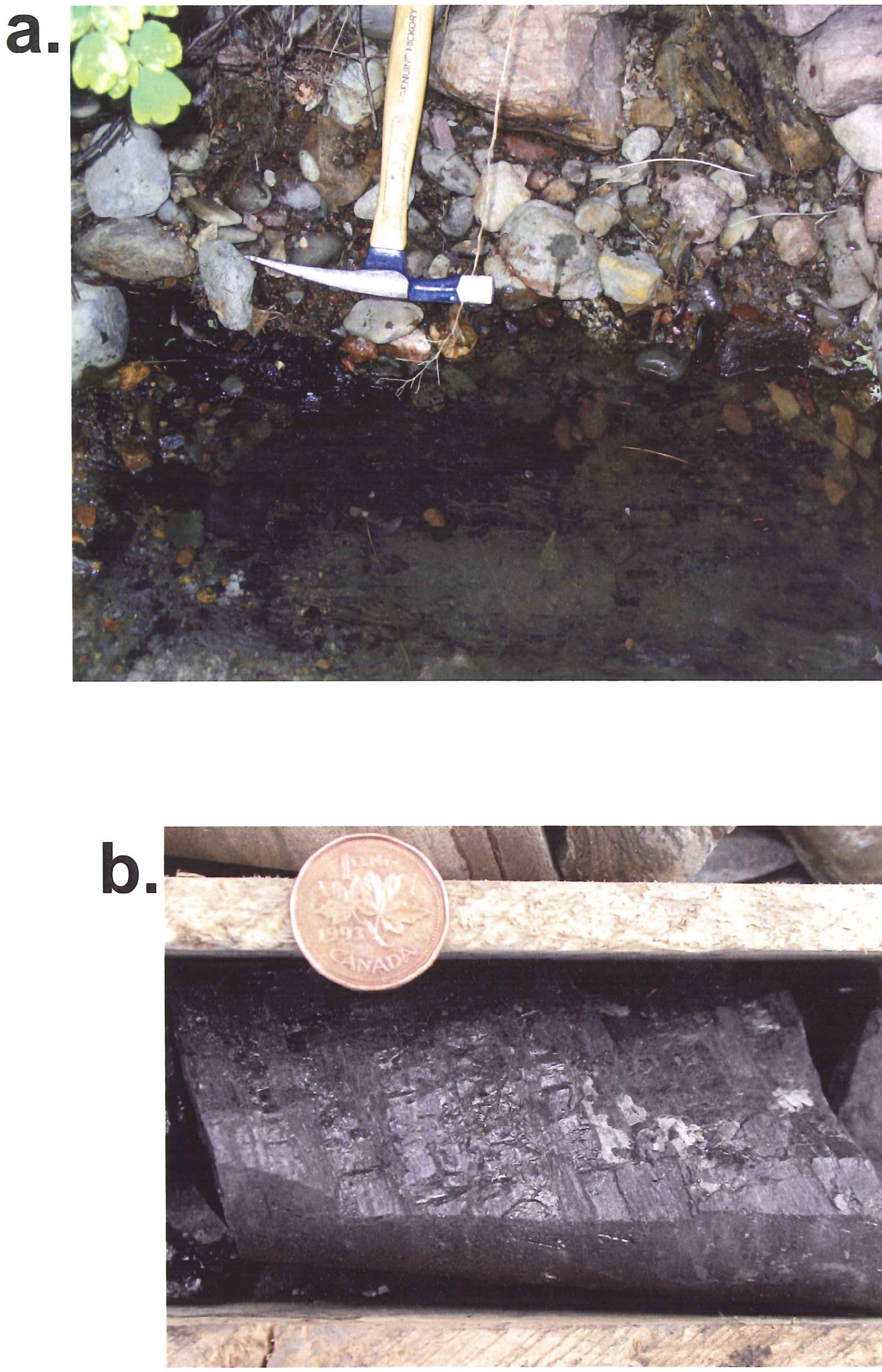


Figure 3.1 a-b. a) Coal seam (1a) cropping out south of the Debert River bridge near Cottam Settlement. Hammer is approx. 25 cm for scale. b) Close-up view of a piece of high volatile A bituminous coal (1a) from drill core DDNSD-2. Note penny for scale.

depositional conditions) and their influence on coal quality. Low-sulfur coals originate from precursor mires characteristically maintained by freshwater. Mineral matter may be incorporated into peat from groundwater or periodic influxes of detrital clastic material, producing coals with variable and high ash contents. Peat swamps that are occasionally flooded or choked off by influxes of clastic material typically form coaly shale, in which the organic material is not concentrated enough to form coal.

3.3 Mudstone

3.3.1 Black mudstone facies (2a)

Description

Accumulations of this facies are minor, and consist of individual 5-50 cm beds of black mudstone. Each black mudstone bed contains abundant ostracods and estheriids, in addition to occasional plant and shelly fragments.

Interpretation

The black color and high preserved organic content of this facies is indicative of anoxic conditions and a low rate of sedimentation. Similar mudstones described by Fielding (1984a) and Hartley (1993) were deposited in sediment-starved lakes with poorly-oxygenated floors. They formed as transported plant detritus and very fine-grained clastic sediment settled out slowly from suspension during periods of little or no sediment input. Ostracods, branchiopods, and other fauna thrived, at least periodically, in sufficiently oxygenated waters above anoxic lake bottoms that promoted the preservation of abundant organic material.

3.3.2 Grey mudstone facies (2b)

Description

Intervals of this facies range from 0.20-1.95 m in thickness, and generally consist of laminated (frequently carbonaceous) to non-laminated soft and friable grey mudstone (Figure 3.2a). Most mudstone beds contain well-preserved plant fragments (including *Cordaites*) and occasional siderite bands. Ostracods and *Estheria* occur in some intervals, but are rare.

Interpretation

The grey color and lower preserved organic content of this facies is indicative of quiet-water depositional conditions and a low rate of sedimentation. Comparable mudstones described by Fielding (1984a) and Tye and Coleman (1989) were interpreted as prodelta deposits. Benthic fauna are stressed by higher sediment loads (albeit still low) and laminations produced by suspension-settling of clay-sized sediment and transported plant detritus are occasionally preserved due to reduced burrowing (Collinson and Thompson, 1989; Tye and Coleman, 1989). Although similar non-laminated grey mudstones occur in overbank and abandonment deposits described by Coleman and Prior (1980), the absence of roots in this facies favours a prodelta origin for most beds.

3.3.3 Red-mottled grey mudstone facies (2c)

Description

The mudstone beds of this facies are similar to Facies 2b, but characterized by more abundant plant fragments and siderite bands, and commonly appear bioturbated with poorly-preserved root traces (Figure 3.2b). Red-mottled intervals up

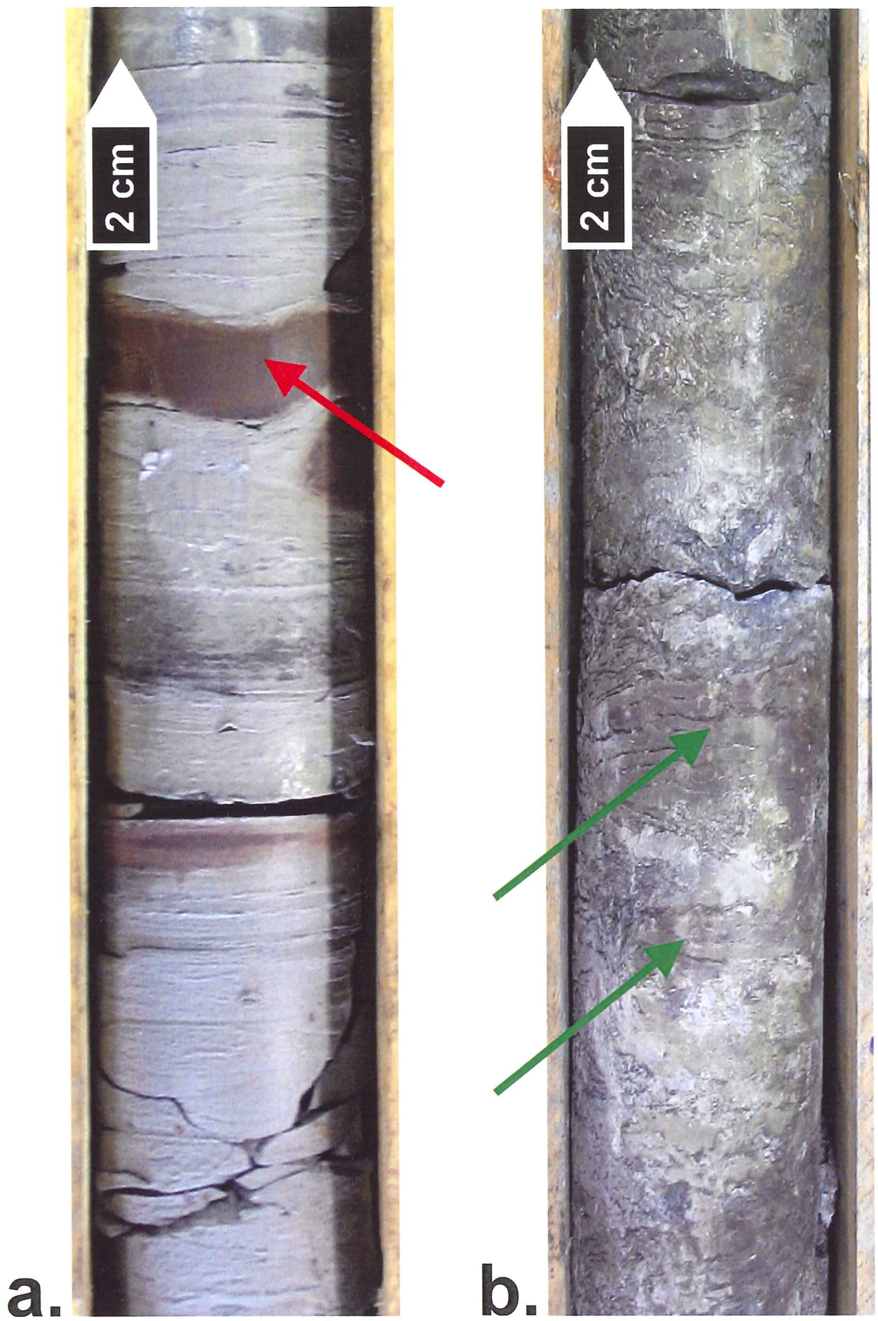


Figure 3.2 a-b. a) Faintly-laminated grey mudstone (2b) with a prominent siderite band indicated by the red arrow. b) Bioturbated grey mudstone (2c) with faint siderite bands or nodules indicated by the green arrows.

to 1.5 m thick, but which average 0.5 m in thickness, commonly occur within beds of this facies.

Interpretation

This facies is interpreted as hydromorphic paleosols formed in poorly-drained environments (cf. Gibling et al., 1994). The presence of diagenetic siderite and abundance of plant detritus suggests that clay-sized sediment settled out from suspension under primarily reducing conditions (Fielding, 1984a). Slightly oxidized grey mudstones described by Tye and Coleman (1989) formed in overbank areas that were occasionally sub-aerially exposed. Low sedimentation rates and water levels promote plant growth, and overbank deposits are characteristically rooted (Tye and Coleman, 1989).

3.3.4 Dark grey mudstone facies (2d)

Description

Accumulations of this facies range from 0.20-4.0 m in thickness. Abundant plant fragments characterize the dark grey mudstones (Figure 3.3a), which also contain siderite bands up to 3 cm thick. Beds commonly appear bioturbated with poorly-preserved roots, except near coal or coaly shale, where well-preserved roots frequently occur with coaly laminae. Some beds grade into coaly shale or coal, in which case coaly laminae, plant fragments, and roots are more evident.

Interpretation

This facies appears to have been deposited under similar conditions to those responsible for Facies 2c, and is interpreted as hydromorphic paleosols formed in more poorly-drained or continuously-flooded environments. The abundance of

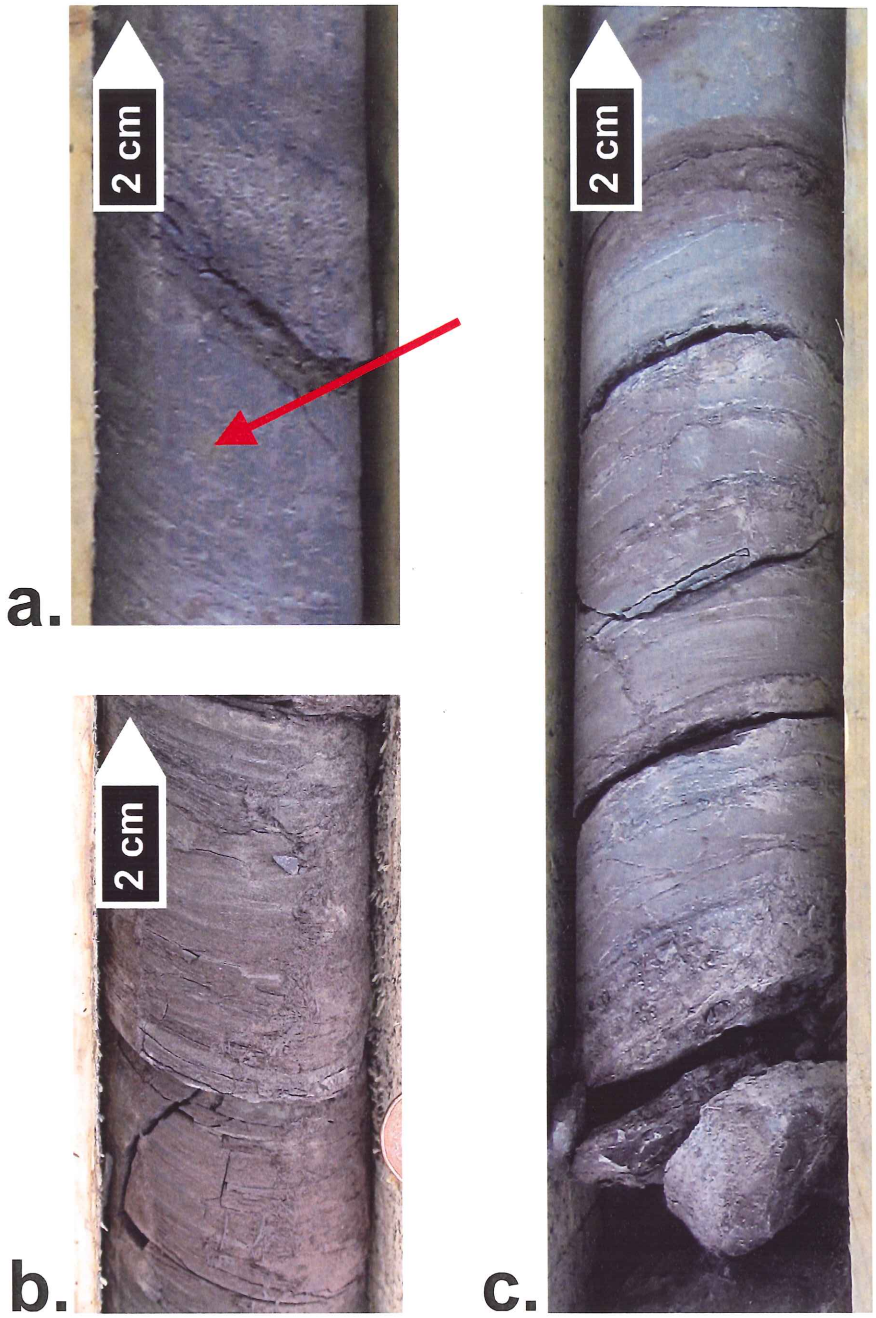


Figure 3.3 a-c. a) Dark grey mudstone (2d) with small siderite nodules indicated by the red arrow. b) Red mudstone (2e). c) Grey mudstone near top grading into reddish mudstone (2e) towards bottom.

diagenetic siderite and un-oxidized organic material suggests that clay-sized sediment accumulated entirely under chemically reducing conditions (Tye and Coleman, 1989; Aslan and Autin, 1999). Comparable dark grey mudstones described by Tye and Coleman (1989) and Naylor et al. (1999) were deposited in poorly-drained swamps or forested backswamps. Water-tolerant vegetation develops quickly in the backswamp, and deposits are usually rich in plant fragments and intensely rooted (Tye and Coleman, 1989). These deposits are sometimes referred to as 'seatearth' or 'underclay' because of their tendency to occur above or associated with coals (Hartley, 1993; Naylor et al., 1999).

3.3.5 Red & grey mudstone facies (2e)

Description

Intervals of this facies range from 0.40-6.35 m in thickness, and are characterized by thick interbedded red and grey mudstone (Figure 3.3b). Beds contain occasional siderite bands, and in rare instances, poorly-preserved root traces. The lower portions of some grey mudstone beds are red-mottled and subsequently grade downwards to mostly red mudstone near the bases (Figure 3.3c).

Interpretation

The paleosols represented by this facies are more mature than Facies 2c or 2d, and are interpreted to have formed under periodic wetting and drying conditions in well-drained settings (cf. Schutter and Heckel, 1985). The absence of well-defined bedding suggests roots penetrated the strata, but were subsequently oxidized and destroyed. Similar mudstones described by Tye and Coleman (1989) and Naylor et al. (1999) were deposited in well-drained overbank areas. They formed as clay- and silt-sized sediment settled out from suspension under mildly reducing conditions (grey) before becoming sub-aerially exposed and oxidized (red). Red-beds can also form in well-drained overbank deposits from the precipitation of iron oxides (Tye and Coleman, 1989).

3.4 Siltstone

3.4.1 Interbedded siltstone & mudstone facies (3a)

Description

Accumulations of this facies range from 0.30-3.35 m in thickness, and commonly comprise interbedded brown siltstone and thin grey mudstone (Figure 3.4a). Beds appear massive to parallel laminated, with rare ripple cross-lamination. Some intervals contain well-preserved plant fragments and poorly-preserved roots. However, intervals without evidence of rooting are equally as common. Some beds become coarser locally, with minor parallel laminated and ripple cross-laminated very fine-grained sandstone and rare convolute structures. Siderite bands or lenses (1-5 cm) and nodules (1-2 cm) are abundant within cored intervals, and occur prominently in outcrop (Figure 3.4a, b).

Interpretation

This facies developed under quiet-water conditions similar to Facies 2c, but with infrequent periods of active sediment transport indicated by rare ripple cross-lamination. Comparable mudstone and siltstone sequences described by Fielding (1984a) and Tye and Coleman (1989) were interpreted as outer minor delta or prodelta deposits. The dominance of parallel lamination in the prodelta reflects

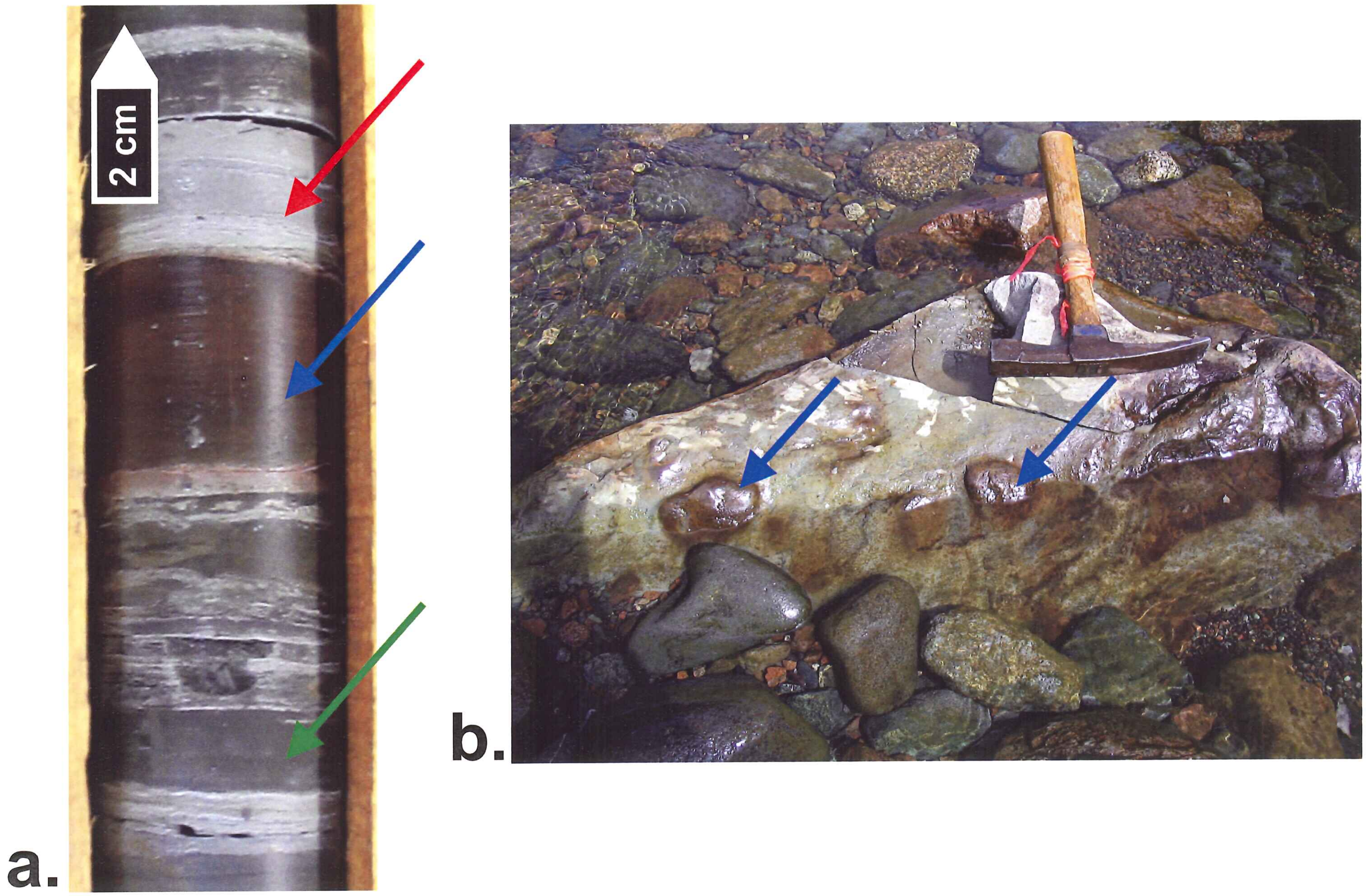


Figure 3.4 a-b. a) Faintly parallel laminated siltstone (green arrow) and mudstone (red arrow) (3a) with a thick siderite band or lense indicated by the blue arrow. b) Large siderite nodule or lense (blue arrows) contained in an outcrop of siltstone or very fine-grained sandstone (3a) north of the Debert River bridge near Cottam Settlement. Hammer is approx. 30 cm for scale.

suspension-settling of sediment from low-velocity, suspension-dominated currents (Collinson and Thompson, 1989; Tye and Coleman, 1989). The absence of lamination in some beds, and evidence of rooting in others, may reflect deposition in shallow-water overbank environments. Overbank and abandonment deposits described by Coleman and Prior (1980) contain similar non-laminated mudstone and siltstone sequences, and are extensively bioturbated by roots.

3.5 Sandstone

3.5.1 Interbedded sandstone & siltstone facies (4a)

Description

Intervals of this facies range from 0.30-2.55 m in thickness, and commonly consist of interbedded grey to brown very fine-grained sandstone, brown siltstone, and rare thin grey mudstone (Figure 3.5a, b). Most sandstone and siltstone beds have parallel lamination and ripple cross-lamination occasionally defined by carbonaceous lamination, although numerous beds appear massive, and contain slumped structures and convolute lamination. The massive beds are frequently rooted, with well-developed vertical root traces and horizontal stigmarian root systems particularly evident in outcrop (Figure 3.6a, b). Rare bivalve escape burrows were noted in some sandstone beds, which commonly load into underlying siltstone and mudstone beds (Figure 3.5a). Siderite bands and lenses occur infrequently, and are associated with, or appear to replace thin mudstone interbeds.

Interpretation

The complexly interbedded sandstone, siltstone, and mudstone sequences of this facies are interpreted to have been deposited by variable-velocity, unidirectional

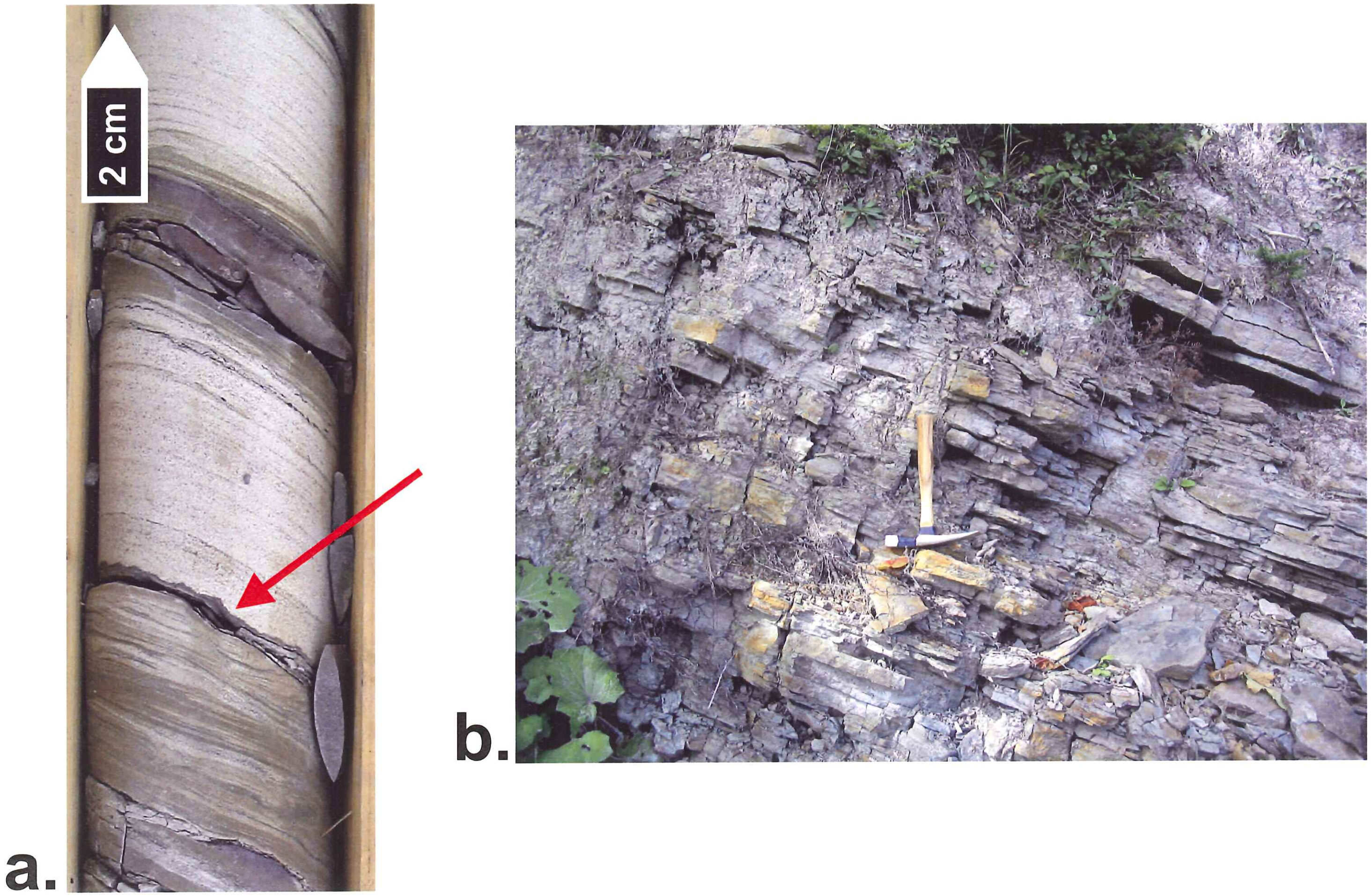


Figure 3.5 a-b. a) Parallel and ripple laminated sandstone, siltstone, and mudstone sequence (4a) loading into an underlying siltstone bed (red arrow). b) Interbedded sandstone, siltstone, and mudstone (4a) exposed along a bank of the Debert River south of the bridge near Cottam Settlement. Hammer is approx. 30 cm for scale.

a.

b.

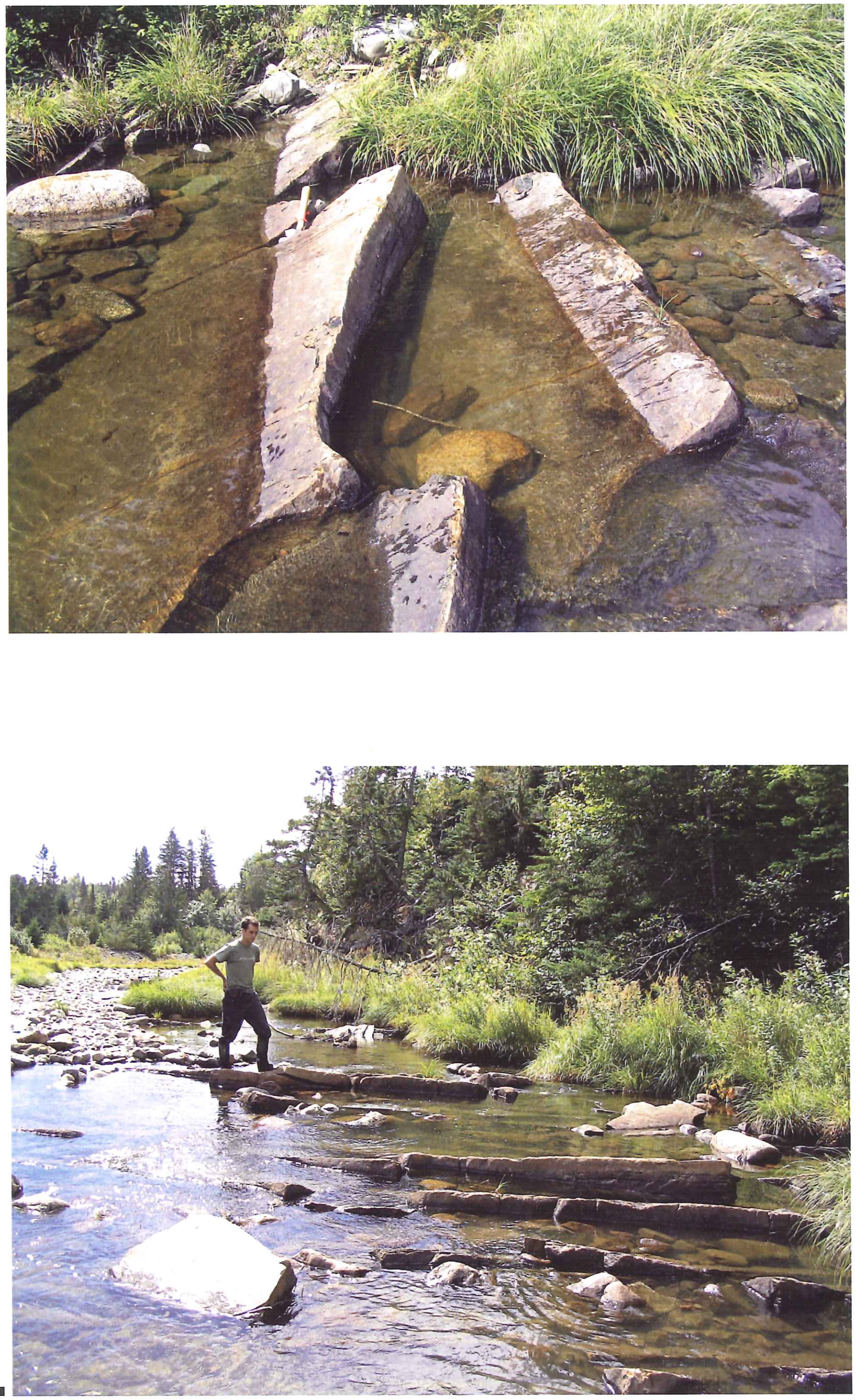
Figure 3.6 a-b. a) Well-preserved horizontal stigmaria root and b) vertical root traces in very fine-grained sandstone outcrops (4a) north of the Debert River bridge near Cottam Settlement. Note (a) loonie and (b) penny for scale.

currents. This interpretation is supported by the presence of parallel lamination produced by suspension deposition, and ripple cross-lamination indicative of traction-current deposition (Collinson and Thompson, 1989; Tye and Coleman, 1989). Similar parallel and ripple laminated sequences described by Fielding (1984a) and Tye and Coleman (1989) were interpreted as delta front deposits. Influxes of coarse-grained sediment in the delta front force large-shelled organisms to abandoned their borrows, and commonly deform unstable mud- and silt-rich beds, producing a variety of soft-sediment deformation features and escape burrows (Collinson and Thompson, 1989; Tye and Coleman, 1989). The rooted intervals may reflect lower water levels and exposure of the delta front (Tye and Coleman, 1989), or may alternatively represent vegetated abandonment or overbank deposits similar to those described by Coleman and Prior (1980).

3.5.2 Planar-bedded sandstone facies (4b)

Description

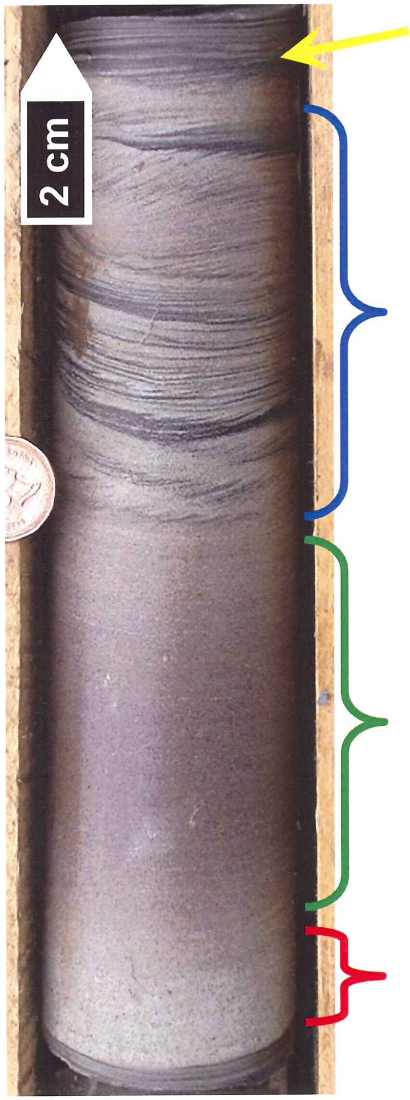
Accumulations of this facies range from 0.35-3.5 m in thickness, and consist of planar pale grey to buff fine-grained sandstone beds that appear slightly low-angle cross-stratified in outcrop (Figure 3.7a, b). Beds commonly fine upwards in cycles capped by mudstone or siltstone. Individual 0.05-0.40 m cycles generally have massive bases, parallel laminated centres, and ripple cross-laminated tops that frequently display climbing ripple forms (Figure 3.8a, b). Lamination is predominantly defined by carbonaceous layers with abundant plant fragments. The siltstone and mudstone caps of some cycles are slumped, and display wavy lamination and



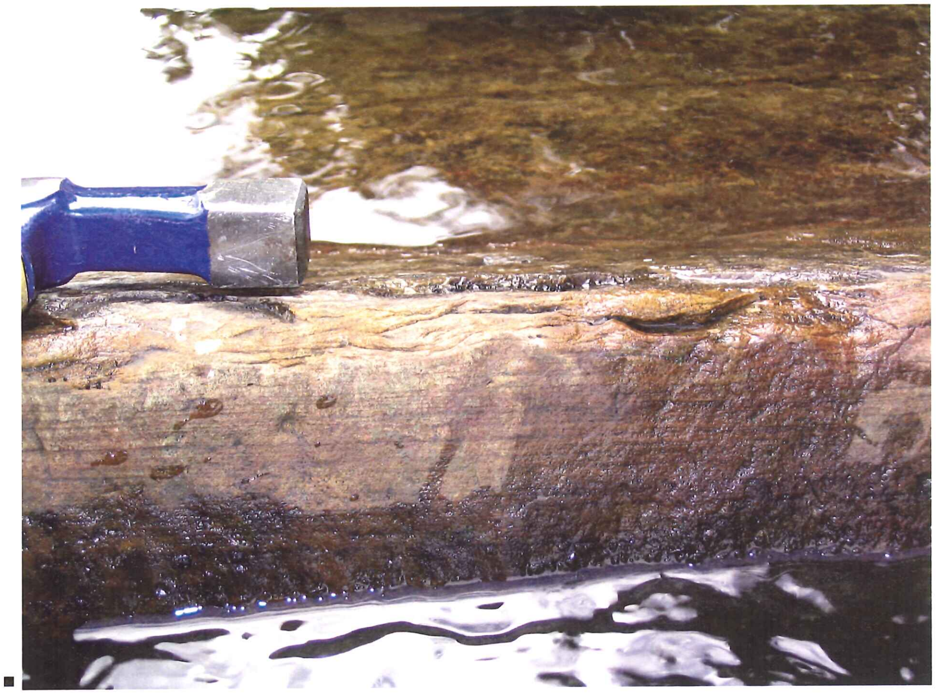
a.

b.

Figure 3.7 a-b. a) Planar sandstone beds (4b) cropping out in the Debert River north of the bridge near Cottam Settlement. Hammer is approx. 30 cm for scale. b) Low-angle cross-stratified sandstone beds (4b) cropping out in the Debert River north of the bridge near Cottam Settlement.



a.



b.

Figure 3.8 a-b. a) Close-up view of a planar sandstone cycle (4b) capped by mudstone (yellow arrow), and showing massive (red bracket), parallel laminated (green bracket), and climbing ripple or ripple cross-laminated intervals (blue bracket). b) Close-up view of a parallel laminated sandstone bed (4b) with ripple cross-laminated top from outcrop north of the Debert River bridge near Cottam Settlement. Hammer is approx. 7 cm for scale.

various soft-sediment features. Siderite bands associated with the mudstone caps occur infrequently within some beds, which commonly load into underlying beds.

Interpretation

The erosively-based sandstones of this facies are interpreted to have been deposited initially by successive unidirectional flows. This interpretation is supported by the dominance of low-angle cross-stratified planar beds, typically produced by the migration of small-scale sub-aqueous dunes or sand waves under high-velocity conditions in the lower or transitional/upper flow regime (Coleman and Prior, 1980; Collinson and Thompson, 1989). They are comparable with the mouth-bar sandstones discussed by Naylor et al. (1999) and the minor delta deposits of Fielding (1984a). Normal graded bedding sequences in mouth-bar deposits (massive, parallel lamination, ripple/climbing ripple cross-lamination) reflect rapid sediment fallout from suspension by decelerating, sediment-laden flows (Collinson and Thompson, 1989). Later stage deposition of each sequence was probably achieved by lower velocity traction currents (ripple-laminated tops) and suspension-settling (mudstone caps) (cf. Fielding, 1984a).

3.5.3 Massive sandstone facies (4c)

Description

Intervals of this facies range from 0.5-4.0 m in thickness, and comprise pale grey to buff fine-grained sandstone, with occasional very fine-grained and medium-grained intervals. Beds appear massive or faint parallel laminated in drill core (Figure 3.9a), and occasionally fine upwards into parallel laminated and ripple cross-laminated siltstone intervals (10-30 cm) with convolute structures and/or thin grey

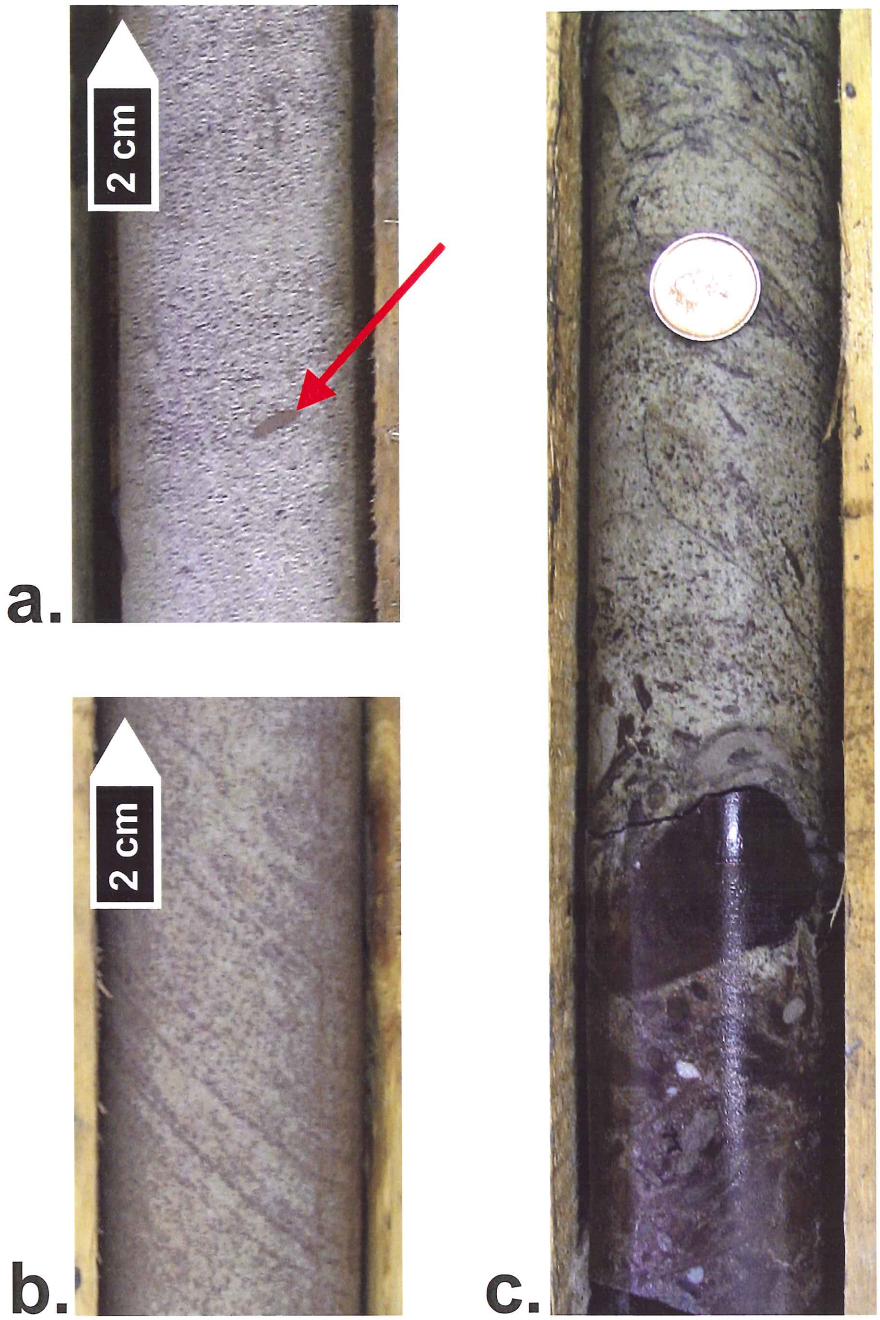


Figure 3.9 a-c. a) Massive fine-grained sandstone (4c) with a small intraformational mudstone clast indicated by the red arrow. b) Parallel laminated (inclined) or trough cross-stratified fine-grained sandstone (4c). c) Fine-grained sandstone (4c) with abundant intraformational siderite and mudstone clasts. Note penny for scale.

mudstone partings (< 1cm), before becoming coarse again. The sandstone beds appear high-angle cross-stratified and less commonly low-angle cross-stratified in outcrop, implying that inclined parallel lamination observed in drill core may actually represent trough cross-bedding (Figure 3.9b). Thin carbonaceous layers occur occasionally within some beds, but are far less prominent than in Facies 4b. Small intraformational mud and siderite clasts occur occasionally within the coarsest beds, (Figure 3.9a), but are larger and far more abundant near the bases, which frequently load into underlying units (Figure 3.9c).

Interpretation

From the coarse grain size and abundance of intraformational clasts, this facies is interpreted as having been deposited from bedload by highly-erosive, unidirectional flows. This interpretation is supported by the presence of trough cross-bedding, which typically develops from the migration of sub-aqueous sand dunes under high-velocity conditions in the lower flow regime (Collinson and Thompson, 1989). Comparable trough cross-bedded sandstones described by Fielding (1984a), Tye and Coleman (1989), and Naylor et al. (1999) were interpreted as the deposits of distributary or crevasse splay channels. Channel deposits also commonly contain massive sandstone beds (Coleman and Prior, 1980), which may reflect rapid deposition of sediment from suspension, or alternatively originate from the physical disruption (dewatering) of water-logged sediment (Collinson and Thompson, 1989). Flow velocities and sediment loads within channels vary over time, and channel deposits commonly contain fine-grained intervals and mudstone partings indicative of lower velocity conditions (Fielding, 1984a).

CHAPTER 4: FACIES ASSEMBLAGES

4.1 Introduction

Detailed facies analysis has revealed the presence of five facies assemblages (open lacustrine, lacustrine delta, mire, distributary channel, and overbank), which are interpreted as the deposits of lacustrine and delta plain environments (this point forward termed the lacustrine and delta plain associations). This chapter describes each facies assemblage in terms of the major depositional environment and conditions involved in its formation.

4.2 Lacustrine Association

Strata of the lacustrine association are broadly sub-divided into open lacustrine (16%) and lacustrine delta (84%) facies assemblages (Figure 4.1). Figure 4.2 a-b shows the average distribution of facies within each facies assemblage of the lacustrine association. The open lacustrine assemblage is characterized by predominantly grey (2b, 49%) and black mudstone (2a, 46%), with minor interbedded siltstone & mudstone (3a, 5%). The lacustrine delta assemblage comprises mostly interbedded sandstone & siltstone (4a, 36%), interbedded siltstone & mudstone (3a, 28%), planar-bedded sandstone (4b, 22%), and grey mudstone (2b, 11%). Small portions of massive sandstone (4c, 3%) and dark grey mudstone (2d, 1%) also occur within lacustrine delta deposits, but are generally uncommon.

4.2.1 Open lacustrine facies assemblage

Open lacustrine assemblages comprise 1-2.5 m sequences of thin interbedded black (2a) and grey mudstone (2b) with abundant fauna (Figure 4.3a), or slightly thicker zones of grey or black mudstone containing less abundant fauna

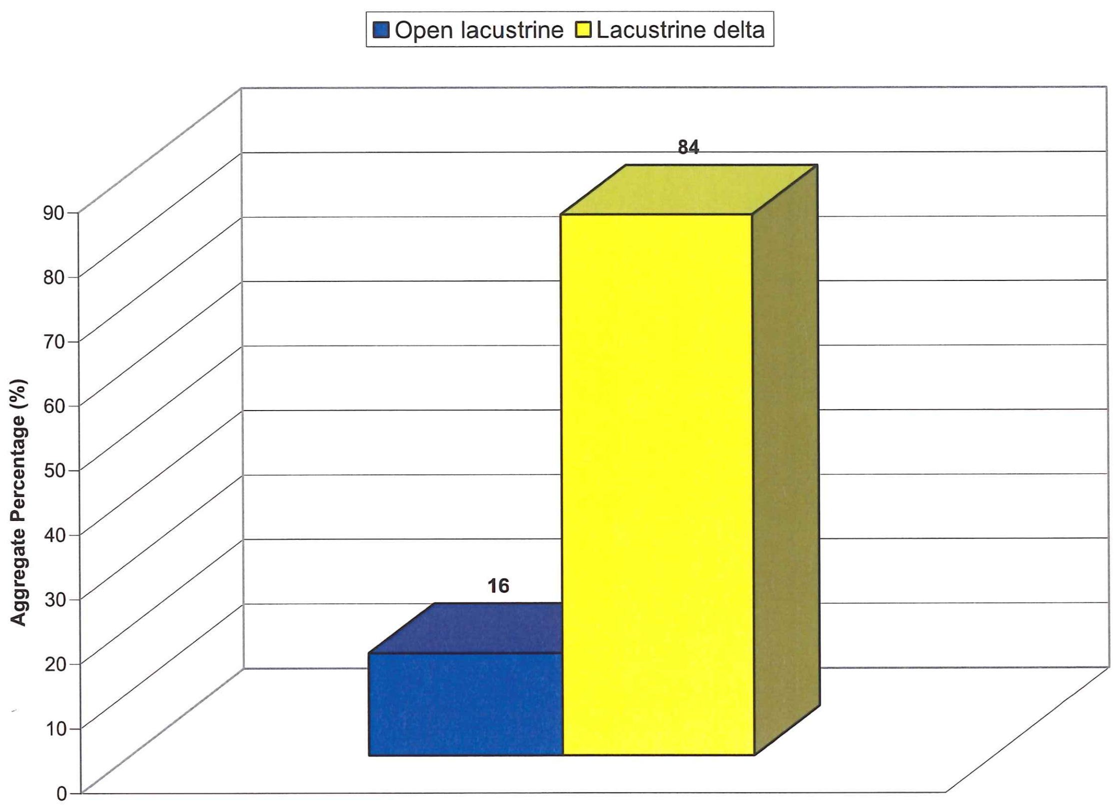


Figure 4.1. Aggregate percentage of open lacustrine and lacustrine delta deposits in the lacustrine association.

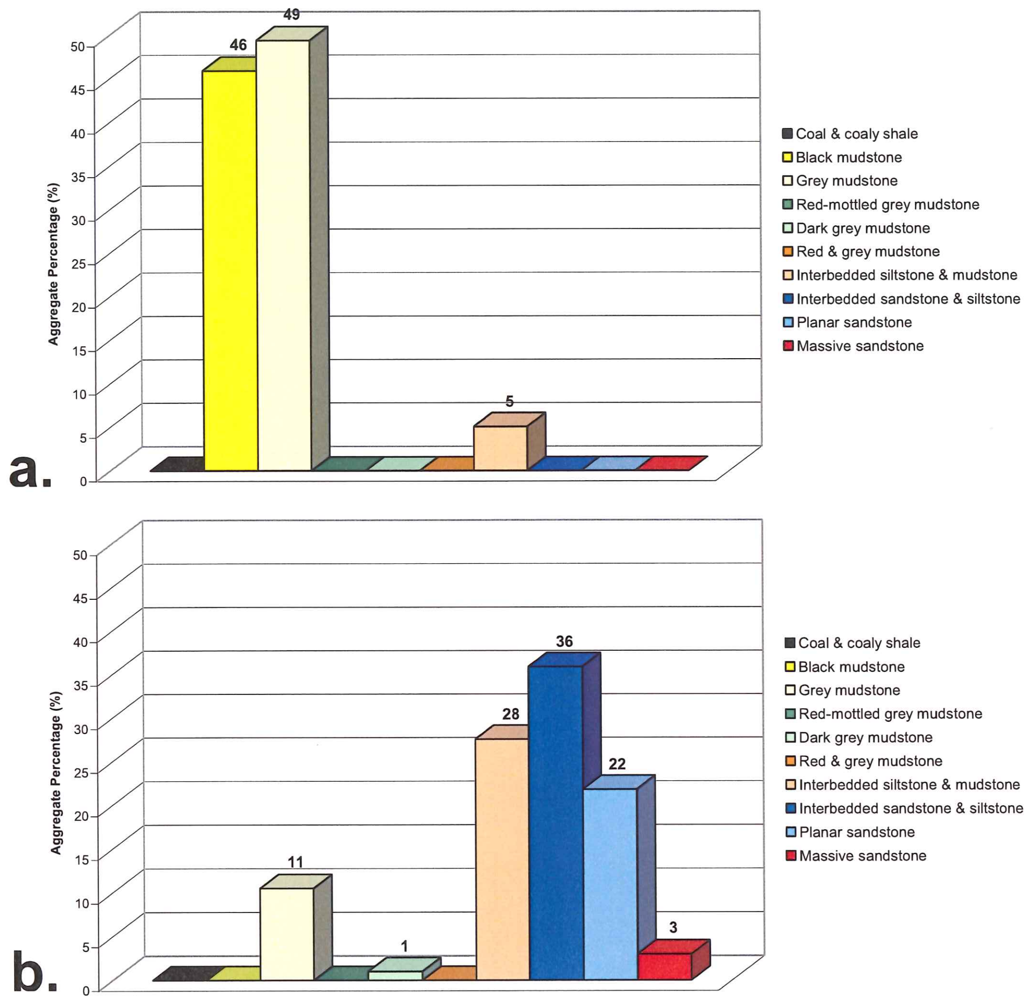


Figure 4.2 a-b. The average proportions of facies in the (a) open lacustrine and (b) lacustrine delta facies assemblages within drill cores DDNSD-2 and DDNSD-6.

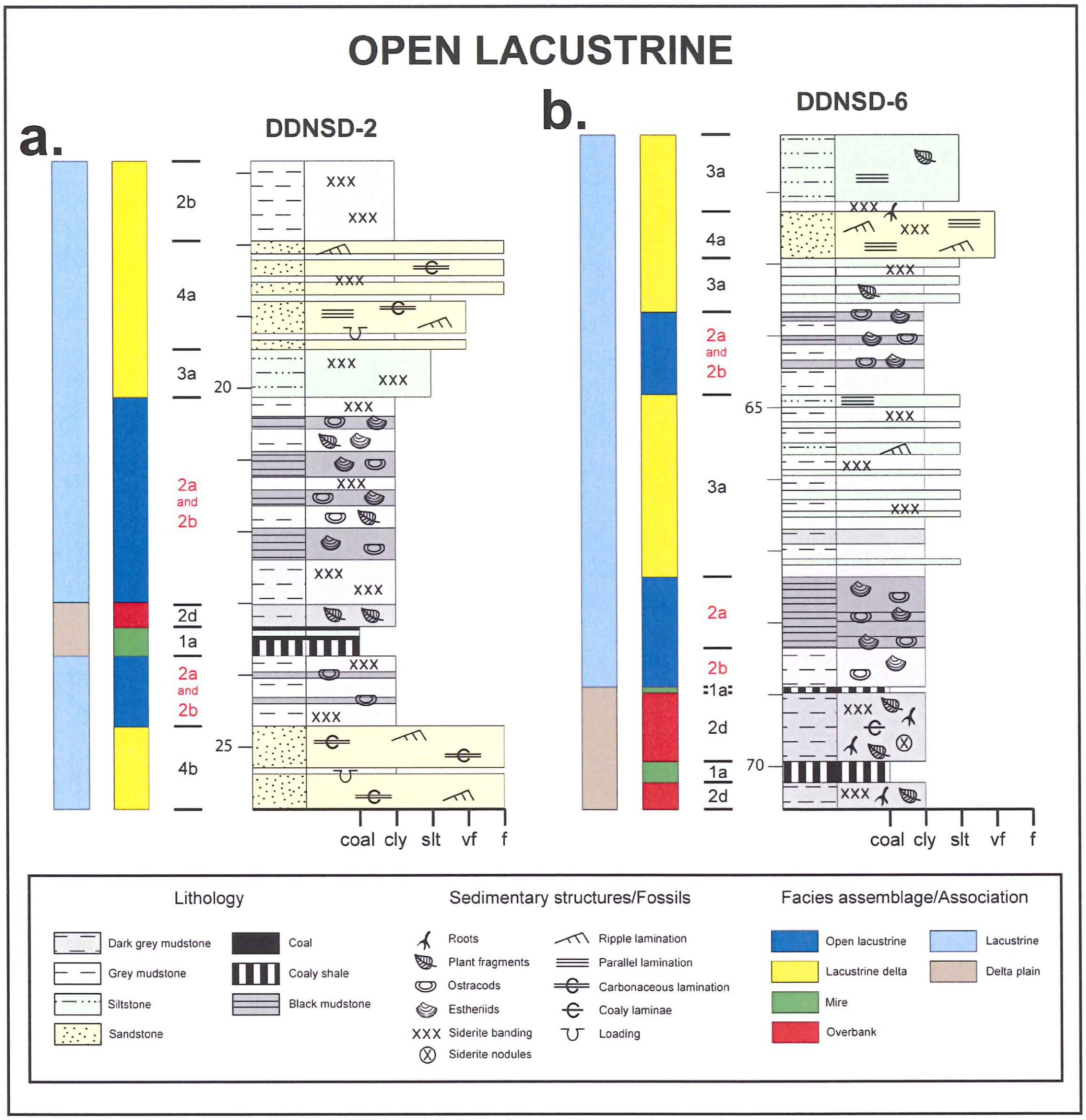


Figure 4.3 a-b. Stratigraphic columns from drill cores DDNSD-2 and DDNSD-6 showing open lacustrine deposits of the lacustrine association. Scale is in metres.

(Figure 4.3b). The deposits commonly overlie dark grey mudstone or coal and coaly shale, and are frequently overlain by mud- and silt-rich sediments, which occasionally represent the bases of coarsening upward successions.

Interbedded black (organic-rich) and grey (organic-poor) mudstone successions resemble open lacustrine deposits described elsewhere in the geologic record by Fielding (1984a) and Hartley (1993). Lacustrine deposits preserved in the British coal measures contain grey parallel laminated and black organic-rich mudstones with ostracods, *Estheria,* and other freshwater fauna. They formed as periodic influxes of organic-poor sediment, transported from distal lake margins during exceptional floods, were deposited across lake-centre bottoms that were isolated from clastic sediment input and accumulating organic material.

The abundant freshwater fauna in this assemblage suggests the lakes were not saline. The predominance of open lacustrine successions overlying thin beds of coaly shale and/or coal suggests that freshwater lakes may have in part developed through drowning of peat swamps (Fielding, 1984). The association between open lacustrine sediments and coal and/or coaly shale is considered in more detail in Section 4.3.1.

4.2.2 Lacustrine delta facies assemblage

Lacustrine delta deposits normally occur as thick 5-8 m sandstone-rich (Figure 4.4b) or thinner 3.5-5 m sandstone-poor (Figure 4.4a) coarsening-upward successions. The basal regions of coarsening-upward sequences, which commonly overlie ostracod- and branchiopod-rich mudstones or occasionally coal and coaly shale, comprise grey mudstone (2b) or less frequently dark grey mudstone (2d).

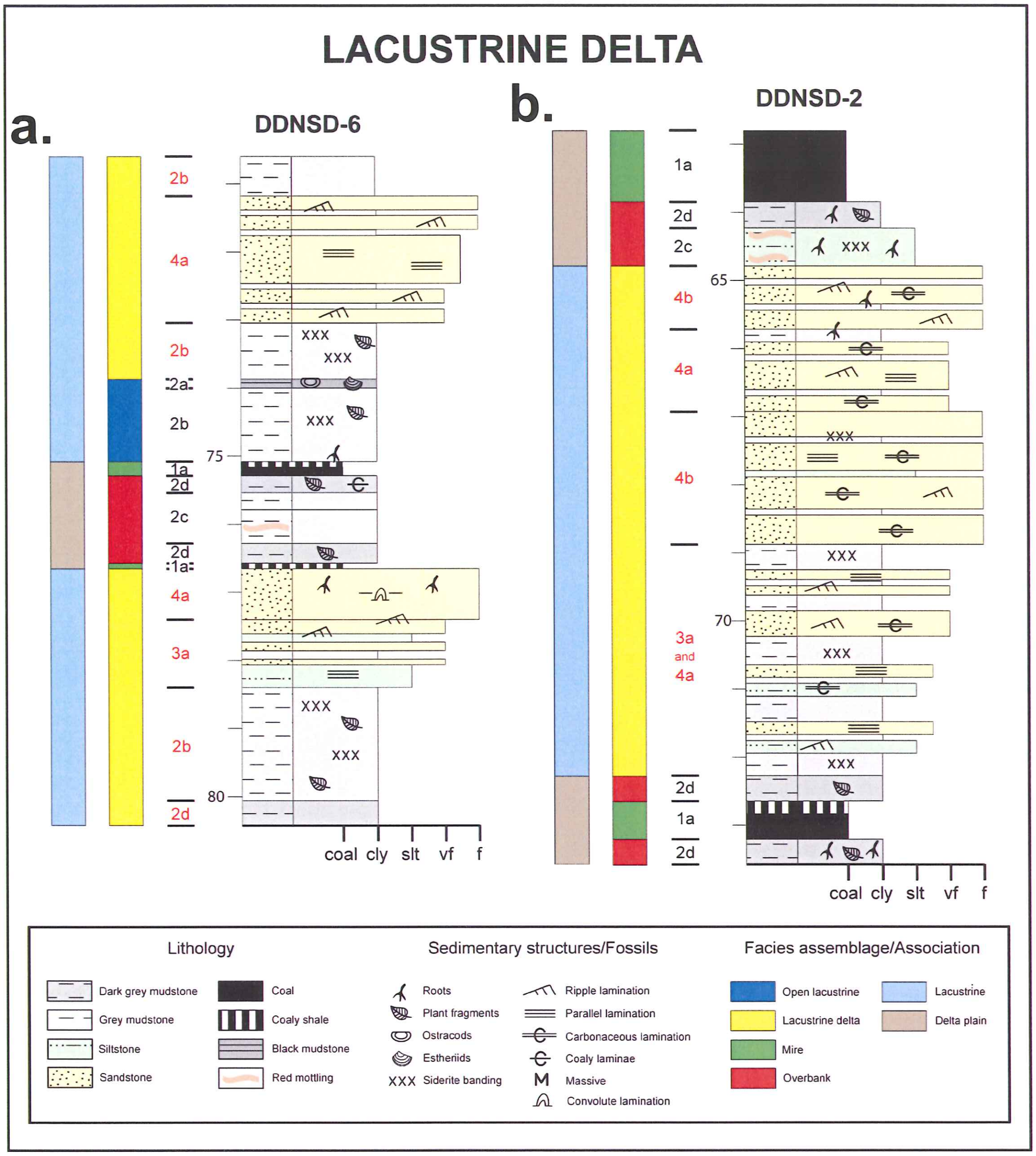


Figure 4.4 a-b. Stratigraphic columns from drill cores DDNSD-6 and DDNSD-2 showing lacustrine delta deposits of the lacustrine association. Scale is in metres.

Thin organic-rich horizons (2a) occur infrequently within the basal parts of some sandstone-poor successions. Muddy sediments become increasingly interbedded with siltstone and minor ripple cross-laminated and parallel laminated very fine-grained sandstone (3a) upwards through the succession. Following the slit- and mud-rich sediments is an upward progression into parallel laminated and ripple cross-laminated siltstone and very fine to fine-grained sandstone (4a). The basal parts of many sandstone-rich successions contain these coarser sediments (3a and 4a) rather than mudstones. These deposits frequently cap sandstone-poor coarsening-upward sequences, in which case they are commonly rooted and occasionally overlain by coal or coaly shale. The tops of sandstone-rich successions typically consist of low-angle cross-stratified to planar-bedded (4b) or massive (4c) erosively-based fine-grained sandstone. Thick sandstone-rich successions are capped by rooted siltstone and very fine-grained sandstone, and/or coal and coaly shale. Sandstone-rich and sandstone-poor coarsening-upward successions form 20-25 m thick packages of several stacked sequences separated by coal seams.

The coarsening-upward successions resemble the deposits of lacustrine delta complexes (e.g. Coleman and Prior, 1980; Guion, 1987; Tye and Coleman, 1989; Naylor et al., 1999). Coleman and Prior (1980) and Naylor et al. (1999) describe the typical progradational delta succession. Basal mud- and silt-rich prodelta sediments accumulate slowly near lake centres during the waning phases of episodic floods, and represent the most distal deltaic deposits. The upward transition into silt- and sand-rich delta front sediments reflects increased sedimentation by unconfined floodwaters closer to lake margins. Upper sand-rich distributary-mouth bar sediments are rapidly deposited near lake margins as floodwaters become unconfined upon leaving distributary channels, and form the most proximal deltaic deposits.

The deltas appear to have advanced into formerly quiet freshwater lakes. Evidence for this is ostracod- and estheriid-rich open lacustrine deposits that commonly underlie lacustrine delta deposits. The upward transition through prodelta, delta front, distributary-mouth bar, and rooted abandonment deposits records a progressive change from deep to shallow-water depositional conditions, as lakes were presumably infilled by prograding delta complexes and subsequently abandoned (cf. Tye and Coleman, 1989). The presence of stacked coarsening upward successions suggests multiple episodes of delta progradation separated by periods of emergence or shallow water levels (Guion, 1987), which allowed vegetation and peat to grow on abandoned delta platforms.

4.3 Delta Plain Association

Strata of the delta plain association are broadly sub-divided into mire (8%), distributary channel (10%), and overbank (82%) facies assemblages (Figure 4.5). Figure 4.6 a-c shows the average distribution of facies within each facies assemblage of the delta plain association. Mire deposits are comprised primarily of coal & coaly shale (1a, 98%) and minor dark grey mudstone (2d, 2%). The distributary channel assemblage is dominated by massive sandstone (4c, 42%) and interbedded sandstone & siltstone (4a, 39%), together with minor interbedded siltstone & mudstone (3a, 13%) and planar sandstone (4b, 6%). Overbank

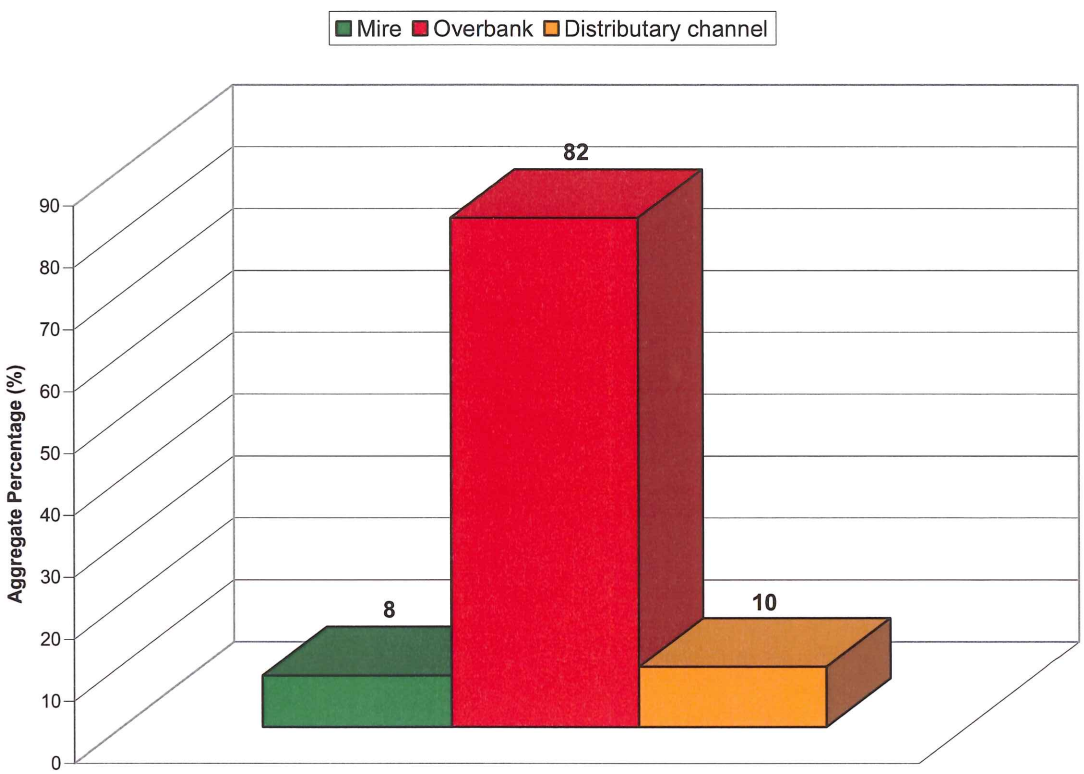


Figure 4.5. Aggregate percentage of mire, overbank, and distributary channel deposits in the delta plain association.

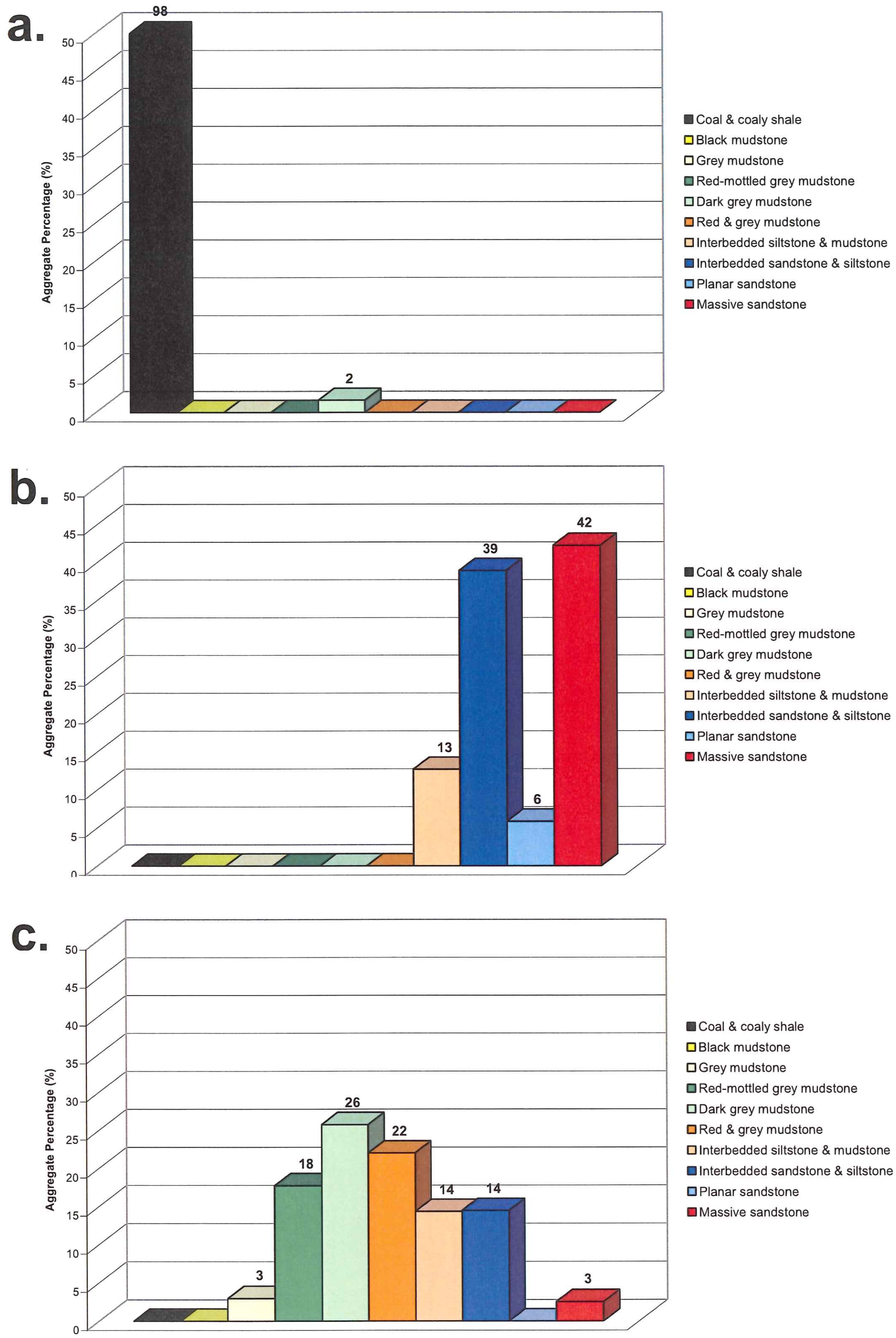


Figure 4.6 a-c. The average proportions of facies in the (a) mire, (b) distributary channel, and (c) overbank facies assemblages within drill cores DDNSD-2 and DDNSD-6.

assemblages comprise mostly dark grey mudstone (2d, 26%), red & grey mudstone (2e, 22%), red-mottled grey mudstone (2c, 18%), interbedded siltstone & mudstone (3a, 14%), and interbedded sandstone & siltstone (4a, 14%). Small portions of massive sandstone (4c, 3%) and grey mudstone (2b, 3%) also occur within this assemblage.

4.3.1 Mire facies assemblage

Mire deposits comprise 0.10-1.30 m thick successions of coal and coaly shale (1a), which commonly overlie rooted dark grey mudstone (2d). The thickest coals with minor coaly shale range from 0.60-1.30 m and generally overlie sand-rich coarsening upward sequences (Figure 4.7a), whereas thinner coal and coaly shale sequences 0.10-0.45 m thick mostly occur within the basal mudstone-rich regions of sandstone-poor coarsening upward sequences (Figure 4.7b). Thin coaly shale or coal layers are commonly overlain by mud- and silt-rich deposits, whereas thick coals are overlain by stacked coarsening upward successions. Coal and coaly shale layers are rarely interbedded with ostracod- and branchiopod-rich mudstone, or occasionally preserved in dark grey mudstone.

The coal and coaly shales originated as peat that presumably formed in forested swamps that were initially poorly drained and not well aerated, as indicated by underlying rooted paleosols or seat earths, which suggest an autochthonous or hypautochthonous origin (Fielding, 1984; Naylor et al., 1989; Naylor et al., 1999). Naylor et al. (1999) attributed the upward transition into coal and coaly shale to the development of peat-forming conditions and consequently mires. The probability that most coal and coaly shale developed as low-lying (rheotrophic) mires can explain

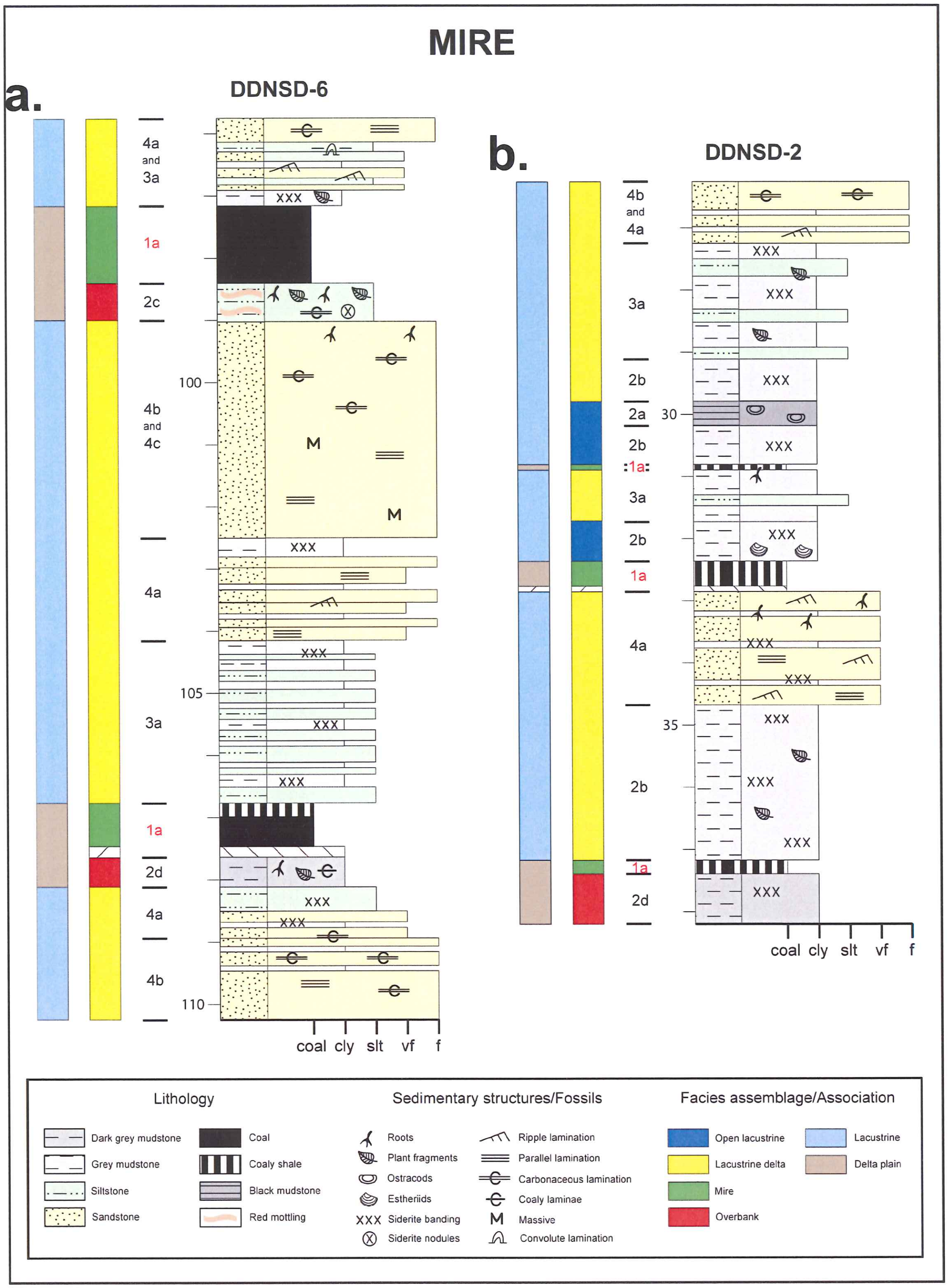


Figure 4.7 a-b. Stratigraphic columns from drill cores DDNSD-6 and DDNSD-2 showing mire deposits of the delta plain association. Scale is in metres.

their relatively thin character. Peat requires minimal clastic input and an elevated water table maintained by continual subsidence to accumulate (Fielding, 1987). Unlike raised mires, low-lying mires cannot prevent flood events from breaching the mire and depositing clastic detritus, and are more susceptible to drowning by sudden rises in the water table due to rapid subsidence (McCabe, 1984).

The common occurrence of lacustrine deposits over most thin coal or coaly shale beds suggests that nearly all mires were drowned. Development of the thickest coals may be attributed to mires being far removed from active clastic deposition, but also may have in part occurred because abandoned deltas provided platforms for peat accumulation. Tibert and Gibling (1999) suggested that non-compactable fluvial sand provided a stable platform that promoted the accumulation of thick peat, which formed the Mullins Coal. Thick mouth-bar sandstones, which underlie the thickest coal seams, may have provided a similar non-compactable platform for peat growth.

4.3.2 Distributary channel facies assemblage

Definitive channel deposits occur infrequently and typically comprise erosively-based sandstone-dominated successions. A 2-2.5 m trough cross-stratified sandstone (4c) succession comprising beds up to 60 cm thick, appears laterally discontinuous in outcrop and pinches out against underlying red-mottled grey mudstone to siltstone (2c) (Figures 4.8, 4.9a). A 6 m thick fining upward succession loads into underlying grey and red-mottled grey mudstone in drill core (Figure 4.9b). The basal region of this channel-fill succession comprises massive sandstone (4c) with abundant intraformational mud and siderite clasts (up to 4 cm), and appears

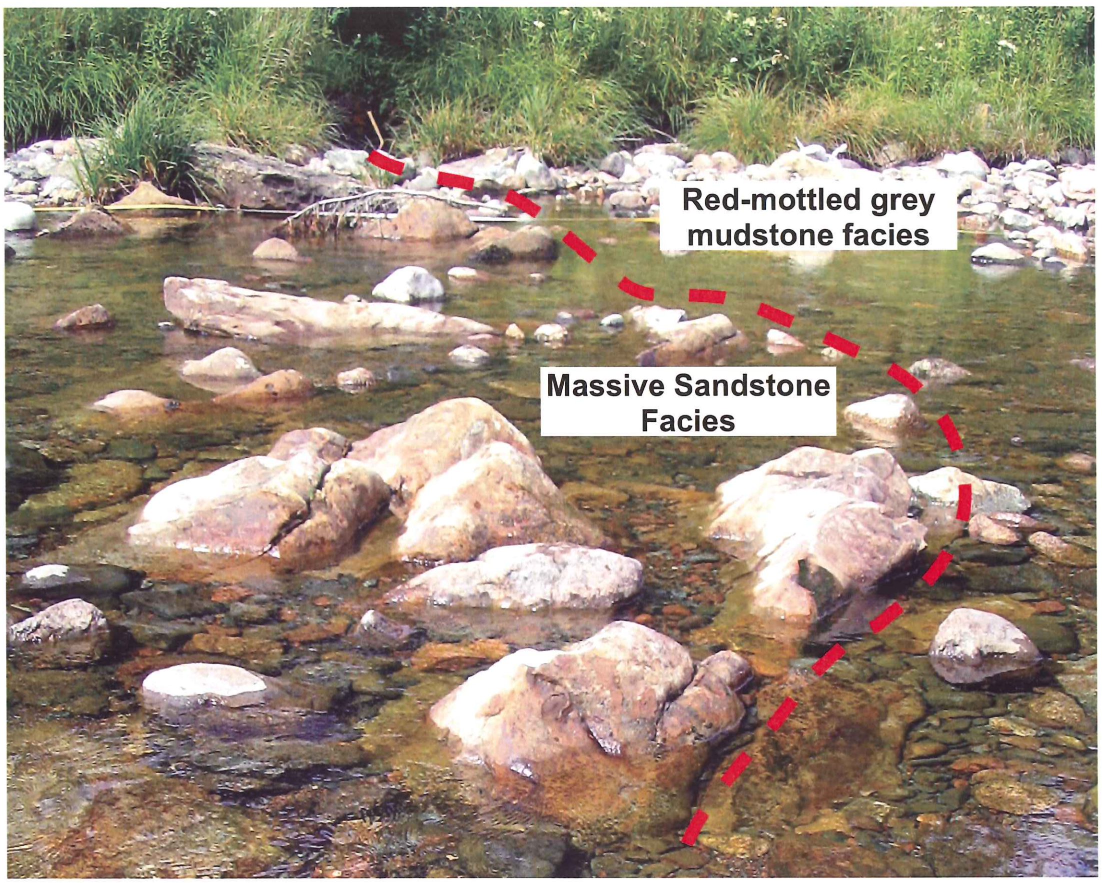


Figure 4.8. Laterally discontinuous trough cross-stratified channel sandstone from the outcrop section south of the Debert River bridge near Cottam Settlement. Channel body is 2-2.5 m thick.

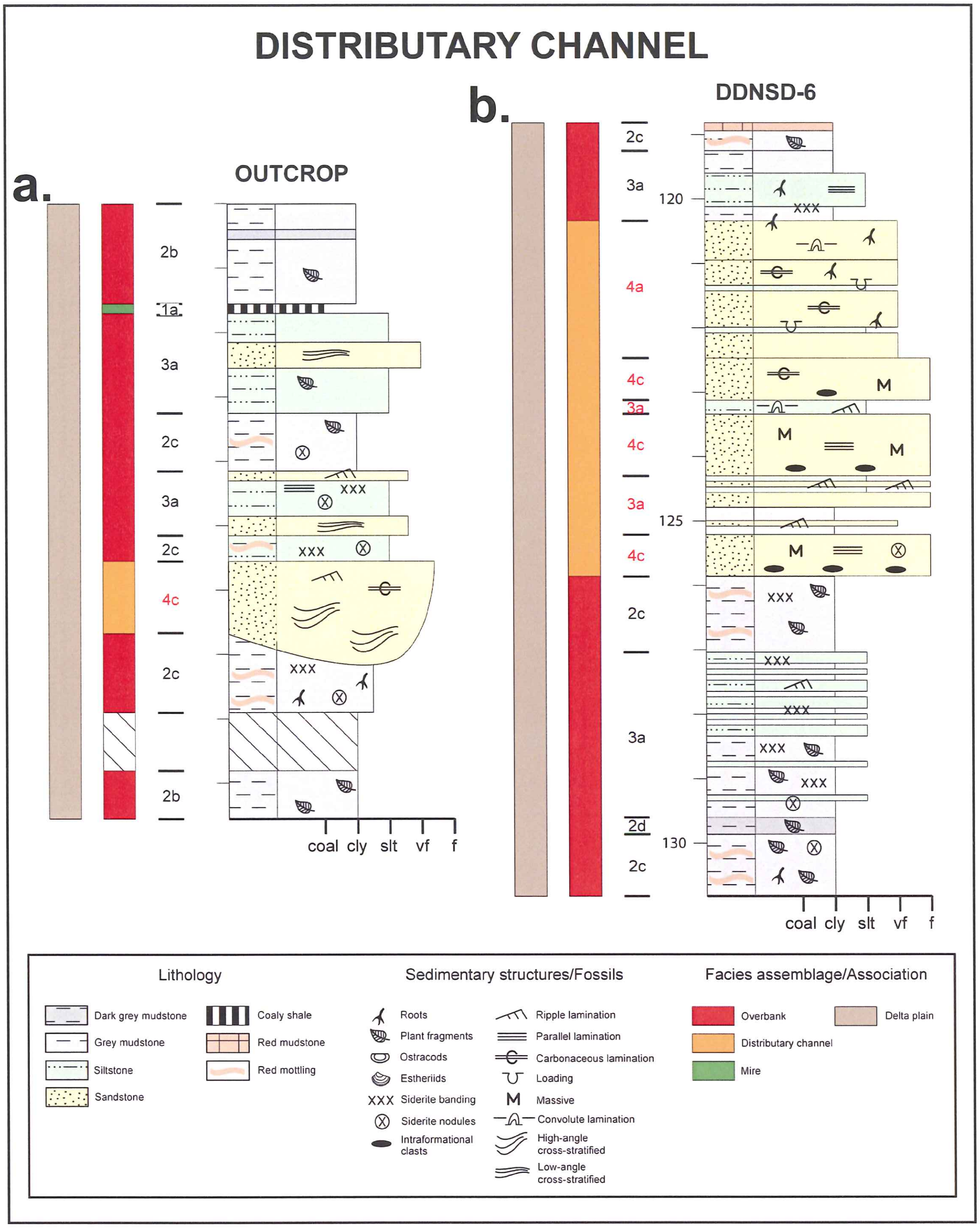


Figure 4.9 a-b. Stratigraphic columns from the outcrop section south of the Debert River bridge near Cottam Settlement and drill core DDNSD-6 showing distributary channel deposits of the delta plain association. Scale is in metres.

increasingly parallel laminated or cross-stratified before grading upwards into thinly interbedded mudstone, siltstone, and fine to very fine-grained sandstone (3a). Massive or cross-stratified sandstone sequences (4c) overlie the basal region. Each sequence contains rare intraformational clasts near the base and thin ripple cross-laminated and parallel laminated mudstone and siltstone layers (2b or 3a) with occasional soft-sediment features towards the top. The upper half of the succession comprises finer grained sandstone (4a) and appears increasingly bioturbated by roots. The succession is capped by pervasively rooted siltstone and red-mottled grey mudstone.

Although limited outcrop and drill core exposure of this assemblage makes channel morphology analysis difficult, several aspects are considered. Rare laterally discontinuous sandstone successions are interpreted as distributary channels that eroded into overbank deposits. The channel lag at the base of the cored succession was presumably eroded from overbank material given the large siderite intraclasts, which typically form in silt- and mud-rich lithologies (Guion, 1987).

Intraformational mudstone clasts that occur above scours and at the bases of coarse fining-upward beds may also be related to lateral channel migration. Sandstone successions separated by thin mudstone and siltstone partings in drill core may represent lateral accretion sets characteristic of meandering systems, which commonly form laterally discontinuous sand bodies contained within thick vegetated overbank deposits (Cant, 1982; Rust et al., 1984). Major high sinuosity (meandering) channels in the South Wales coal measures contain up to 6 m of inclined heterolithic stratification composed of fine-grained sandstone, siltstone, and mudstone, with occasional internal erosion surfaces (Hartley, 1993). Rust et al. (1984) suggested that although internal erosion surfaces are uncommon in meandering channels, they do modify lateral accretion surfaces when present, possibly through re-working of within-channel fines during episodic high stage flood events. This could explain the occurrence of thin mudstone partings together with occasional intraformational clasts in the cored succession.

Laterally discontinuous anatomising channels in thick overbank deposits south of Joggins provide evidence of vertical and lateral channel migration (Rust et al., 1984), which could also explain lateral accretion and internal erosion surfaces occurring together. However, because accumulation was principally vertical, these successions typically form relatively thick multi-storied forms, and most other candidate channels in the studied strata, with the exception of the thick cored channel-fill, appear single-storied and rather thin.

Channels were eventually abandoned and inhabited by water-tolerant vegetation, given the prevalent rooting in the upper portion of the cored succession, which is similar to a bioturbated and rooted channel noted by Naylor et al. (1999) in the Stellarton Basin. The later stages of channel abandonment are characterized by infilling of mudstones and siltstones during low flow episodes (Guion, 1987), which presumably accounts for the mud- and silt-rich overbank deposits that cap most channel successions.

4.3.3 Overbank facies assemblage

Overbank deposits comprise alternating mudstone, siltstone, and sandstone successions. Interbedded red and grey mudstone (2e) sequences range from 4-5 m in thickness (Figure 4.10), whereas thinner, more common mudstone-dominated sequences comprising red-mottled grey mudstone (2c), laminated siltstone and grey mudstone (3a), and occasional dark grey mudstone (2d), attain thicknesses of 0.50-3.50 m in drill core (Figure 4.11a) and upwards of 4.5 m in outcrop. The coarsest overbank deposits, which consist of parallel laminated and ripple cross-laminated siltstone and sandstone (4a), massive sandstone (4c), and thin mudstone-dominated sequences (3a), form 0.5-2.5 m thick successions that occasionally display coarsening upward trends (Figure 4.11b).

The alternating mudstone and minor siltstone/sandstone successions resemble overbank deposits described by Guion (1987) and Naylor et al. (1999), which formed in overbank areas prone to flooding by overtopping of distributary channels during flood events. The coarsest sediments, which comprise sandstones, siltstones, and minor mudstones, presumably accumulated adjacent to channel margins, and may have a levee or crevasse splay origin given their lateral discontinuity and in some instances pervasive rooting (cf. Guion, 1987; Naylor et al., 1999). The finer sediments, represented by mudstones and siltstones, were most likely deposited further from channel margins, and constitute floodplain and swamp deposits.

Overbank areas were poorly-drained during the sub-aqueous deposition of mud- and silt-rich sediment, presumably during high flood stage, although prevalent rooting suggests that sedimentation rates and water levels were sufficiently low to allow plant growth. Red-mottled intervals provide evidence of seasonality, most likely as overbank areas became sub-aerially exposed between flood events and

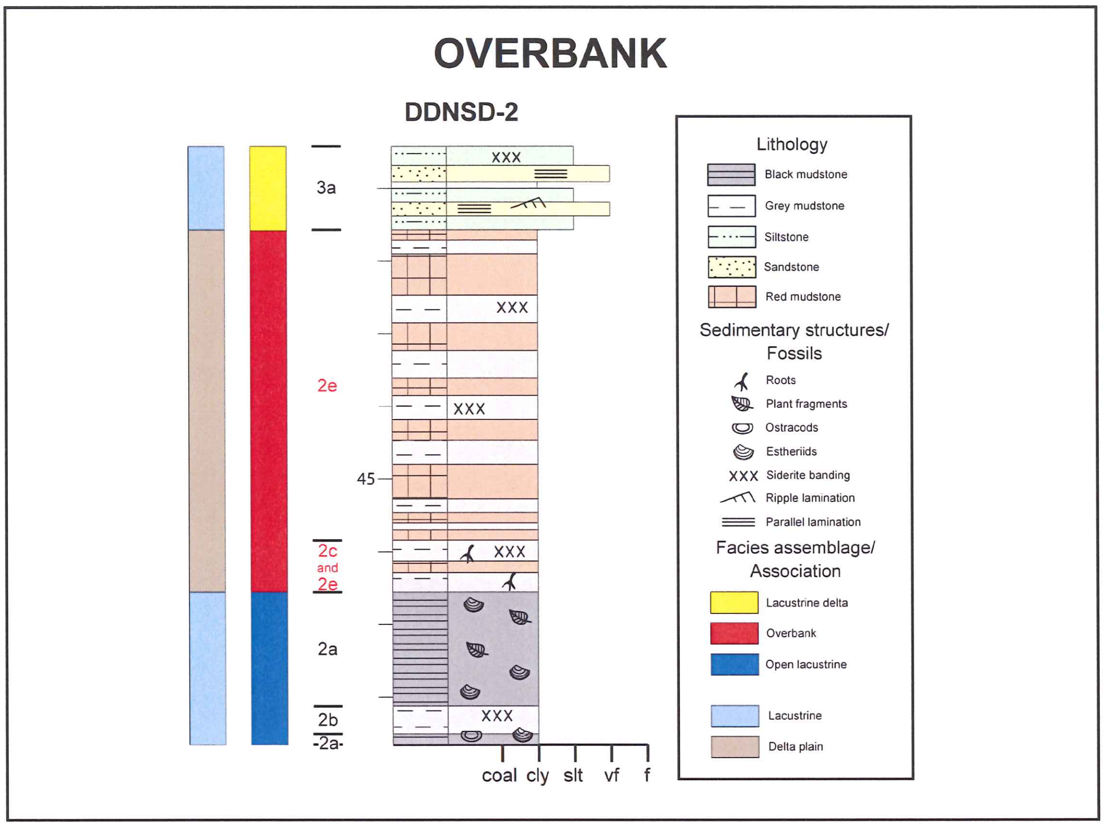


Figure 4.10. Stratigraphic column from drill core DDNSD-2 showing overbank deposits of the delta plain association. Scale is in metres.

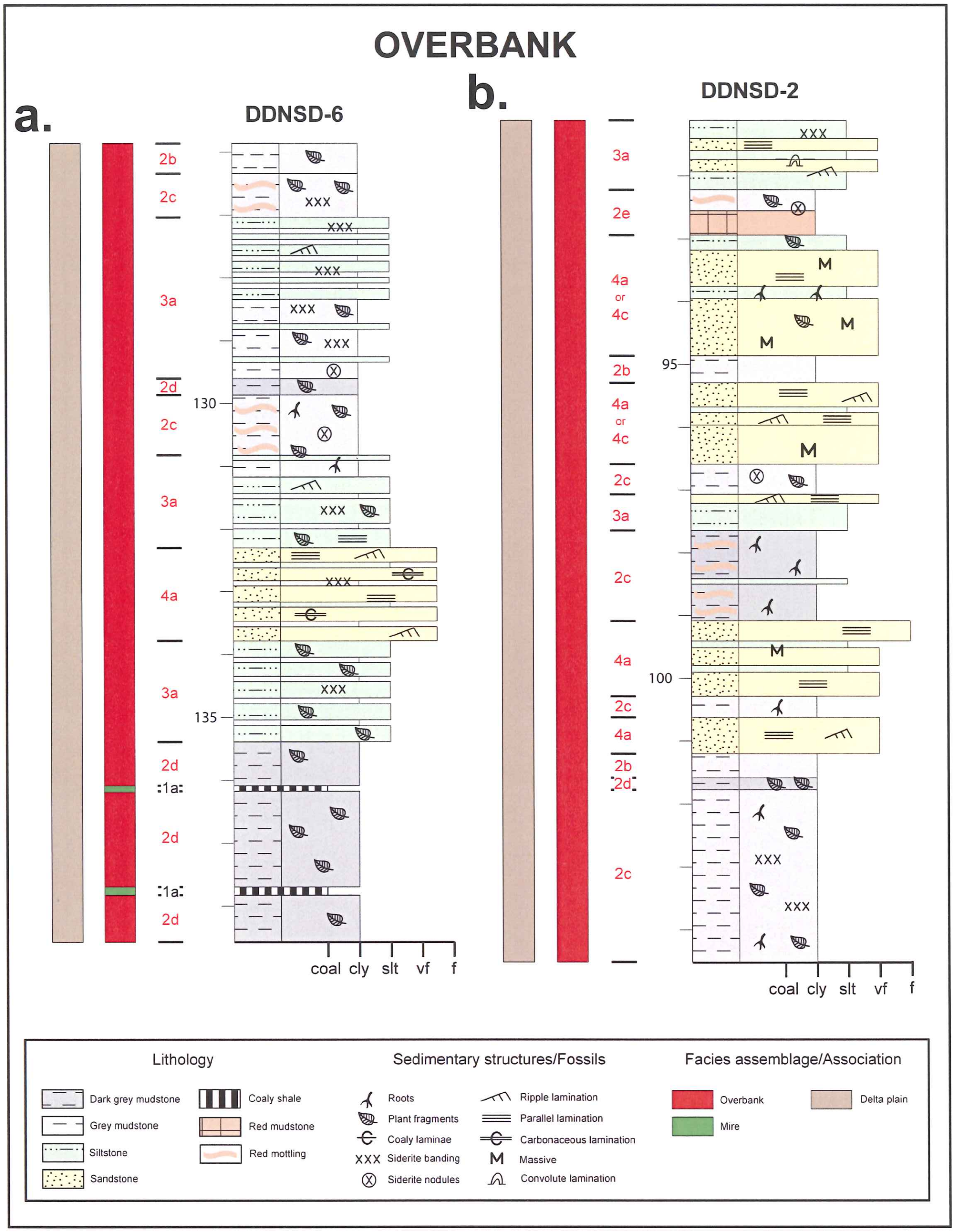


Figure 4.11 a-b. Stratigraphic columns from drill cores DDNSD-6 and DDNSD-2 showing overbank deposits of the delta plain association. Scale is in metres.

experienced some soil formation (cf. Rust et al., 1984; Naylor et al., 1999). Davies and Gibling (2003) attributed red and grey mudstone intervals to improved drainage and lower water table, which Naylor et al. (1999) suggests may occur due to greater incision of distributary channels that divert floodwaters and sediment away from an area.

Davies and Gibling (2003) suggested that similar silt- and mud-rich successions, with occasional sandstone beds and rare channel bodies, were deposited in areas distant from major channels. This could explain the apparent lack of definitive channels in drill core. However, some sandstone, siltstone, and mudstone sequences interpreted as crevasse splay or levee deposits may actually be the deposits of small distributary channels. Minor high-sinuosity (meandering) channels in the South Wales coalfield, which contain up to 1.5 m of inclined heterolithic stratification characterized by fine-grained sandstone, siltstone, and mudstone, are interpreted as small-scale distributary systems or crevasse channels supplied by major high-sinuosity channels (Hartley, 1993). Rust et al. (1984) similarly interpreted thin sandstone and siltstone-dominated sequences as small channels that never developed into channel complexes because of diversion of flow elsewhere.

CHAPTER 5: DISCUSSION AND CONCLUSIONS

5.1 Introduction

This chapter presents a detailed account of the depositional history of the study interval followed by a discussion on possible controls on sedimentation and peat accumulation in the context of other sub-basins in the Maritimes Basin and elsewhere in the geologic record.

5.2 Lateral variability of strata within the study interval

The distribution of facies near Cottam Settlement was determined from the correlation of all three measured sections (Figure 5.1). Most facies assemblages (including coals) correlate reasonably well over a distance of 300 m between studied sections, with the exception of thin coal and coaly shales. However, coal seams and sedimentary facies noted elsewhere in the basin (including near Cottam Settlement) appear laterally discontinuous, and are thought not to be traceable across the basin due to structural complications (Naylor, pers. comm., 2005). Thus, it remains to be tested whether the strata observed in the modest study interval can be correlated more widely within the basin and might represent near-basinwide events, or whether they are part of facies-belt migration and pass laterally into one other towards the basin margins.

5.3 Depositional history of the study interval

A relatively undisturbed (slightly affected by faulting) record of Westphalian C sedimentation and peat accumulation is preserved near Cottam Settlement. The depositional history of the study interval can be divided into five stages, which are illustrated in Figure 5.1. Although the strata that represent the individual stages were

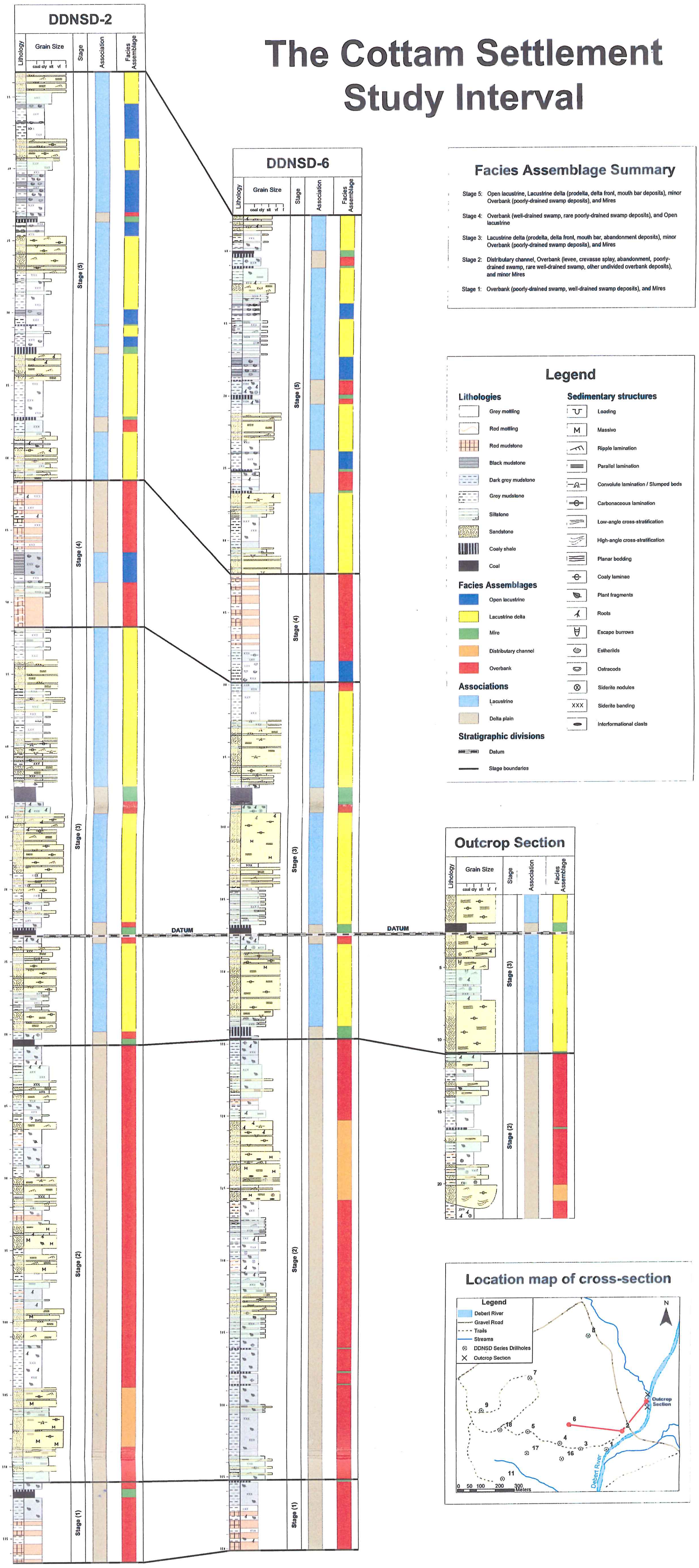


Figure 5.1. Detailed stratigraphic cross-section of the study interval showing the distribution of facies assemblages. A common coal seam among all three sections is used as a datum. The boundaries between depositional stages described in Section 5.3 are represented by solid black lines. Appendix A contains a larger, higher resolution print out of this figure.

deposited successively in the modest area of the study site, they may represent part of a continuum of facies across the broader Debert region, with lateral migration of facies belts across the basin area in response to forcing factors.

Stage 1

Red-beds at the base of the section indicate deposition of the study interval began with the widespread development of well-drained swamps (red-beds) on an abandoned delta plain (Figure 5.2a). Emergent conditions and low rates of sedimentation prevailed, with infrequent periods of slightly higher water table and increased sedimentation, perhaps caused by major floods. This was apparently followed by the gradual development of poorly-drained swamps that eventually evolved into localized mires, as indicated by laterally discontinuous coals.

Stage 2

The dominance of grey overbank deposits indicates that relatively poorly-drained conditions persisted on the delta plain (Figure 5.2b). Coarser overbank and distributary channel deposits indicate higher rates of sedimentation, possibly through in-channel deposition or crevassing of nearby channels during frequent floods. Red-beds (well-drained swamps), poorly-drained swamps, and mires formed locally away from active areas of sedimentation or during periods of lower sedimentation. This was followed by the re-establishment of swampy conditions and the formation of the first major coal.

Stage 3

Alternating sandstone-rich lacustrine delta deposits and thick coals indicate recurring periods of lake and mire establishment (Figure 5.2c). Poorly-drained

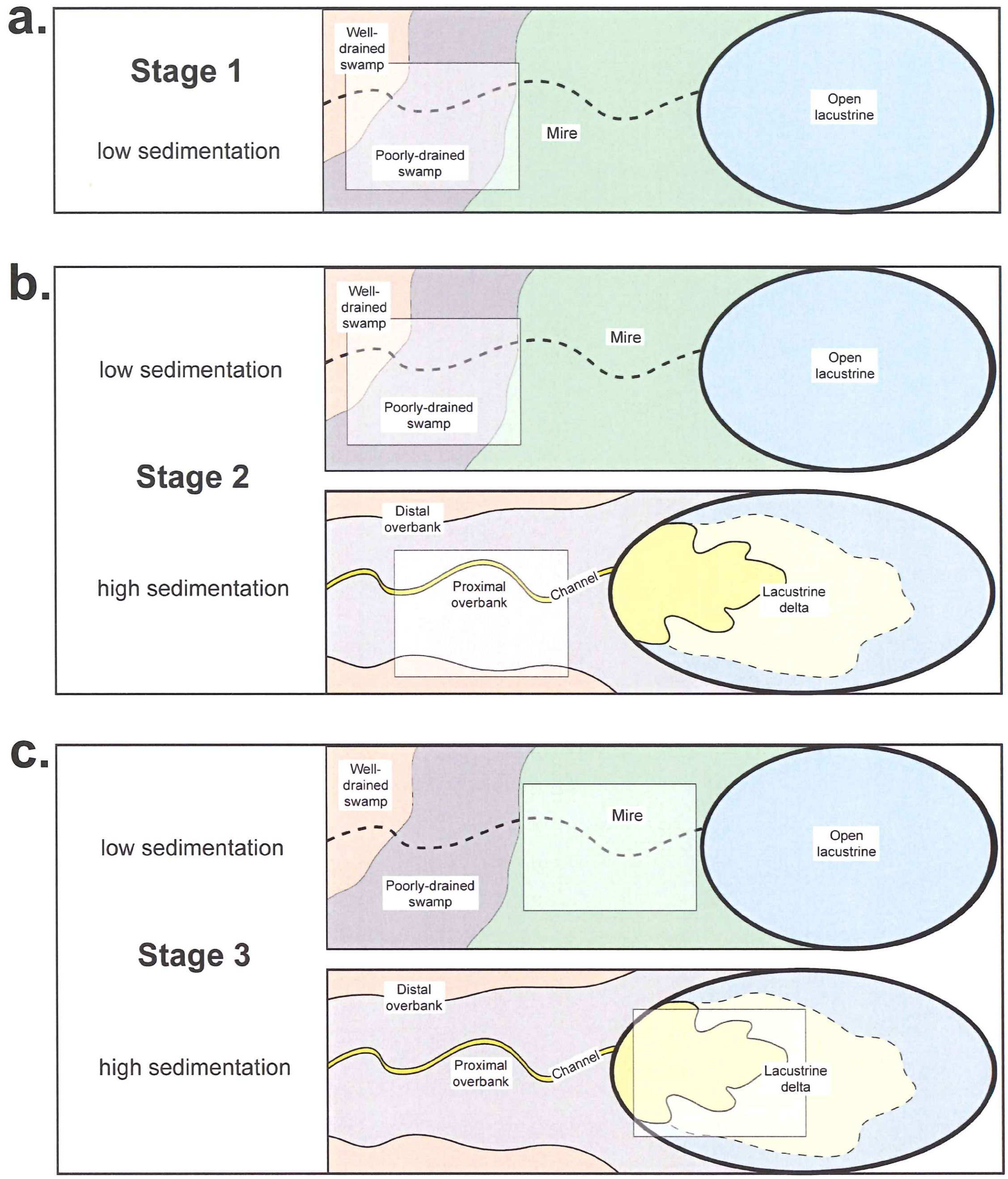


Figure 5.2 a-c. Palaeogeography of the Debert-Kemptown area during Stage 1, 2, and 3 deposition of the study interval near Cottam Settlement. Semi-transparent outlines indicate the position of the study interval at each depositional stage with respect to rates of sedimentation.

swamps evolved into extensive mires during periods of low sedimentation and stable water table. Gradual rises in water table formed lakes and drowned mires. Lakes were infilled by lacustrine deltas during periods of higher sedimentation. Poorly-drained swamps and mires were established on abandoned delta plains when sedimentation rates were low.

Stage 4

Red mudstone-rich overbank deposits indicate re-establishment of well-drained swamp conditions on the delta plain (Figure 5.3a). Emergent conditions and low rates of sedimentation prevailed, except during a period of higher water table, when a shallow lake drowned the delta plain. The abrupt transition to open lacustrine deposits suggests red-beds developed close to lake margins. Well-drained conditions were re-established as the water table was once again lowered.

Stage 5

The predominance of sandstone-poor lacustrine delta and open lacustrine deposits towards the top of the section indicates deposition of the study interval concluded with the widespread re-establishment of lakes and an overall higher water table (Figure 5.3b). Open lacustrine conditions and low rates of sedimentation prevailed except during infrequent periods of higher sedimentation, when prograding lacustrine deltas partially infilled the lakes, but did not build far enough out to form widespread delta plains. Open lacustrine deposits overlying and/or passing laterally into thin coals and coaly shales indicate fluctuating lake levels. Poorly-drained swamps and mires locally bordered lakes during times of low sedimentation and were frequently drowned when lake levels rose.

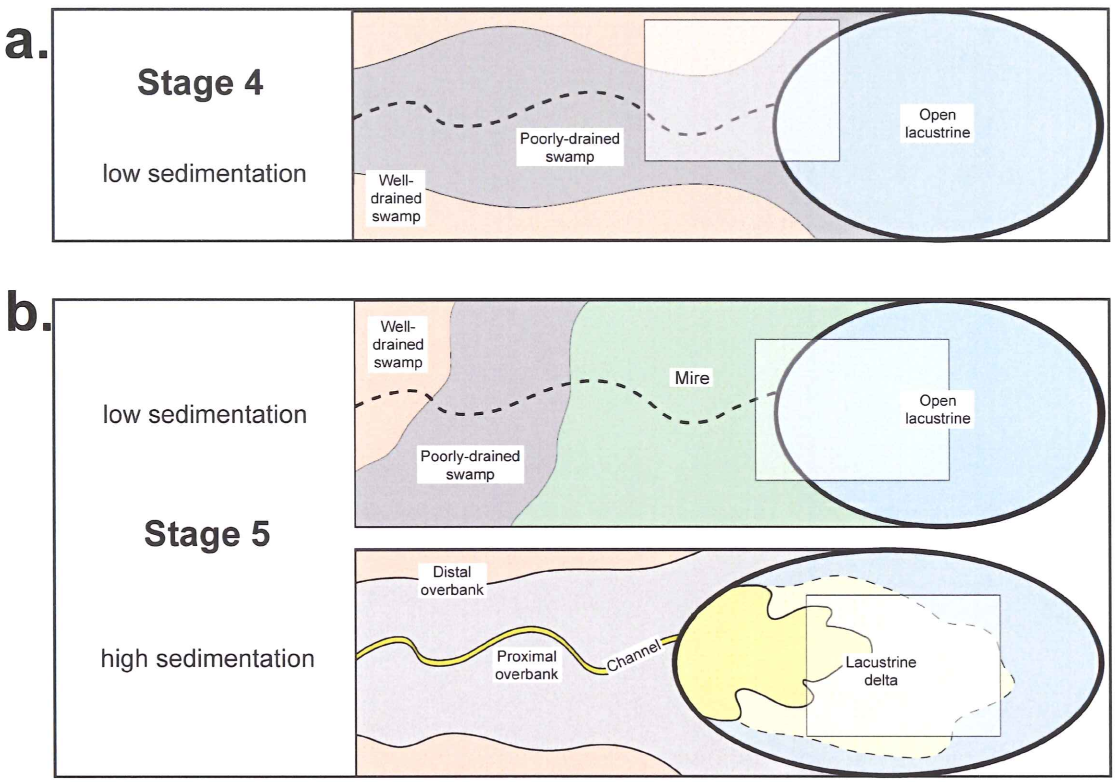


Figure 5.3 a-b. Palaeogeography of the Debert-Kemptown area during Stage 4 and 5 deposition of the study interval near Cottam Settlement. Semi-transparent outlines indicate the position of the study interval at each depositional stage with respect to rates of sedimentation.

5.4 Controls on sedimentation

Tectonics (subsidence), sediment supply, climate, hydrology, and eustasy have all been considered important controls on deposition of Late Carboniferous coal-bearing strata within the Maritimes Basin (e.g. Naylor et al., 1992; Gibling and Bird, 1994; Davies and Gibling, 2003). Although the stratigraphic interval examined during this study is somewhat restricted, it is still possible to suggest what the regional and local controls on sedimentation may have been.

5.4.1 Tectonics (subsidence)

The accumulation of fluvio-lacustrine strata near Cottam Settlement was highly dependent on the position of the Debert-Kemptown Basin with respect to major faults (e.g. Cobequid Fault). Late Westphalian subsidence caused by dominantly strike-slip movement along the Cobequid fault (Yeo and Ruixiang, 1987) undoubtedly created significant accommodation space throughout the Debert-Kemptown area. The amount and rate of subsidence remains speculative as structural complications make estimation of stratigraphic thickness difficult. However, the age and thickness of Late Carboniferous strata in the Cumberland (Namurian-Westphalian B) and Stellarton (Westphalian B-C) basins to the west and east suggest they underwent rapid subsidence (Davies and Gibling, 2003; Waldron, 2004).

Waldron (2004) suggested that the distribution of depositional environments in the Stellarton Basin was strongly controlled by differential subsidence. Mires formed on slightly more elevated northern regions of the basin. Higher rates of subsidence along the southern basin boundary caused fluvial and lacustrine systems to become isolated in this area. A similar scenario is theorized to have occurred in the Durham coalfield, where rapid differential compaction of peat, clay, and sand-rich sequences (among other factors) caused some areas to subside more rapidly than others (Fielding, 1984b). Differential subsidence may have also played a role in controlling depositional environments within the Debert-Kemptown Basin. However, much more detailed stratigraphic evidence is needed to test this hypothesis.

5.4.2 Sediment supply

The Debert-Kemptown Basin occupied an upland position adjacent to the paleo-Cobequid Highlands. Recent mapping within the Debert-Kemptown Basin has identified alluvial fan deposits sourced from the Cobequid Highlands that interfinger basinward with Westphalian C coal measures (Naylor, pers. comm., 2005). Therefore, denudation of the paleo-Cobequid Highlands certainly contributed some sediment to the Debert-Kemptown basin.

Westphalian C siliciclastic strata are widespread throughout the Maritimes Basin. Gibling et al. (1992) suggested that during the Late Carboniferous sediment was transported northeasterly into the Maritimes Basin by rivers whose headwaters may have been as far away as the central Appalachians. This suggests that sediment supply to the Debert Kemptown Basin solely from the erosion of the adjacent paleo-Cobequid Highlands is unlikely. Instead, it appears more likely that large amounts of sediment were supplied to the Debert-Kemptown Basin by the regionally sourced drainage systems described by Gibling et al. (1992). Naylor et al. (1991) suggested that during the Westphalian C, northeasterly flowing rivers might have been diverted along major structural features into local sub-basins (e.g. Stellarton Basin) within the Maritimes Basin. Diversion of rivers into the Debert-Kemptown Basin along the Cobequid Fault appears to provide a reasonable explanation for how large amounts of sediment could have been supplied to the basin.

There is evidence to suggest that the sediment supply to the Debert-Kemptown Basin may have been quite variable. The distributary channel and lacustrine delta deposits identified within the study interval require relatively high rates of sediment supply. The mires that were precursors of the thick coals could only have been deposited in an area where sediment supply was restricted. The occurrence of fine-grained red-beds and organic-rich open lacustrine deposits also suggests periods of restricted sediment supply. Changes in sediment supply were probably affected by both local and regional factors. The location of various depositional environments/geomorphic regions within the basin would have exerted a local control on sediment supply. For example, areas more proximal to distributary channels would receive much more sediment than the more distal areas of the floodplain.

However, major vertical changes in deposit types (e.g. lacustrine delta to mire deposits) could have been caused by changes in the availability of sediment from regionally sourced rivers. The Debert-Kemptown Basin, like the Stellarton Basin (Naylor et al., 1992), could have acted as a local base level for regionally sourced drainage systems. Therefore, as the basin became infilled with sediment, rivers entering the basin would have become choked with sediment and probably diverted back to following the regional paleoslope. A reduction in sediment-carrying capacity of the regional drainage systems or any type of diversion of major rivers away from the Debert Kemptown Basin would also have temporarily reduced sediment supply.

5.4.3 Climate (hydrology)

One of the most difficult questions arising from the analysis of the study interval is whether alternating periods of high and low sediment influx, superimposed on an overall upward rise of the water table and increase in coals, may in part reflect climate change and resulting improved hydrology. As of yet, no workers have attempted to establish the relative time span of sequences within the basin-fill record of the Debert-Kemptown Basin (Naylor, pers. comm., 2005), making the inference of potentially important climatic controls rather difficult. However, climatic factors described by Calder (1994) and Cecil (1990) may in part explain the sedimentary sequence preserved in study interval, and are thus considered.

Cecil (1990) proposed a model for deposition of coal-bearing strata in the Appalachian Basin based on the assumption that climate is a primary control on sediment flux in most sedimentary systems. Coals formed during wet periods with minimal clastic input, whereas siliciclastic strata were deposited during periods of seasonal rainfall. Applied to the study interval, mire deposits (coals) could represent minimally seasonal wet climates, and lacustrine delta, coarse overbank, and distributary channel deposits more strongly seasonal wet-dry climates. The predominance of levee, crevasse splay, and waning flow deposits in the overbank and lacustrine delta assemblages would also seem to suggest a seasonal climate with frequent floods.

Calder (1994) suggested that the upward reddening of the Cumberland basin-fill and associated decline of coals in the Springhill coalfield could have occurred, at least in part, due to orographic climate change. The paleo-Cobequid Highlands may have acted as a rainshadow during deposition of middle-Westphalian strata in the more northerly Cumberland Basin (Calder, 1994). The upward increase in water table observed in the study interval may reflect increased orographic precipitation in the Debert-Kemptown Basin, which would have occupied a windward position adjacent to the southern Cobequid Highlands.

Increased precipitation in the Debert-Kemptown Basin would have promoted wetter conditions and the development of mires, although mires may have also developed from increased groundwater flow. Calder (1994) suggested that precursor peatlands of the Springhill coalfield were nourished at least in part by groundwater discharge from alluvial fans. Alluvial fan deposits sourced from the Cobequid Highlands interfinger with coal-bearing strata in the Debert-Kemptown Basin, and could have easily contributed groundwater discharge, promoting mire development and elevated water table levels.

5.4.4 Eustasy

Recent studies of coal-bearing strata in the British coal measures and Sydney Basin have revealed the presence of numerous cyclothems or cycles attributed to glacio-eustatic sea level fluctuations (Hartley, 1993; Gibling and Bird, 1994). Similar cycles noted in the Cumberland Basin by Davies and Gibling (2003) could have been caused by high magnitude sea-level fluctuations, although rapid basin subsidence may have played a more important role. Because these cycles were clearly operating in major sub-basins of the Maritimes Basin and elsewhere in Europe while coal-bearing strata were being deposited in the Debert-Kemptown Basin, eustatic controls on sedimentation must be considered.

Davies and Gibling (2003) suggested that drowning of laterally extensive mires within the Joggins Formation of the Cumberland Basin could have been driven by direct marine flooding or indirectly as a response of the water table to rising base level. The former seems very unlikely to have occurred in the Cottam Settlement area. Although the rather distant Sydney Basin may have experienced limited marine influence (Gibling and Bird, 1994), the predominance of low-sulfur coal seams and absence of marine fauna in Cottam Settlement strata preclude marine influence. The Debert-Kemptown Basin also occupied an upland position, and would have been less susceptible to rises in sea level.

Superimposed on a gradual rise in water table are periods of significant peat accumulation (low sediment supply) and high rates of sedimentation (high sediment supply). These variations in sediment supply could have been caused by eustatically driven changes in sediment distribution within Maritimes Basin. Gibling et al. (1994) attributed cyclic sedimentation within the Westphalian D-Stephanian Sydney Mines Formation of the Sydney Basin to eustatic controls. It would seem possible that lowstand conditions recorded within the coastal Sydney Mines Formation could correspond to sediment by-passing in the more upland Debert-Kemptown Basin. However, Blum and Tornqvist (2000) suggested that upriver effects of sea-level change in the Mississippi and other river systems were limited to several hundred kilometres upstream of the present coastal area. Although coals could have formed during low stands (low sediment supply) and lakes/lacustrine deltas during high stands (high sediment supply), the Debert-Kemptown area is currently several hundred kilometres west of Sydney, and would have been near the upper limit for inland effects.

5.5 Economic potential of the coals

Although the focus of this study was primarily on the sedimentology of a rather restricted study interval preserved near Cottam Settlement, several economic aspects of the coals are briefly considered, including coal quality, coal continuity, and mining considerations. The thickest coal seams occur within Stage 3 of the study interval (Figure 5.1), and attain thicknesses of 0.5-1.50 m. They have been previously classified as high volatile bituminous in rank, with average sulfur and ash contents of 1% and 15% respectively (Bain and Cullen, 1998), making them of economic significance. Furthermore, the coal seams extend from the bedrock cropline to a maximum depth of 39 m near the former Berichan Resources mine site (Bain and Cullen, 1998) and 70-95 m in the study interval, making them easily accessible from the surface.

Although the coals are of high enough grade and shallow depth to permit mining by open pit methods (Bain and Cullen, 1998), their apparent lateral discontinuity near Cottam Settlement and across the broader Debert-Kemptown region has complicated exploration and coal mining (Naylor, pers. comm., 2005). This argument was seemingly supported by the examination of additional drill cores from the DDNSD-series that bore little resemblance to the other three measured sections (DDNSD-2, DDNSD-6, outcrop section), even though they were located only a few hundred metres away. Although structural complications are not particuilarly evident in the modest study interval, coal seams contained within Stage 3 and elsewhere in the stratigraphic section (Figure 5.1), with the exception of the thickest seam, commonly grade laterally into coaly shale or rarely pinch out.

5.6 Conclusions

Depositional Environments/Sedimentary deposits

The Upper Carboniferous (Westphalian C) coal measures preserved near Cottam Settlement resemble the fluvial-lacustrine deposits of the British coal measures and those preserved in major sub-basins (e.g. Stellarton Basin) of the regional Maritimes Basin. Two major facies associations are recognized within these strata, and represent deposition in lacustrine conditions and on poorly to well-drained delta plains.

1. Lacustrine deposits are sub-divided into open lacustrine and lacustrine delta facies assemblages.
    a. Open lacustrine: organic-rich mudstones with abundant fauna are interpreted as the deposits of freshwater lakes.
    b. Lacustrine delta: coarsening-upward mudstone, siltstone, and planar to cross-laminated sandstone successions are interpreted as deltaic deposits formed along shoaling freshwater lake margins.
2. Delta plain deposits are sub-divided into distributary channel, overbank, and mire facies assemblages.
    a. Distributary channel: predominantly massive to trough cross-bedded sandstones are interpreted as meandering river deposits.

b. Overbank: pervasively rooted red, grey, and dark grey mudstones are interpreted as well- to poorly-drained floodplain/swamp deposits of distal overbank areas; siltstones and sandstones may represent levee and crevasse splay deposits of more proximal overbank areas.

c. Mire: coaly shale and high volatile A bituminous coals are interpreted as the deposits of mires.

Summary of depositional events

Coal-bearing strata preserved within the study interval record a five stage depositional history that began with the development of a well-drained swamp (red-beds), which gradually evolved through a poorly-drained swamp to a mire. This was followed by an extensive period of sedimentation on a delta plain. Distributary channels and coarse overbank deposits predominated during periods of high sedimentation, while localized mires and poorly-drained swamps formed during times of reduced sedimentation. The water table rose following this extensive period of delta plain development. A period of peat accumulation was followed by formation of a shallow lake, drowning the mire. Distributaries were then diverted into the lake forming a lacustrine delta. Successive periods of delta abandonment, mire development, lake formation, and lacustrine delta progradation were followed by the re-establishment of more well-drained conditions near lake margins. Deposition of the study interval concluded with consecutive phases of lake formation, lacustrine delta progradation, and localized mire development near lake margins.

Probable and potential controls on sedimentation

Late Westphalian sedimentation in the localized, intermontane Debert-Kemptown Basin could have been controlled by a combination of subsidence (accommodation), sediment supply, climate (hydrology), and possibly eustasy.

1. Probable controls (most likely controlled sedimentation)
   a. The bounding Cobequid fault would have produced high rates of subsidence and generated significant accommodation space in the basin.
   b. Denudation of the paleo-Cobequid Highlands would have almost certainly contributed some sediment to the basin, although large amounts of sediment were presumably supplied by regionally sourced drainage systems. Rivers could have been diverted into the basin along the Cobequid fault. Major vertical changes in deposit types (lacustrine delta to mire) could have been caused by changes in the availability of sediment from regionally-sourced rivers.
   c. Alluvial fan deposits sourced from the paleo-Cobequid Highlands could have contributed additional groundwater discharge. An increase in fan size could also explain the overall rise in water table and concomitant increase in coals.
2. Potential controls (might have controlled sedimentation; more evidence required)
   a. Regional climate change could have influenced deposit types. Mires may represent seasonally wet climates and lacustrine delta, coarse overbank, and distributary channel deposits seasonal wet-dry climates.

b. The paleo-Cobequid Highlands could have caused local orographic change. Orographic precipitation or loss of rainshadow could explain the overall rise in water table and upward increase in coals.

c. Differential subsidence could have controlled the distribution of depositional environments. Changes in deposit type (lacustrine delta/distributary channel to mire) may reflect higher or lower rates of subsidence in different regions of the basin.

d. Eustatically driven changes in sediment distribution within Maritimes Basin could explain changes in deposit types in the more upland Debert-Kemptown Basin, although the basin would have been near the upper limit for inland effects.

Economic considerations

The thickest coal seams within the study interval are of sufficient grade and depth to permit recovery by open pit mining methods. However, there is evidence to suggest that the coals are laterally discontinuous, which would complicate any future mining development.

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APPENDIX 1

Large print-out of the stratigraphic cross-section measured at drill holes DDNSD-2 and DDNSD-6, and the outcrop section along the Debert River (identical to Figure 5.1). The appendix is included in a folder at the back of the thesis.