Chapter 4 - Sedimentology

Introduction

Various aspects of the sedimentology of Cumberland Basin rocks are discussed in this chapter including the lithofacies, lithofacies transition relationships, lithofacies associations, and facies assemblages. Sediment dispersal patterns are also summarized in this chapter; inferences derived from these dispersal patterns are an aid to interpretation of the depositional sedimentary environments in the Cumberland Basin.

Sediment Dispersal Trends

Introduction

Sediment dispersal trends are useful tools in basin analysis and help define the basin configuration and the source areas of basin fill. Sediment dispersal pattern analysis by paleocurrent determinations became commonplace as part of sedimentological studies in the Maritimes Basin during the late 1960s and the early 1970s. Early studies using sediment dispersal trends include works on the Carboniferous of Cape Breton by Belt (1965), on the Pictou Group in New Brunswick by van de Poll (1973), and on the Cumberland Group along the Joggins shore by Walton and Duff (1973).

Paleocurrent Measurement and Analysis

An important factor in the proper application of paleocurrent studies is the reliability of the primary sedimentary structure measured. This is governed to a large degree by the extent to which the structures are exposed in outcrop. Allen (1966) and Miall (1974) concluded that directional variance of the paleocurrent indicator increases with decreasing dimensions of the flow indicator. Miall (1974) outlined a ranking system for current indicators in modern streams. Ranks 1 to 3 represent active river systems, meander belts and major channel reaches within the meander belts, respectively. Minor channels and large sediment bars are rank 4. Rank 5 includes large-scale trough and planar cross-stratification. Rank 6 structures include small-scale cross-stratification, current (parting) lineations, imbrication, flute casts, groove casts and associated erosional and tool marks. Ripple mark orientations in fluvial strata pose problems in sediment dispersal reconstructions, as they are often more representative of waning flow conditions and, therefore, do not necessarily conform to the overall gradient of the stream. Although ripple orientations have been used with some success in the Cumberland Basin (Walton and Duff, 1973), there are many areas in the basin where the authors have observed ripple drift with paleocurrent directions at up to 90° variance to the underlying trough directions. Van de Poll (1983) found similar discrepancies in the Pictou Group strata of Prince Edward Island and suggested that some of the ripples may have been wind generated. Duff *et al.* (1982) suggest that variations in the ripple orientations might also reflect dispersal patterns of associated crevasse splay deposits, based on their work in the Carboniferous strata of the Sydney Basin. This explanation may also apply to many of the ripples (ripple drift) in the Cumberland Basin.

The database for this study (Fig. 4-1) has been primarily compiled from rank 5 paleocurrent indicators, large-scale troughs, but also includes a few instances of ranks 2 and 3 structures where channel fills have been mapped in the mines and through diamond-drilling in the Springhill and Tatamagouche areas and where fan trends can be determined along the southern margin of the basin. The paleocurrent measurements were taken primarily on well-exposed coastal and river sections where three-dimensional observations enhanced reliability. Paleocurrent determinations based on trough cross-stratification on the scale of individual outcrops are a measure of local sediment dispersal, whereas regional compilations by vector summation provide regional directions of sediment transport rather than local transport direction (van de Poll, 1983).

Over 1500 paleocurrent measurements were recorded in the study area, including measurements based on ripple marks, parting lineations, cross-bed intersection ridges, plant fragment orientations, flute molds, tool marks, pebble imbrication, isopachs of sand or conglomerate bodies, and large- and small-scale trough cross-stratification. The large-scale trough cross-stratification data represent the most abundant source of reliable (rank 5) indicators of flow directions (n=1254) in the study area. Paleocurrent data from large-scale troughs in Carboniferous strata exposed along the shores and rivers in the study area (Fig. 4-1) are, therefore, the data used to calculate vector means and strengths of the dispersal patterns.

The trough cross-stratification data are presented in two forms: (1) as paleoflow arrows on a map where each

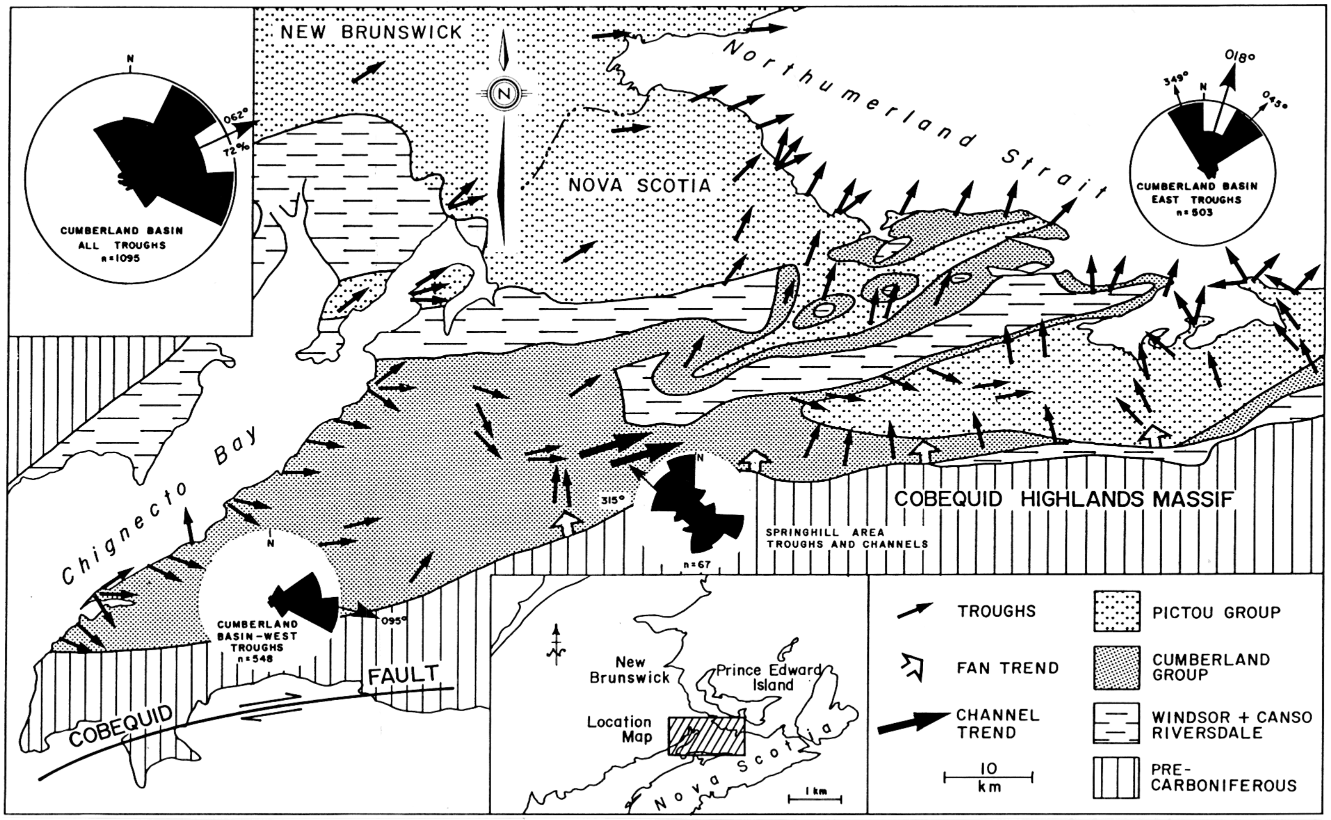


Figure 4-1. Paleocurrent - sediment dispersal trends in the Cumberland Basin, Nova Scotia.

arrow represents the mean of at least five measurements from an area within a 250 m radius (Fig. 4-1) and (2) as a rose diagram compiling the data in 30° class intervals (Fig. 4-2). Additional paleocurrent determinations based on pebble imbrication, groove casts, parting lineations, etc., are included in a separate rose diagram to confirm the cross-stratification directions and to demonstrate the increased variability when these measurements are included (Fig. 4-2).

Paleocurrent Variations

Ryan (1985) stated that there are few significant variations in the flow directions measured from the various formations in the Tatamagouche area, and that the north-northwesterly dispersal direction was consistent from the Namurian to the Early Permian strata of the Tatamagouche Syncline. Subsequent paleocurrent studies (Ryan *et al.*, 1988a; Ryan and Boehner, 1986) in the remainder of the basin have shown similar trends. It appears that the relative position of the strata to highland areas is more important to paleocurrent direction than the stratigraphic position of the bedforms being measured and, therefore, discussions of the data will include all the strata overlying the Windsor Group in the basin.

Dispersal Trends

For discussion purposes, Ryan *et al.* (1988a) divided the basin into three geographic areas: (1) south-central Cumberland Basin, (2) western Cumberland Basin, and (3) eastern Cumberland Basin.

Eastern Cumberland Basin (Tatamagouche Area)

This part of the basin shows two dispersal trends: (1) the southern Tatamagouche Syncline trend of 349° (Fig. 4-1: TS) and (2) the northeastern Cumberland Basin trend of 045° (Fig. 4-1). The eastern Cumberland Basin has a vector trend of 018° which is at a variance of approximately 45° to the overall Cumberland Basin trend of 062° (Fig. 4-1). The Tatamagouche trend reflects the presence of the Cobequid Highlands Massif, which contributed recharge of water and a variance in the gradient of the basin margin. The influence of the Cobequid Highlands Massif on sedimentation is clearly demonstrated by thick alluvial fanglomerate deposition recorded by the Falls, Claremont and Polly Brook formations. These fans indicate that there were significant quantities of surface water entering the basin

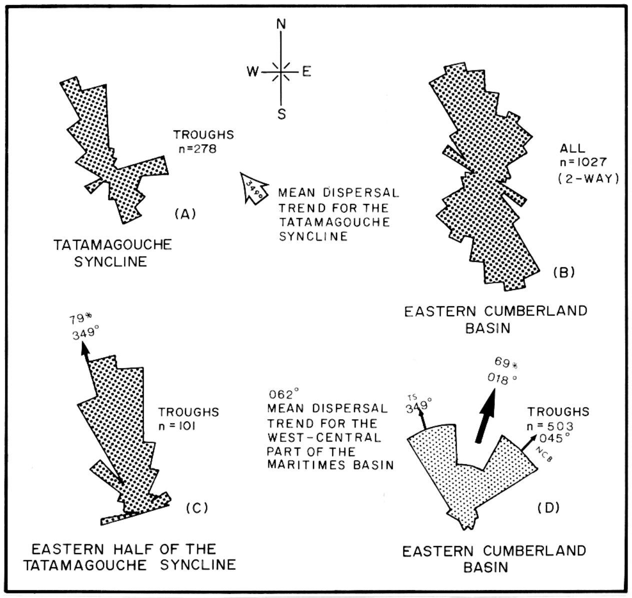


Figure 4-2. Rose diagrams for paleocurrent measurements from the eastern part of the Cumberland Basin.

from the highland areas. The presence of material derived from the Cobequid Highlands Massif in fanglomerates that interfinger with the more distally derived units, such as the Boss Point Formation (Boehner *et al.*, 1986), indicates that the sedimentological influence was persistent even during periods of slower subsidence and basin margin onlap. North of the Claremont Anticline the influence of the Cobequid Highlands Massif diminished and dispersal trends more closely approximate the regional trends and conform well to the trends in Prince Edward Island and southern New Brunswick, indicating that the influence of the Cobequid Highlands Massif did not extend much beyond the Tatamagouche Syncline area (Fig. 4-1).

The western part of the Tatamagouche Syncline has a division of flow into two directions at approximately the synclinal axis (Fig. 4-2). The northern limb exhibits easterly and southeasterly trends. These are attributed to flow away from incipient evaporite diapirs during the time of Pictou Group sedimentation (Ryan, 1986c). The southeastern flow directions are found in progressively older strata toward Springhill suggesting that if diapirism is the cause of the flow variations, then diapirism of the Windsor Group evaporites may have been initiated along the Claremont Anticline, during the Westphalian C in the west and not until the Stephanian in the east. Syndepositional diapirism is confirmed by the presence of flat-lying Malagash Formation pebble conglomerate unconformably overlying overturned Windsor Group strata at Dewar Quarry in the Pugwash area (Fig. 4-3). This indicates that, at least in this area, Windsor diapirism pre-dates Malagash Formation deposition. The implication of this observation is that diapirism predates the Pictou Group and that the divergent paleocurrent patterns in the basin are quite likely the result of an incipient diapiric structure that was implaced between the late Viséan and Westphalian C times (Fig. 4-4). The divergent trends may provide a useful indicator of when diapirism was initiated in the basin.

South-Central Cumberland Basin (Springhill Area)

Ryan *et al.* (1988) suggest that a degree of caution is necessary in interpreting paleocurrent data in this area. A combination of rank 3 to 5 structures (troughs and hollow fills) from Cumberland Group strata in the area reveal a strong north to northwesterly, bipolar trend. Basinward channel belts and belt margins (rank 2 structures), however, trend northeasterly, indicating a longitudinal drainage pattern parallel to the basin margin. The overall Cumberland Group trend is approximately 315° (Fig. 4-1). Boss Point strata in the area have a more northerly trend with a dispersal of approximately 350°. This trend is also evident in the Polly Brook Formation conglomerate and reflects the gradient off the Cobequid Highlands Massif to the south.

At Salt Springs, rank 4 structures (scour fills) exhibit a vector mean of 101° whereas troughs indicate a mean trend of 044°.

Western Cumberland Basin (Joggins-Athol Area)

Rust *et al.* (1984) and Salas (1986) compiled sediment dispersal data from the western part of the basin in the Ragged Reef and Apple River area, respectively. Salas (1986) found north-northwesterly trends in the beds he thought were older and easterly trends in the beds he believed to be younger. Subsequent mapping and spore dating in the area, by the authors, has documented that much of the section measured by Salas is fault repeated and all of the beds are more or less equivalent in age. This observation indicates that the variations in paleocurrent directions are spatially related rather than variations in dispersal trends through time. Rust *et al.* (1984) suggested that there are two modes of sediment dispersal in the Ragged Reef area, south of Joggins, one east-southeasterly at 110° and the second southwesterly at 240°. These trends have been confirmed by subsequent work (Ryan *et al.*, 1988a), although the

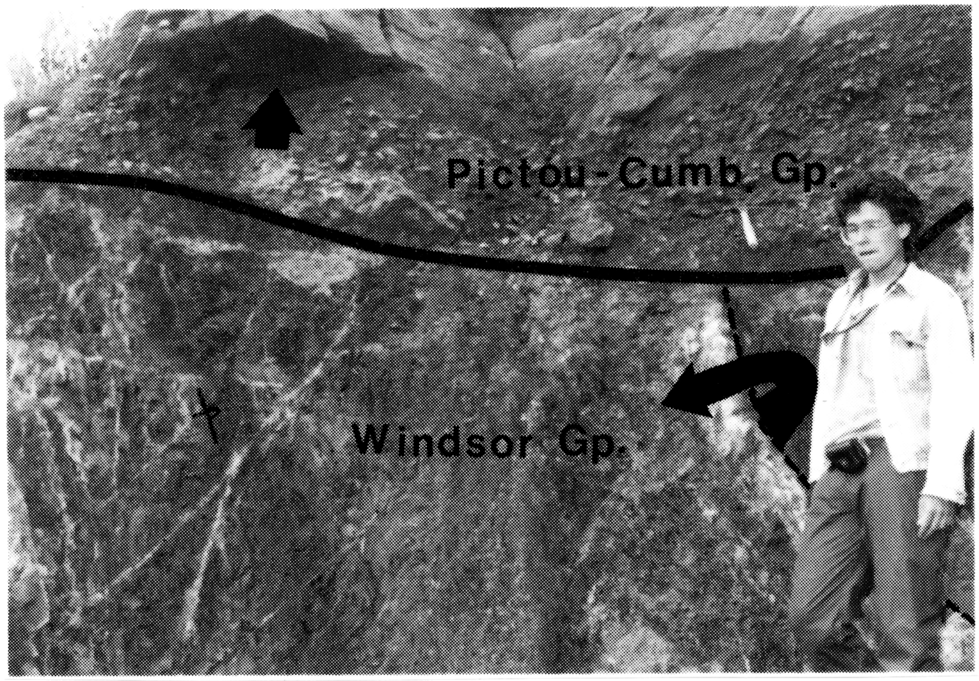


Figure 4-3. Photograph of unconformity, Malagash Formation overlying the overturned strata of the Windsor Group, demonstrating the syndepositional nature of diapirism, Dewar Hill Quarry south of Pugwash.

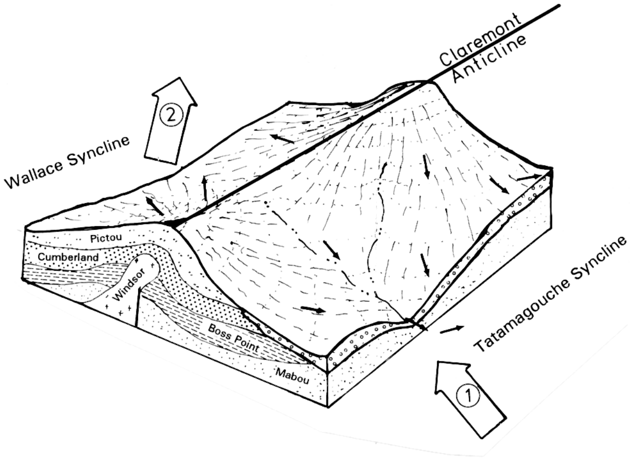


Figure 4-4. Cartoon illustrating the divergence of dispersal trends in the Cumberland Basin resulting from syndepositional diapirism.

southwesterly trend is very minor. The bimodal distribution of sediment dispersal trends in the Ragged Reef area may reflect alternating periods of topographic influence of the Caledonia and the Cobequid Highlands massifs on sedimentation.

Paleocurrents in the Cumberland and Pictou group strata of the western Cumberland Basin are derived from measurements of three-dimensional outcrop exposures on wave cut platforms along the Minudie to Spicer's Cove shoreline and along river sections inland (Fig. 4-1). The sediment dispersal trend for Cumberland and Pictou group strata represents 548 rank 4 measurements and is strongly unimodal with a vector mean of approximately 095° and a vector strength of 88% (Fig. 4-1). The Boss Point and Shepody formation strata have a vector mean of approximately 097° with a vector strength of 92% (Fig. 4-1). The trend confirms easterly dispersal patterns documented by Walton and Duff (1973), Rust *et al.* (1984) and Salas (1986). Dispersal trends adjacent to the Minudie Anticline, especially those in the Boss Point Formation, tend to be more southerly. On the southern limb of the Athol Syncline the trends tend to be more northerly (Fig. 4-1), indicating that the axis of the basin of deposition may have been nearly coincident with the axis of the Athol Syncline.

Overall Cumberland Basin Trends

A total of 1143 measurements from the Cumberland and Pictou group strata were used in the compilation depicted in Figure 4-1. The vast majority of data (n=1095) represent measurements of individual troughs (rank 5 structures of Miall, 1974). Walton and Duff (1973) documented that the dominant sediment dispersal trend, as defined by paleocurrent determinations derived from foreset bedding, in the Cumberland Group of the Joggins area, Nova Scotia, was easterly at 100°.

Subsequent work by Rust *et al.* (1984), Salas (1986) and the authors and other Nova Scotia Department of Natural Resources geologists (Ryan *et al.*, 1988a) has confirmed this easterly trend and shown that it is consistent throughout most of the Upper Carboniferous strata of the western Cumberland Basin. The overall sediment dispersal trend of the late Westphalian A to Permian Cumberland and Pictou group strata in the Cumberland Basin is northeasterly to easterly, indicating a source area located southwest to west of the basin. The trend of sediment dispersal conforms with the larger Maritimes Basin trends discussed by van de Poll (1973) and Gibling *et al.* (1991). Variations in dispersal trends occur adjacent to highland areas such as the Cobequid or the Caledonia Highlands massifs. These variations are caused by the influence of highland recharge and sediment load influx from the massifs along the basin margins. The extent of influence of these features is limited and trends assume the more regional basin trends within a few kilometres from the basin margins. Minor variations also occur in the northern Tatamagouche Syncline and the Minudie Anticline areas where flow diverges from the regional pattern due to slope gradient changes resulting from syndepositional diapirism.

The overall vector mean for the Cumberland Basin is 062° and has a vector strength of 72% (Fig. 4-1).

The Maritimes Basin Dispersal Trends

Data collected for this project, and additional information on dispersal trends from Ryan (1984, 1985), Ryan and Boehner (1986), Calder (1986a), van de Poll and Ryan (1985), Gibling and Rust (1984), Plint and van de Poll (1984), Knight (1983) and Carter (1985b) have been compiled to show the basinal dispersal trends within the south- central part of the Maritimes Basin (Fig. 4-5). The overall northeasterly trend in sediment transport may be slightly misleading as the compilation is based on data from rock units that vary in age from Late Devonian to Early Permian. Although the trends may have varied through time, the observed directions correspond well to the 36,000 measurements for the Cumberland and Pictou group strata by Gibling *et al.* (1991) (Fig. 4-6) and probably represents a good approximation of the prolonged sediment dispersal trend for the Maritimes Basin.

The dispersal pattern of the southern Maritimes Basin indicates that most of the basin fill material must have been derived from platform areas in southwestern New Brunswick and Maine, or perhaps from a more distal source (cf. van de Poll, 1973). Gibling *et al.* (1991) suggest that the major source area lay to the southwest of the Maritimes Basin throughout the Late Carboniferous. Uplands within the basin deflected the paleoflow and locally probably constituted important sources of detritus.

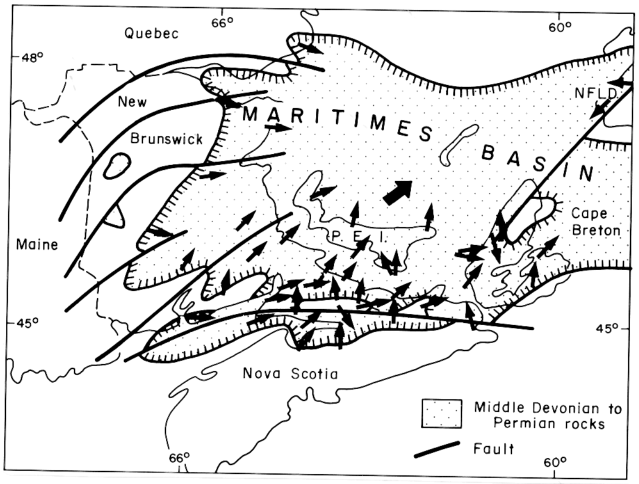


Figure 4-5. Compilation of paleocurrent data from Devonian to Permian strata in the Maritimes Basin (after Ryan, 1986).

Gibling *et al.* (1991) used tectonostratigraphic analysis to suggest that the drainage originated in the fold-and-thrust belt of the central and southern Appalachians, and followed northeast-trending faults and structural troughs through the older Acadian mountains to the Maritimes Basin (Fig. 4-7).

Lithofacies, Lithofacies Associations, and Facies Assemblages

Introduction

The terms lithofacies, lithofacies association, and facies assemblage, have been used by many workers to define various lithological sequences; however, the haphazard application of these terms has led to confusion. Miall (1977) pointed out that without clear definitions it is impossible to know the exact meaning intended by authors using lithofacies terminology. In order to clarify the meaning of the various terms used here, definitions are presented below.

The term *lithofacies* is defined for the purpose of this report as being a rock unit characterized by a distinct lithology. For example, coarse-grained trough cross-stratified arkose is one of the sandstone lithofacies. Lithofacies represent the basic component of which associations, assemblages, and sequences are built.

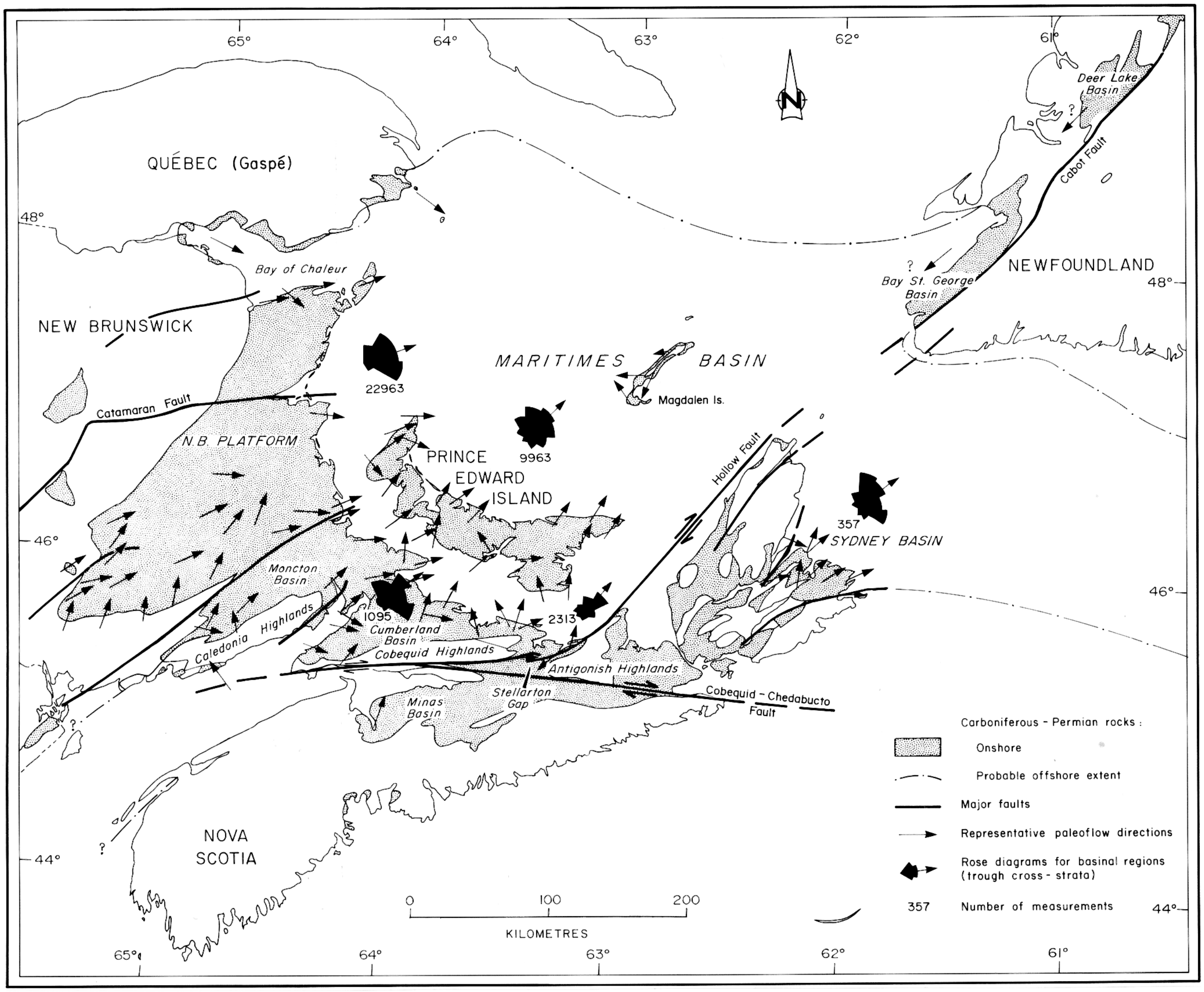


Figure 4-6. Paleodrainage patterns for Cumberland and Pictou group strata in the Maritimes Basin (after Gibling *et al.*, 1991).

Lithofacies association is also a purely descriptive term used to define one or more lithofacies which tend to occur together. For example: calcareous mud-chip trough cross-stratified conglomerate and coarse-grained trough cross-stratified arkose can be grouped together to make up the coarse-grained sandstone lithofacies association. Other lithofacies associations could include: fine-grained sandstone, fine sandstone - mudstone, massive mudrock, and limestone - mudstone.

The terms *lithofacies* and *lithofacies association* are purely descriptive terms applied to the rock units or packages of rock units that tend to occur together. In contrast, the term *facies assemblage*, as defined below, is a process-biased interpretative term which is subjectively applied to rock packages. Care should be taken to clarify that terms containing the prefix *facies* are used as interpretive-environmental nomenclature in this report, whereas terms that have *lithofacies* as a prefix are purely descriptive.

A *facies assemblage* is defined as a group of one or more lithofacies associations which together can be interpreted as being formed in a particular depositional setting. Proportions of the various lithofacies associations may also be important to the interpretation. An example might be: coarse-grained sandstone, fine-grained sandstone and massive mudrock lithofacies associations, where the mudrocks are the most abundant, can be interpreted as a meander plain facies assemblage. Examples of facies assemblages include: sandstone and conglomerate dominated (braidplain); mudrock dominated

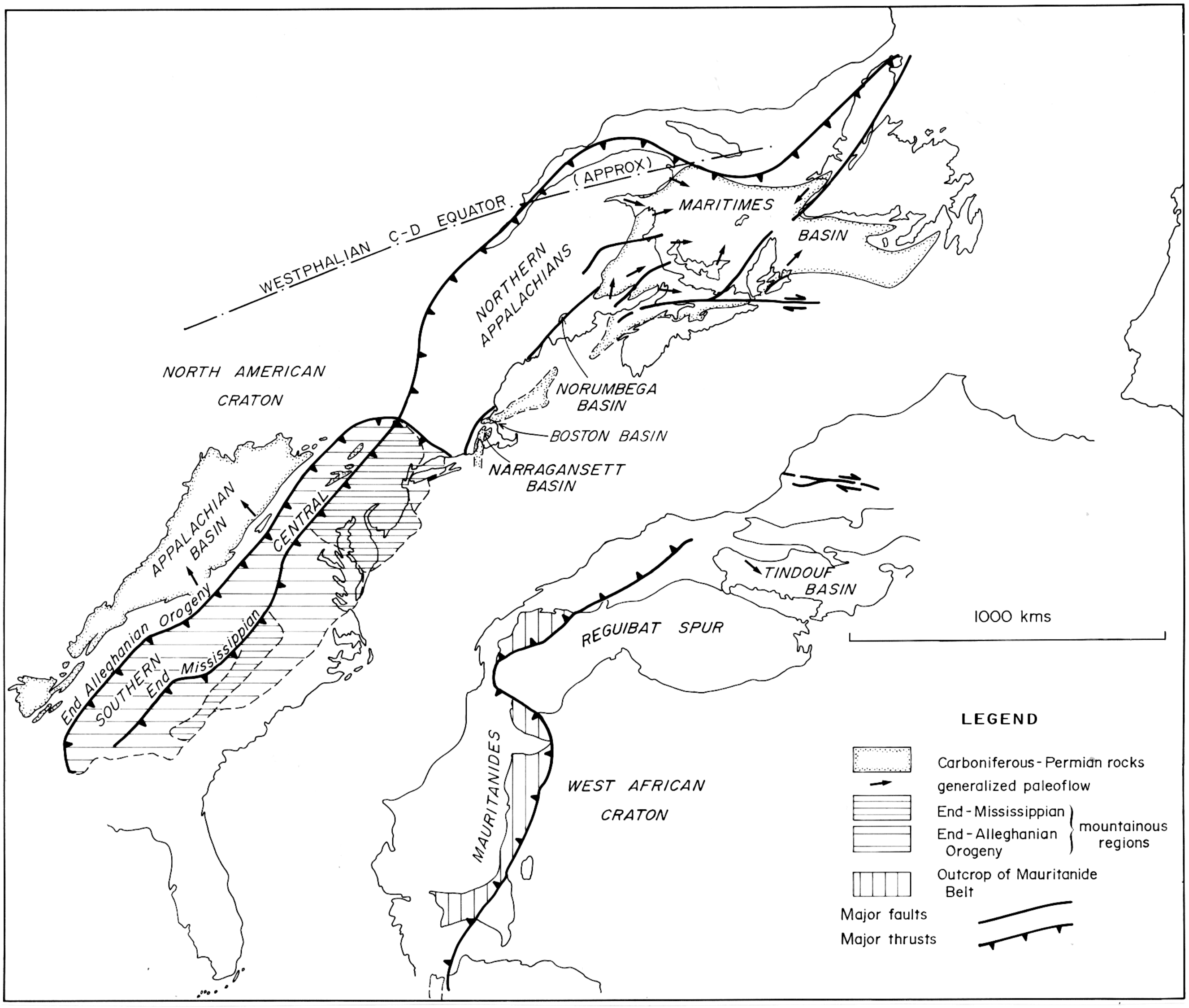


Figure 4-7. Paleogeographic reconstruction of Upper Paleozoic drainage patterns in eastern North America, after Gibling *et al.*, 1991.

(meander plain); conglomerate dominated (alluvial fan). Caution is advised when applying this terminology because interpreted environments are not unique or sharply defined and there are always exceptions to the general rule; for example, not all sandstone- and conglomerate-dominated assemblages need necessarily be interpreted as braidplain deposits.

Lithofacies

Lithology is classified according to Folk's (1974) classification and lithofacies types are modified from Miall's (1977, 1978) depositiona l facies scheme (Table 4-1). Fourteen lithofacies have been defined in the Cumberland Basin and they are summarized below.

Conglomerate Lithofacies

Planar- bedded Boulder to Pebble Conglomerate

Planar-bedded polymictic conglomerate containing subangular to subrounded clasts of rhyolite, basalt, granitoids and metasediments make up this lithofacies. These rocks are clast-supported orthoconglomerate with planar stratification.

Planar-bedded Pebble Conglomerate

The pebble conglomerate is clast-supported or, more rarely, matrix-supported. Planar and graded bedding are the most common bedforms. The matrix is red litharenite containing abundant mica. Clasts include basalt, rhyolite, granite, metasediments, reworked

Table 4-1. Lithofacies types in the Cumberland Basin.

Lithofacies	Lithofacies Type (modified after Miall, 1977b)
Planar bedded boulder to pebble conglomerate	BGp
Planar bedded pebble conglomerate	PGp
Cross-bedded cobble to pebble conglomerate	CGt
Trough cross-bedded calcareous mud-chip conglomerate	PGt
Trough cross-bedded arkose	ASt
Trough cross-bedded pebbly sandstone	PSt
Trough cross-bedded sublitharenite	St
Planar to low-angle foreset-bedded sandstone	Sp
Rippled siltstone and fine-grained sandstone	Fr
Massive mudrock	Fm
Fossiliferous limestone	Lf
Coal	Coal
Gypsum/Anhydrite	Anh
Salt/Potash	NaCl

B = boulder
p = planar
C = cobble
A = arkose
F = mudrock or fine-grained rock
r = rippled
f = fossiliferous

G = gravel
P = pebble
t = trough cross-bedded
S = sandstone
m = massive
L = limestone

Carboniferous sediments and quartz. The relative proportion of the clasts types shows no observable trend.

Cross-bedded Cobble to Pebble Conglomerate

These rocks are polymictic orthoconglomerate. The clasts are granite, basalt, rhyolite, metasediments and some reworked Carboniferous sedimentary fragments. The clasts are usually sub- to well-rounded and hematite stained. Conglomerate clasts are oriented in a manner reminiscent of cross-strata imbrication. The matrix is a coarse-grained feldspathic litharenite.

Sandstone Lithofacies

Trough Cross-bedded Calcareous Mud-chip Conglomerate

Trough cross-stratified conglomerate contains clasts of calcareous lutite as well as red and grey clasts of pedogenic limestone (rhizoconcretions). The clasts are generally elongate and are usually supported in a fine- to medium-grained arkosic sandstone matrix. Clasts range from 0.5 to 3 cm in length and have a diameter of approximately 0.5 cm. Calcareous mud-chip conglomerate occurs either near the base of a channel sandstone or at the base of the component trough cross-strata. Plant debris is locally abundant. The calcareous clasts are most commonly reworked calcrete material that originally formed around plant roots in the silt and mud of floodplain areas.

Trough Cross-bedded Arkose

Arkosic sandstone contains pebble size clasts of quartz and feldspar within a medium- to coarse-grained, subangular, poorly sorted arkosic sandstone matrix. Arkose units usually fine upwards. Their composition is generally 60-70% quartz, 15-25% K feldspar, 0.5% kaolinite, 1% lithic fragments, and up to 4% mica. Arkose is trough cross-stratified, rarely tabular cross-stratified, and may contain thin interbeds of fine-grained subarkose.

Trough Cross-bedded Pebbly Sandstone

This lithofacies is polymictic and contains abundant orthoclase, quartz, and lithic fragments. The clasts vary in size from large to small pebbles. The matrix is a coarse- to medium-grained subarkosic to sublitharenitic sandstone. The composition of this lithofacies is 60% quartz, 10-25% feldspar (orthoclase), 5-12% lithic fragments, 2-4% muscovite, and 1-2% kaolinite.

Trough Cross-bedded Subarkose to Sublitharenite

These trough cross-stratified beds are composed of fine- to medium-grained cross-laminated sandstone, with subangular to angular quartz, 10-20% feldspar (albite and orthoclase), 7-15% lithic fragments, 1-3% mica, and 1-2% kaolinite. Cements in this lithofacies vary from calcite to iron oxides. Where the beds are grey there is abundant, fine, coalified plant material present along bedding planes.

Planar or Low-angle Foreset-bedded Sandstone

These beds are fine- to medium-grained, usually sublitharenite, which have either low-angle foreset or planar bedforms. The rocks are poorly sorted, subangular, and micaceous. Ripple drift laminations are common. The typical composition of these beds is 70-80% quartz, 10-20% K feldspar, 3-5% mica, 2-4% kaolinite, 6-13% lithic fragments, and up to 3% plant debris.

Rippled Siltstone and Fine-grained Sandstone

These beds are micro-micaceous and the strata are usually rippled. There are usually a few thin interbeds of fine-grained subarkosic sandstone. Beds are commonly modified by the presence of calcite cement and bioturbation.

Fine-grained Lithofacies

Massive Mudrocks

Mudrocks are massive bedded, bioturbated, red-brown to green-grey in colour, and have rare obscure laminations. Mudstone is locally calcite cemented. Plant fossils are common in both red and grey mudstone.

Limestone

A few thin, but laterally continuous lacustrine and marine limestone units are present. The lacustrine limestone is fossiliferous, containing fresh water ostracods, bivalves, calcareous algae, stromatolites, and low spired gastropods. The matrix varies in colour from black to grey and light buff. Most of the carbonates are micritic. Some lacustrine limestone is intraclastic, containing intraclastic lumps of ostracodal limestone.

Windsor Group carbonates are variably recrystallized to microsparite, especially those in the near surface; however, primary sparites are rare. Carbonates of the Windsor Group are variably siliciclastic and have a restricted range of lithology. Irregular laminated to mottled, fine to medium crystalline limestone and dolostone occur in an algal stromatolitic facies as columns, laterally linked hemispheroids, or most commonly as nodular oncolitic structures. The carbonates locally contain abundant marine invertebrate fauna including brachiopods, gastropods, bivalves and cephalopods. The carbonates are very intraclastic and include biolithite, wackestone, rare packstone and grainstone. Carbonates occur in complex interbedded sequences and transitions with mudrocks and anhydrite.

In the structurally disturbed exposures, Windsor Group carbonates are commonly recrystallized and variably diagenetically altered. This alteration is in part attributable to the near surface dissolution of evaporites and weathering at unconformities.

Coal

Sapropelic coal and humic coal are present in the study area. Most of the coal seams are thin (<1 m); however, a few attain thicknesses of 2 m in the coalfields of the Cumberland Basin. For simplicity, all of the various forms of coal through coaly shale are grouped together for the purpose of this part of the study.

Anhydrite/Gypsum

In the Windsor Group, and perhaps to a lesser extent in the Mabou Group, thick beds of anhydrite (gypsum where hydrated near surface) occur in the Cumberland Basin. For the purpose of this part of the study, all of the various forms of these rocks are grouped together. Anhydrite occurs as massive to massive mosaic, nodular mosaic, nodular and locally stylolitic nodular, both in a carbonate or mudrock matrix. Laminated anhydrite beds are rare. Anhydrite may have locally abundant inclusions of halite, and minor porphyroblasts of borates (see Carter, 1987, 1989; Rose and Carter, 1988). Anhydrite may occur interstratified with salt and mudstone at the millimetre to metre scale. Colour varies from grey to blue-grey, brown, and locally reddish. Variably calcareous mudrocks, limestone and dolostone occur as inclusions or interbeds up to 10 cm thick within the anhydrite units.

Gypsum invariably occurs as a near surface hydration replacement of anhydrite, as well as secondary satin spar vein- or fracture-fill in structurally disturbed sections. The gypsum occurs both as discrete selenite porphyroblasts and in a fine- to medium-grained massive replacement form.

Salt/Potash

Salt and potash occur within Windsor Group strata of the Cumberland Basin. Salt occurs in various forms and colours from coarse red or grey salt to fine-grained white salt. For the purpose of this part of the study all of these various forms are included within a single lithofacies. For a more detailed discussion of salt the reader is referred to Boehner, 1986.

Salt is dominated by halite of varying grain size, from a few millimetres to megacrystic halite with crystals of 10 cm, but typically grains size is 1-1.5 cm. The salt has varying proportions of insoluble impurities, including anhydrite, as inclusions, dispersed disseminations, and broken interbeds. Mudstone is locally abundant as grey to red-brown interbeds, fine interlaminations, and as dispersed interstitial inclusions. Mudstone interbeds have abundant, well preserved sedimentary structures, and porphyroblasts and inclusions of halite. Mudstones are transitional to both anhydrite and halite.

Potash salts occur as inclusions, stringers, and thin interbeds of carnallite and sylvite within variably halitic mudstone and salt. The potash and salt may be complexly intermixed to interstratified. Mudrocks associated with the salt and potash are typically clayey siltstone to arenaceous claystone. The mudrocks are massive, variably halitic, and probably bioturbated or haloturbated (i.e. mixed and disrupted by evaporite mineral growth/dissolution cycles). Well preserved sedimentary structures, such as laminations, cross-lamination and mudcracks, are locally present. Coloration varies from well separated grey-green and red to red-brown with highly variegated red, grey-green and yellow intercalations.

Lithofacies Relationships (Cyclicity)

Walker (1979) suggested that although lithofacies are the key to environmental interpretation, individual lithofacies are ambiguous and it is necessary to examine all of the lithofacies and their relationships to each other.

There are many inherent problems with the application of facies determination by the use of lithofacies transition analysis. Miall (1980) suggests that there are difficulties in distinguishing allocyclic from autocyclic sedimentation. Allocycles are cycles imposed on the sedimentation of a basin by external mechanisms such as tectonic uplift or subsidence, relative movement of land and sea levels, and paleoclimatic changes. Autocycles (Beerbower, 1964) are interpreted as resulting from mechanisms related to sedimentation, for example, meandering of a river over a floodplain. In the study area, both allocycles and autocycles occur. Ryan *et al.* (1987) suggest that at least three allocycles related to regional tectonism are recorded in the Carboniferous strata of the study area. Many of the smaller scale cycles are probably autocyclic in nature and result from intrabasinal fluvial processes. Differentiation of these cycles where they are of similar thickness is almost impossible.

Walker (1979) pointed out that where facies transitions are not gradational, problems occur, because Walther's Law cannot be applied to sequences with erosional contacts. Where sharp contacts are erosional, it is clear that juxtaposition of facies laterally is not necessarily the case. Although Walther's Law need not apply, the patterns of erosion may themselves be cyclic.

The present study will use the method recommended by Walker (1979) which is the most widely used in the literature. Many other statistical methods may be applied to ascertain the reliability of the facies transition trends; however, the application of additional statistical procedures does not correct for the variables inherent within the observed data. Therefore, these methods only create the illusion of more accuracy. In this study we used the following procedure: (1) the numbers of transitions were observed and converted into observed probabilities; (2) random sequence probabilities were calculated by the following equation,

$$rij = \frac{nj}{N - ni}$$

where rij is equal to the random probability of transition from any lithofacies i to another lithofacies j, ni and nj are the number of occurrences of lithofacies i and j, respectively, and N is equal to the total occurrences of all lithofacies; and (3) a difference matrix was constructed by subtracting the random probability matrix from the observed transition matrix. Positive numerical values greater than 0.05 are considered to represent preferred transitions (Fig. 4-8 to 4-15). Transition diagrams in this study are restricted to the fluvial strata, and only the seven most abundant lithofacies were used in the calculations. Facies transition diagrams were prepared for the Boss Point Formation, Joggins Formation, Springhill Mines Formation, Ragged Reef Formation, and Malagash Formation of the Cumberland Group, and the Balfron, Tatamagouche and Cape John formations of the Pictou Group.

The patterns of preferred lithofacies transitions are different for each of the formations; however, most exhibit fining upward cycles of one sort or another (Figs. 4-8 to 4-15). Coarsening upward cycles, or subcycles, occur in the coarser- grained lithofacies (A to E) and are present in most formations, reflecting the multistoried channel configuration of most sandstone bodies in the study area. Caution is necessary in drawing conclusions as to the frequency of multiple stories from the transition matrices. In many instances the same lithofacies overlies itself in the multistoried channel sequences, and these observations of transition have not been incorporated into the matrices. Harper (1984) suggests that self-transition is meaningless; however, sedimentological processes often repeat themselves and such repetition cannot be ignored. The problem of self-transition has, to date, not been adequately addressed and further study of this problem is warranted.

With the notable exception of the Cape John Formation, the rest of the units also have coarsening upward cycles in the finer-grained lithofacies (E, F, G). These finer-grained, coarsening upward cycles are probably the result of crevasse splay deposition.

Conclusions

Transition matrices for rocks of the study area show typical fining upward fluvial subcycles. Coarsening upward cycles of sandstone and conglomerate are attributed to the preponderance of multistoried configurations of the sand bodies. Coarsening upward cycles in the fine-grained strata are interpreted as splay deposits.

Lithofacies Associations

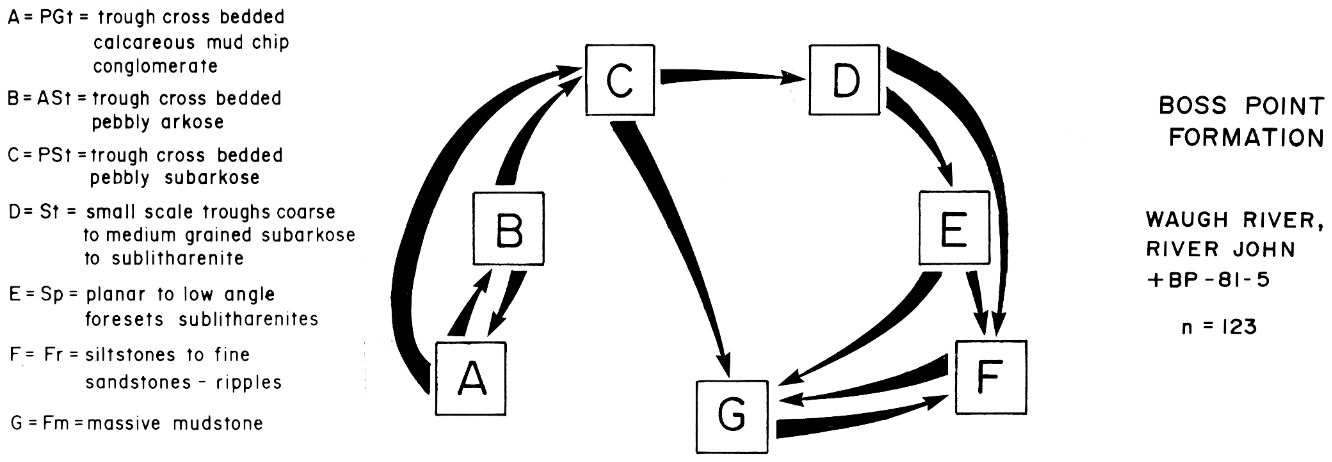
Locally, one or more lithofacies preferentially occur vertically or laterally adjacent to each other. The combination of these lithofacies is referred to as a lithofacies association. In addition to the lithofacies associations, and their relationships, it is also important to consider the thickness, relative proportions of the various lithofacies, and their bounding surfaces. Where exposure permits these lithofacies associations can be categorized as fluvial architectural elements according to the classification proposed by Miall (1985, 1988); however, areas of extensive outcrop are limited within the basin and therefore use of the purely descriptive term lithofacies associations is more appropriate.

There are nine lithofacies associations found in the rocks of the study area: (1) LA-1 conglomerate, (2) LA-2 coarse sandstone, (3) LA-3 fine-grained sandstone, (4) LA-4 fine-grained sandstone-mudstone, (5) LA-5 mudstone, (6) LA-6 limestone-mudstone, (7) LA-7 coal-mudstone, (8) LA-8 mudrock-anhydrite, and (9) LA-9 salt-anhydrite (Table 4-2).

To provide a database for lithofacies association thicknesses, the continental clastic formations of the study area were measured. The sections depicted herein are from the type areas or from a combination of outcrop sections and drill core, if a more complete section of the formation was possible (Figs. 4-16 to 4-25).

Facies Assemblages

Interpretation of environmental settings for the lithofacies associations is the first step in the assignment of interpretive facies assemblages. Thickness, internal features, vertical and lateral relationships, and proportions of lithofacies associations are taken into consideration when establishing facies assemblages. The facies assemblages found in the strata of the study area can be divided into four types: (1) fluvial plain (streams),



PROBABILITIES
OBSERVED MINUS RANDOM

	A	B	C	D	E	F	G
A	0	.22	.19	.04	-.05	-.12	-.22
B	.26	0	.29	-.05	-.09	-.07	-.26
C	.01	-.10	0	.11	-.08	-.17	.17
D	-.07	-.10	-.17	0	.11	.16	.07
E	-.09	-.09	-.06	-.13	0	.14	.25
F	-.15	-.11	-.17	-.03	-.04	0	.50
G	0	.05	-.06	-.09	-.02	.11	0

Figure 4-8. Transition matrices for the Boss Point Formation.

(2) alluvial fan, (3) shallow marine, and (4) lacustrine facies assemblages.

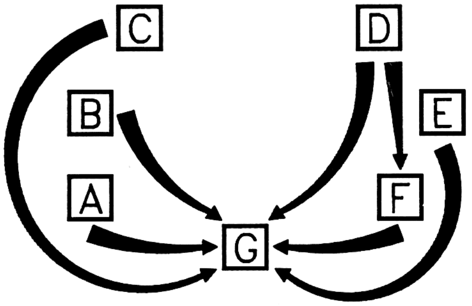
Stream Facies Assemblages

Channel Morphology

Before any consideration can be given to the type of stream system that may have deposited a particular facies assemblage it is necessary to determine prevailing channel morphology and paleoflow. Channel sandstone morphology is the result of the particular environment of deposition and even slight variations in the stream type are reflected in the sedimentary record.

Most of the bed-load sediment carried by a fluvial system is contained in the channel-fill deposits. Depositional style of the channel-fill strata can be expected to vary with the type of channel configuration that has deposited the sequence. Channel morphology is commonly divided into three different types: (1) braided, (2) meandering, and (3) anastomosing. Straight streams have also been documented (Moody-Stuard, 1966) and the characteristics of a fifth, transitional style referred to as a composite stream will be presented in the following section. The type of channel that deposits a particular sequence of rocks can be deduced from the coarse to fine ratios, the paleocurrent patterns, and the internal organization of grain sizes and sedimentary structures (Collinson, 1978; Galloway, 1979). The shape of sand bodies should also be considered in determination of the channel type. Collinson (1978) and Miall (1980) point out that no single vertical sequence can adequately demonstrate the variability existing in vertical profiles within a single system. This criticism refers to many facies models for fluvial systems because most models oversimplify the variability within a stratigraphic sequence. This problem stems from the use of lithofacies transitions in modelling, which emphasizes ideal sequences at the expense of variability. Miall (1980) states that a total basin analysis approach is necessary to

A = PGt = trough cross bedded calcareous mud chip conglomerate
B = ASt = trough cross bedded pebbly arkose
C = PSt = trough cross bedded pebbly
D = St = small scale coarse to medium grained subarkose to sublitharenites
E = Sp = planar to low angle foresets sublitharenites
F = Fr = siltstone to fine sandstones – ripples
G = Fm = massive mudstone



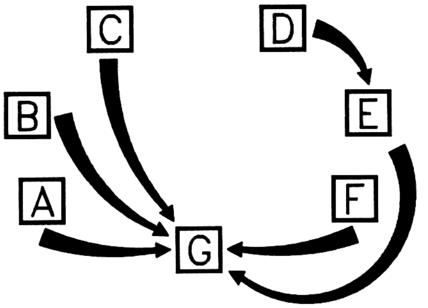
JOGGINS FORMATION
TYPE SECTION
n=166

PROBABILITIES
OBSERVED MINUS RANDOM

	A	B	C	D	E	F	G
A	0	−.01	−.01	−.01	−.01	−.01	+.99
B	−.01	0	−.01	−.01	−.01	−.01	+.99
C	−.08	−.08	0	−.08	−.11	−.09	+.85
D	−.06	−.06	−.07	0	−.08	+.13	+.68
E	−.25	−.25	−.27	−.26	0	−.18	+.41
F	−.11	−.11	−.12	−.12	−.15	0	+.89
G	−.49	−.50	−.39	−.43	−.19	−.39	0

Figure 4-9. Transition matrices for the Joggins Formation.

A = PGt = trough cross bedded calcareous mud chip conglomerate
B = ASt = trough cross bedded pebbly arkose
C = PSt = trough cross bedded pebbly
D = St = small scale coarse to medium grained subarkose to sublitharenites
E = Sp = planar to low angle foresets sublitharenites
F = Fr = siltstone to fine sandstones – ripples
G = Fm = massive mudstone



SPRINGHILL MINES
FORMATION

TYPE SECTION
n=173

PROBABILITIES
OBSERVED MINUS RANDOM

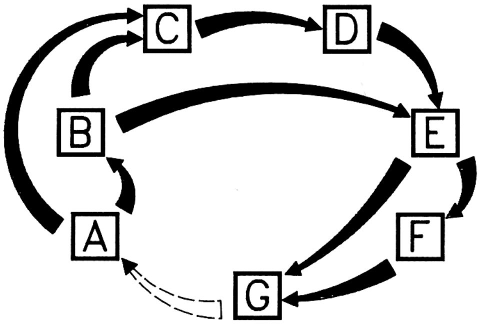
	A	B	C	D	E	F	G
A	0	−.01	−.01	−.01	−.01	−.01	+.98
B	−.02	0	−.02	−.02	−.02	−.02	+.97
C	−.16	−.16	0	−.19	−.13	−.20	+.64
D	−.15	−.15	−.17	0	+.62	−.15	−.06
E	−.20	−.20	−.24	−.21	0	−.18	+.58
F	−.03	−.03	−.03	−.03	−.04	0	+.97
G	−.43	−.38	−.15	−.51	−.03	−.37	0

Figure 4-10. Transition matrices for the Springhill Mines Formation.

deduce channel morphology. Although this is a sweeping statement it is true that most sedimentary factors within a study area should be used and such an approach was undertaken during this study.

The statement, " the present is the key to the past", is often thought of as a basic tenet of sedimentology, even though it can be misleading. Schumm (1968) suggested that the evolution of land vegetation in the

A = PGt = trough cross bedded calcareous mud chip conglomerate
B = ASt = trough cross bedded pebbly arkose
C = PSt = trough cross bedded pebbly
D = St = small scale coarse to medium grained subarkose to sublitharenites
E = Sp = planar to low angle foresets sublitharenites
F = Fr = siltstone to fine sandstones — ripples
G = Fm = massive mudstone



RAGGED REEF FORMATION

TYPE SECTION

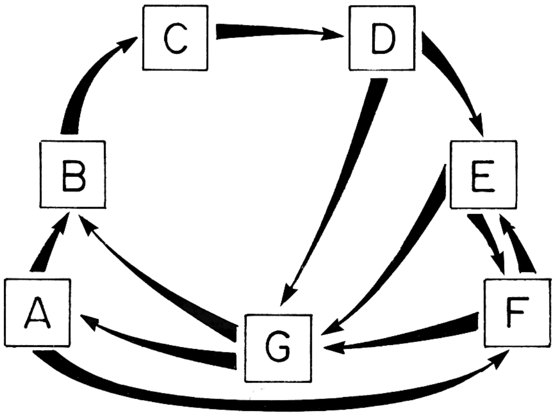
n=126

PROBABILITIES
OBSERVED MINUS RANDOM

	A	B	C	D	E	F	G
A	0	+.31	+.50	−.09	−.09	−.08	−.10
B	−.03	0	−.35	−.08	+.47	−.08	−.09
C	−.22	−.22	0	+.25	+.03	−.06	−.16
D	−.17	−.17	−.20	0	+.31	−.08	+.20
E	−.18	−.18	−.21	−.20	0	+.30	+.31
F	−.10	−.10	−.12	−.11	−.11	0	+.88
G	+.04	−.06	−.10	−.05	−.16	−.21	0

Figure 4-11. Transition matrices for the Ragged Reef Formation.

A = PGt = trough cross bedded calcareous mud chip conglomerate
B = ASt = trough cross bedded pebbly arkose
C = PSt = trough cross bedded pebbly subarkose
D = St = small scale troughs coarse to medium grained subarkose to sublitharenite
E = Sp = planar to low angle foresets sublitharenites
F = Fr = siltstones to fine sandstones - ripples
G = Fm = massive mudstone



MALAGASH FORMATION

RIVER JOHN AND WALLACE RIVER

n = 67

**PROBABILITIES
OBSERVED MINUS RANDOM**

	A	B	C	D	E	F	G
A	0	.36	−.01	−.02	−.14	.09	−.30
B	−.04	0	.31	.01	−.14	.02	−.17
C	0	−.14	0	.14	.03	−.03	−.04
D	−.02	−.13	−.18	0	.15	.04	.13
E	−.16	−.13	−.05	.02	0	.28	.09
F	−.17	−.14	−.02	−.12	.19	0	.20
G	.17	.09	.04	−.07	−.09	−.06	0

Figure 4-12. Transition matrices for the Malagash Formation.

Table 4-2. Lithofacies associations in the Cumherland Basin.

LITHOFACIES ASSOCIATION	LITHOFACIES	INTERPRETATION
LA-1 conglomerate	BGp, PGp, CGt, PSt	sheet\debris flow, steep gradients (GB)
LA-2 coarse sandstone	St, ASt, PGt, Pst, SP	channel dunes\bars (CH, SB, DA, TLA)
LA-3 fine-grained sandstone	Sp, St, Fr	flood stage breaches of the levees
LA-4 fine sandstone-mudstone	Sp, Fr	natural levees (LS)
LA-5 mudstone	Fm, Fr	floodplain (OF) deposition
LA-6 limestone-mudstone	Fm, Lf	shallow water marine/lacustrine deposits
LA-7 coal-mudstone	Coal, Fm	vegetated swamp
LA-8 mudrock-anhydrite	Fm, Anh	subaerial/subaqueous marine-salt pan-salina
LA-9 salt-anhydrite	NaCl, Anh, Fm	subaqueous evaporitic marine salt pan

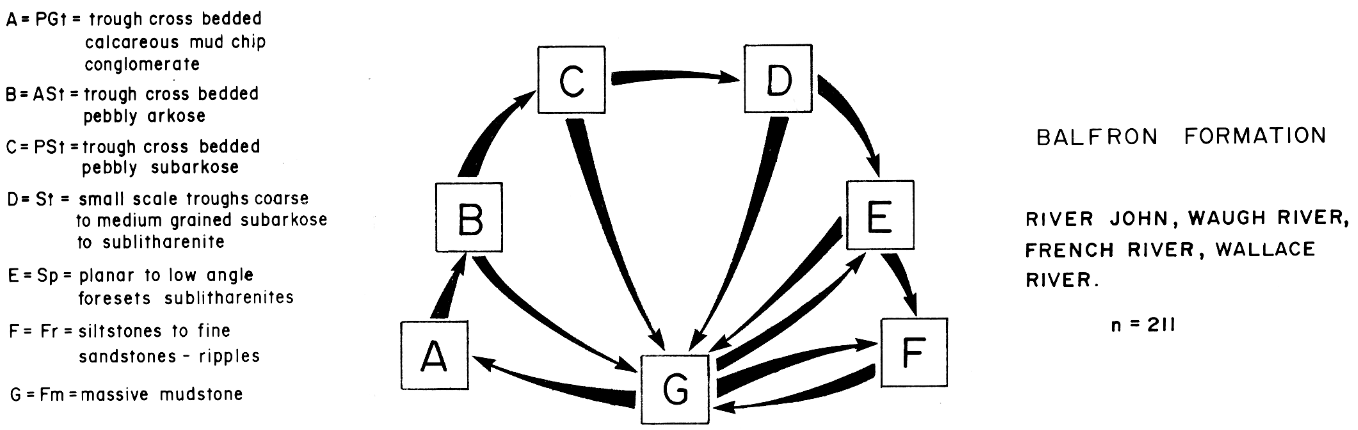
(GB, CH, SB, DA, TLA, LS, OF) refers to architectural elements symbol (Miall, 1988)

mid-Paleozoic was an important parameter in the control of fluvial styles. If so it would follow that modern streams are not necessarily good analogues for ancient sedimentary river systems. Cotter (1978) confirmed Schumm's (1968) hypothesis by comparing Paleozoic fluvial styles in Pennsylvania. He found that the "sheet braided" style dominates pre-Devonian strata whereas younger strata exhibit "channelized braided" to meandering configurations. During the Upper Carboniferous there was abundant terrestrial vegetation; however, drawing analogies between modern and ancient sedimentary environments in the absence of rooted mats of grasses (cf. Schumm, 1968) is likely to have contributed to differences in ancient stream morphology with respect to modern streams. Friend (1978) suggested that the lack of sediment-binding vegetation during accumulation of the Old Red Sandstone may have increased the cohesion of the banks and impeded incision of the channels. He also suggests, quite logically, that this lack of vegetation must have increased the rate of run-off, instantaneous transport, and deposition. Highly seasonal rainfall, such as in monsoon-savannah climates in modern environments, similarly causes very limited stabilization of grassland vegetation. During droughts the vegetation on savannah floodplains is mostly limited to areas adjacent to stream beds, whereas during flood stage the flood waters cover vast areas. Pedogenic processes are, therefore, important in the stabilization of such floodplains.

Scale (size) is also an important parameter for interpretation of fluvial style and, unfortunately, one that is often omitted from facies models. Miall (1980) points out that little attention has been given to the size of channels except where point bars have been clearly recognized. Cotter (1978) suggests that large rivers in molasse basins are important depositional sites; however, as Miall (1980) points out, it is difficult to recognize these deposits in the sedimentary record because of the paucity of studies in large modern river systems. Another important consideration is that rivers may be braided on a local scale while showing large scale meandering on a regional scale. The only way to determine if this is the case is to undertake regional sediment dispersal studies.

Two other parameters relating to the evaluation of fluvial styles within a basin are paleoclimatic changes and tectonics. These factors can affect channel shape and pattern and deserve to be considered.

Table 4-3 is a summary of channel morphological



PROBABILITIES
OBSERVED MINUS RANDOM

	A	B	C	D	E	F	G
A	0	.40	.09	-.04	-.08	-.11	-.22
B	-.15	0	.24	-.10	-.13	-.05	.20
C	-.09	-.08	0	.21	-.08	-.10	.13
D	-.04	-.16	-.09	0	.18	-.01	.11
E	-.03	-.15	-.12	-.05	0	.14	.22
F	.05	-.05	-.09	-.05	-.04	0	.17
G	.06	-.07	-.07	.01	.06	.09	0

Figure 4-13. Transition matrices for the Balfron Formation.

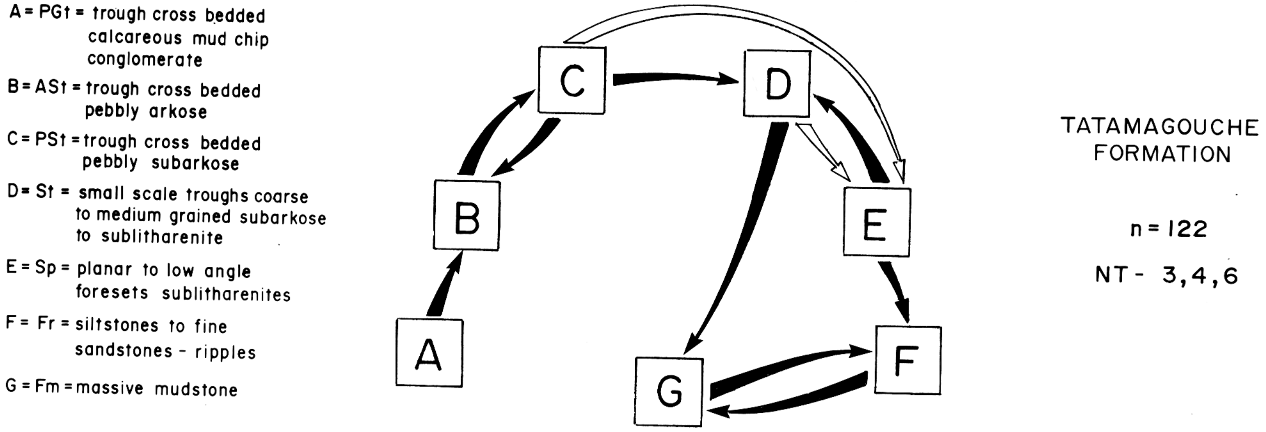
interpretations compiled from existing literature on the characteristics of streams with various channel forms. Mud-rich straight streams have been omitted from this chart because of poor documentation of their sedimentological characteristics. Braided and meandering channel patterns have been well documented from modern and ancient stream settings (Allen, 1965, 1970, 1983; McGowan and Garner, 1970; Jackson, 1976; Cant and Walker, 1976, 1978; Miall, 1977; Collinson, 1978; Gersib and McCabe, 1981; Cant, 1982; Galloway and Hobday, 1983) and further elaboration on these fluvial styles should not be necessary here.

The anastomosing system has been a recent addition as a distinct facies model separate from the meandering and braided systems; therefore, a brief description and possible revisions to the model will be presented. A possibly new channel pattern, the 'composite stream', will also be introduced here as it best conforms to the fluvial characteristics found in part of the Pictou Group strata in the study area.

Anastomosing Streams

Smith and Smith (1979) propose a depositional model for an anastomosing stream system. The terms anastomosing and braided have been used interchangeably in the past; however, Smith and Smith (1980) reviewed the criteria for both patterns, and proposed that braided streams be defined as having channel separation by unstable sand and gravel bars, whereas anastomosing streams have fine-grained stable (vegetated) material between the channels (cf. Schumm, 1968, 1971; Fig. 4-26). They further describe these streams as being an interconnected network of low gradient, relatively deep and narrow, straight to sinuous channels with stable banks.

According to Smith and Smith (1980) and Rust *et al.* (1984) anastomosing streams are characterized by the following sedimentological features: (1) they comprise multistoried channel deposits, (2) they have a coarse to fine ratio of 1:5 to 1:8, (3) they display stepped channel bases, (4) they have weakly unimodal paleocurrents, (5) they are usually homogeneous but rarely have a fining-



PROBABILITIES
OBSERVED MINUS RANDOM

	A	B	C	D	E	F	G
A	0	.39	.01	.01	-.05	-.07	-.27
B	0	0	.05	-.09	0	-.12	-.29
C	.01	.09	0	.11	.05	-.09	-.18
D	.01	-.11	-.09	0	.05	.01	.13
E	-.09	-.10	-.09	.31	0	.12	-.16
F	-.11	-.11	-.11	-.08	-.03	0	.43
G	.02	-.05	-.05	-.05	-.01	.17	0

Figure 4-14. Transition matrices for the Tatamagouche Formation.

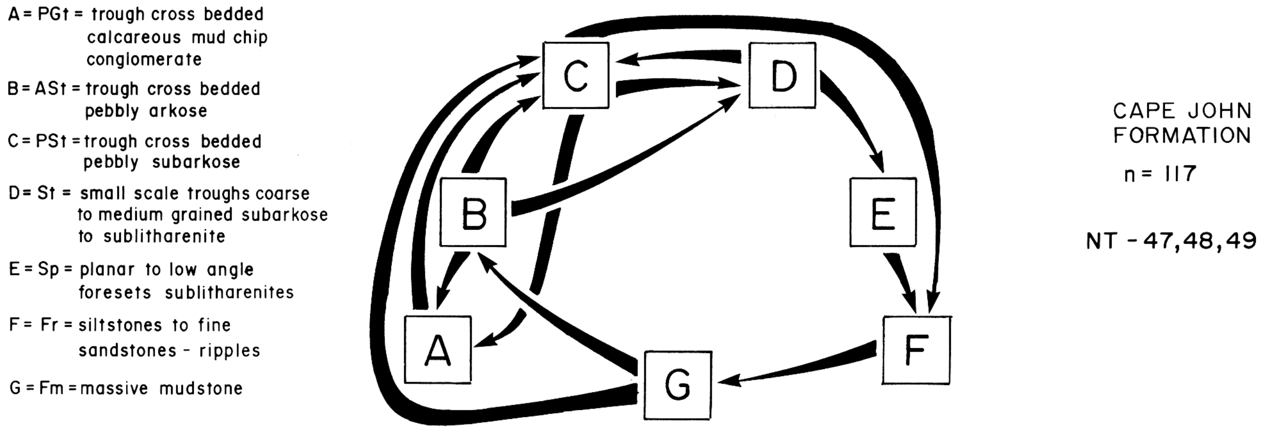
upward grain size distribution, (6) they have abundant splays deposits, (7) they show rare development of lateral accretion and horizontal bedding, (8) they have low width to depth channel ratios, and (9) they show no upward decrease in the scale of the sedimentary structures. Galloway and Hobday (1983) proposed an anastomosing stream model for mud-rich low sinuosity streams that is a variation on the model proposed by Smith and Smith (1980). This model differs somewhat from the model of Rust *et al.* (1984) because Smith and Smith's (1980) model provides that in mud-rich anastomosing streams there are fining upward cycles and the scale of the sedimentary structures deceases upward. Smith and Smith (1980) did not provide a specified scale nor do they indicate the degree of channel meandering possible, except that they are sinuous. Figure 4-27 has been modified, for the purpose of this study, from the original diagram of Smith and Smith (1980), in order to indicate a scale and to present a more reasonable representation of the vertical succession which better reflects the configuration of channel deposits with stepped bases.

Walker and Cant (1984) suggest that the main controlling factor for the formation of anastomosing channel patterns is a rapid rise in base level at the downstream end forcing high rates of aggradation, deposition of fines, which in turn results in the stabilization of channel patterns. Care must be taken not to confuse anastomosed stream patterns, which may occur in braided streams, with anastomosing rivers.

Composite Streams

Introduction

Characteristics of the fluvial strata in the Balfron and Tatamagouche Formations do not conform well to any of the stream facies models (Table 4-3). Sand bodies are up to 50 m thick, multilateral and multistoried, and can be traced along strike for 40 km. The sand to silt ratio is 1:<3 and the channel bases are slightly concave and stepped. Paleocurrent data from these formations are strongly unimodal. The sandstone bodies have well developed fining upward cycles and exhibit an upward



PROBABILITIES
OBSERVED MINUS RANDOM

	A	B	C	D	E	F	G
A	0	.03	.17	-.02	-.10	-.05	-.04
B	.23	0	.07	.06	-.10	-.14	-.13
C	.16	-.06	0	.06	-.01	.12	-.32
D	-.10	-.06	.07	0	.24	-.14	.03
E	-.10	-.06	-.10	-.11	0	.42	-.11
F	-.03	-.07	-.13	-.14	-.06	0	.43
G	-.05	.07	.07	-.09	-.10	.02	0

Figure 4-15. Transition matrices for the Cape John Formation.

decrease in the scale of the sedimentary structures. Abundant crevasse splays, marginal to the channels, are interbedded with overbank mudrocks. Rare abandoned channels are parallel to the major channels. The lateral consistency of this fluvial style within the study area is incompatible with an interpretation of a locally restricted facies transition from braided to meandering as suggested by Calder (1984b). The narrow dispersion of data around the paleocurrent mean for the Balfron and Tatamagouche formations suggests that the channel patterns were essentially straight. How extensive these straight patterns were is difficult to determine. A lack of point bar deposits and the fact that 75% of the sandstone and calcareous mud-chip conglomerate are trough cross-stratified suggest that most of the channel sediment accumulation took place as a result of progradation of sinuous crested dunes or side bars. Lateral bars were probably developed with bar surface sand waves resulting in formation of the rare tabular cross-stratification found within these strata. Levee deposits are rarely preserved except at the very top of multistoried sequences.

Channel Configuration: In order to calculate sinuosity indices for the strata of the study area, the authors devised a graphic method for extrapolation of indices by considering the paleocurrent data within one standard deviation of variance (approx. 35°; Fig. 4-28). Given that the variance is 35°, a maximum of 70° deviation is possible, thus the meander index must equal 1.22, independent of the scale of the meanders. Even if the remainder of the paleocurrent measurements are considered and weighted according to their percentage of occurrence, it is unlikely that the meander index would exceed 1.35; therefore, the streams are classified as low sinuosity.

Within any stream channel, flow conditions vary laterally, and consequently sinuous dunes, ripples, and flat beds coexist in cross-section or upstream within a single channel (cf. Allen, 1984). These sedimentary structures therefore, might, yield by progradation a fluvial fining-upward cycle similar to that of a meandering stream even though the stream may be essentially straight.

Table 4-3 represents the common characteristics of

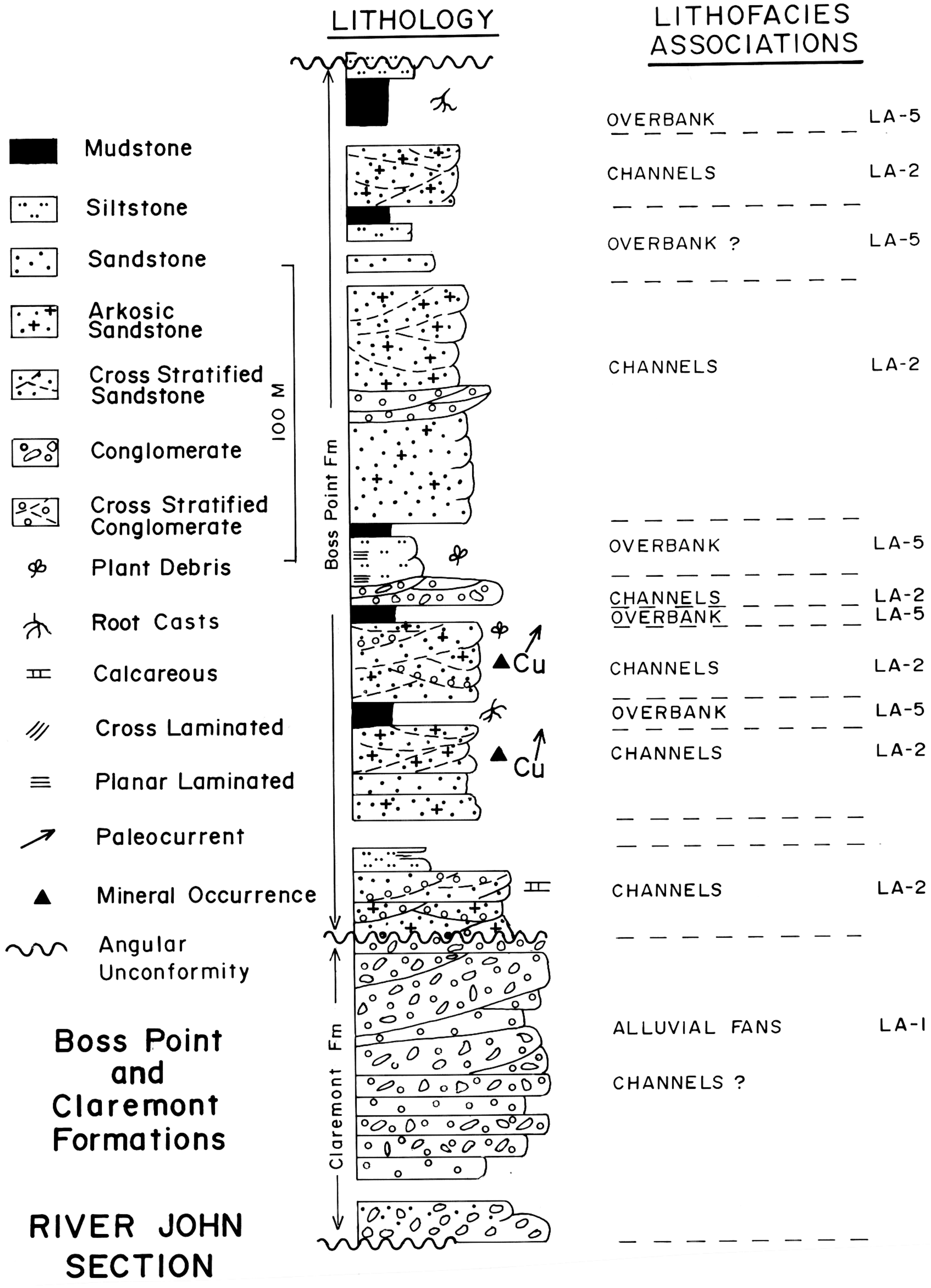


Figure 4-16. Lithofacies of the Boss Point and Claremont formations.

the three established stream facies models and compares them with the characteristics of the proposed 'composite' streams found in the study area. These streams differ from meandering streams by: (1) paleocurrent variance, (2) stepped and concave-upward channel bases, (3) absence of lateral accretion beds, (4) paucity of meander cut-offs or oxbows, and (5) the multistoried as well as multilateral nature of sand bodies.

BOSS POINT FORMATION
TYPE SECTION

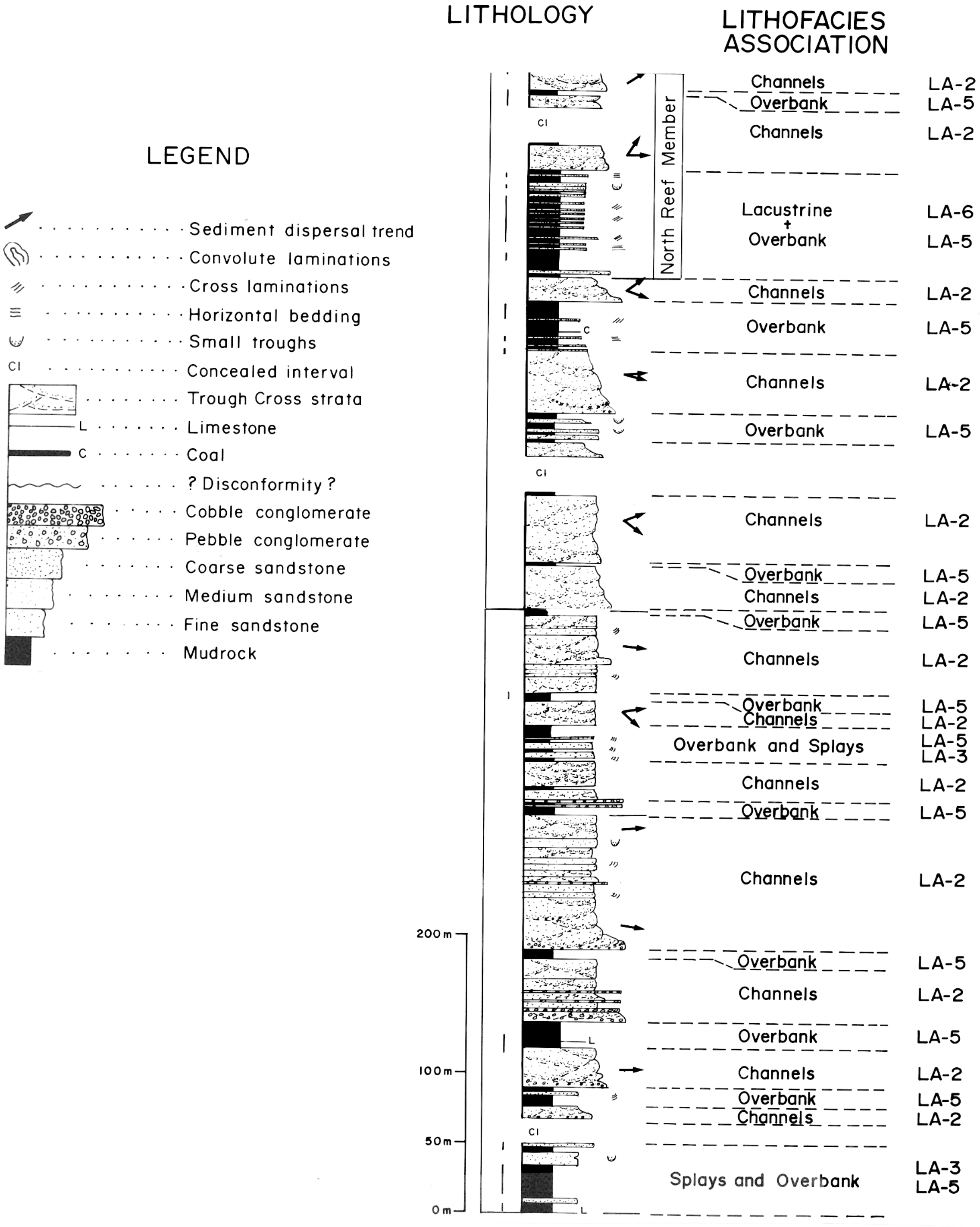


Figure 4-17. Lithofacies of the Boss Point Formation.

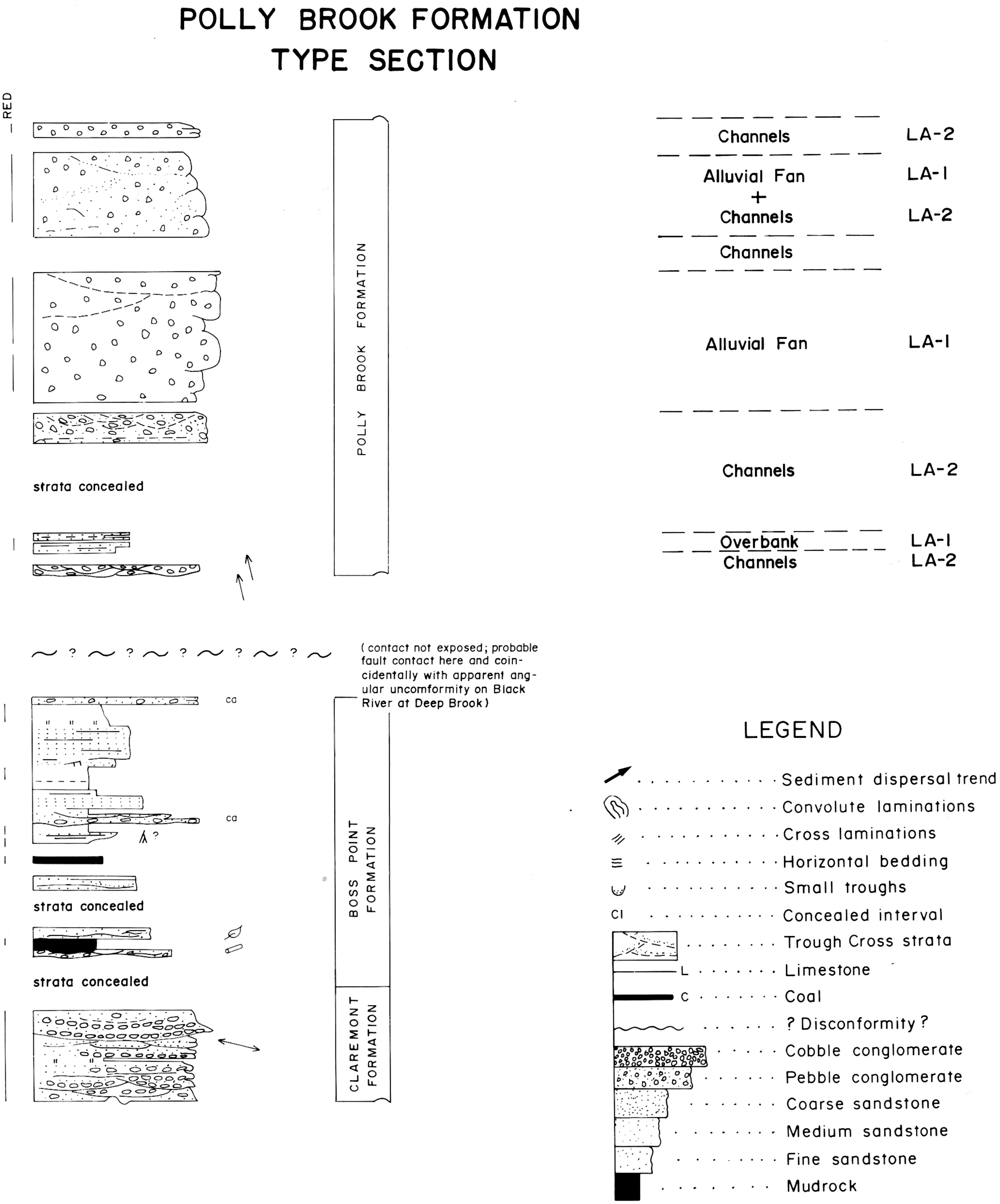


Figure 4-18. Lithofacies of the Polly Brook Formation.

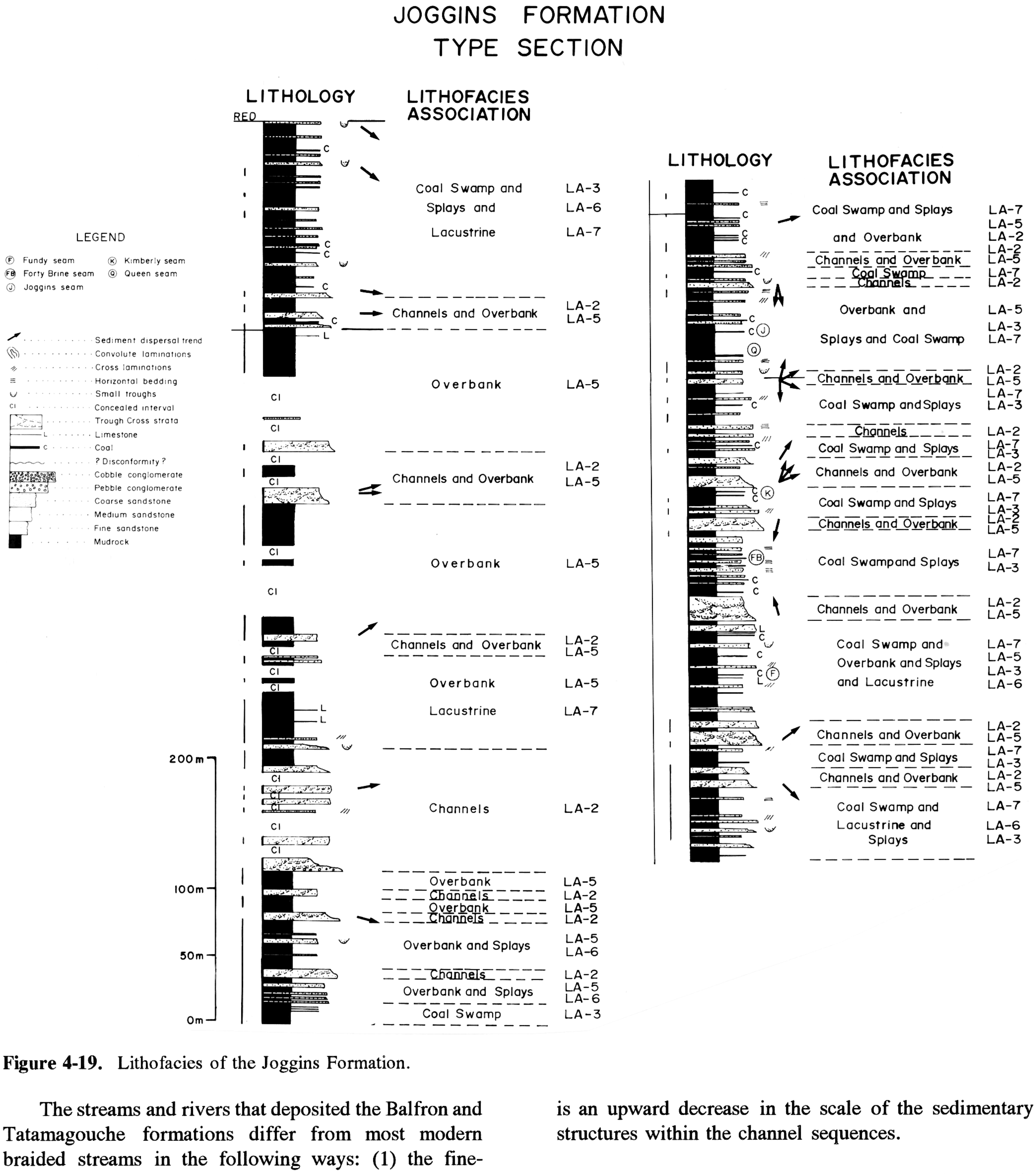


Figure 4-19. Lithofacies of the Joggins Formation.

The streams and rivers that deposited the Balfron and Tatamagouche formations differ from most modern braided streams in the following ways: (1) the fine-grained sediments exceed the coarse-grained sediments, (2) the channel bases are stepped, (3) there are well developed fining-upward cycles, (4) there are abundant crevasse splay sandstones interbedded with the overbank material, (5) the presence of levee deposits, and (6) there is an upward decrease in the scale of the sedimentary structures within the channel sequences.

Composite streams show the following features, in contrast to anastomosing streams: (1) the multilateral nature of the sand and conglomerate channel deposits, (2) strongly unimodal paleocurrent directions, (3) well developed fining-upward cycles, (4) high width to depth

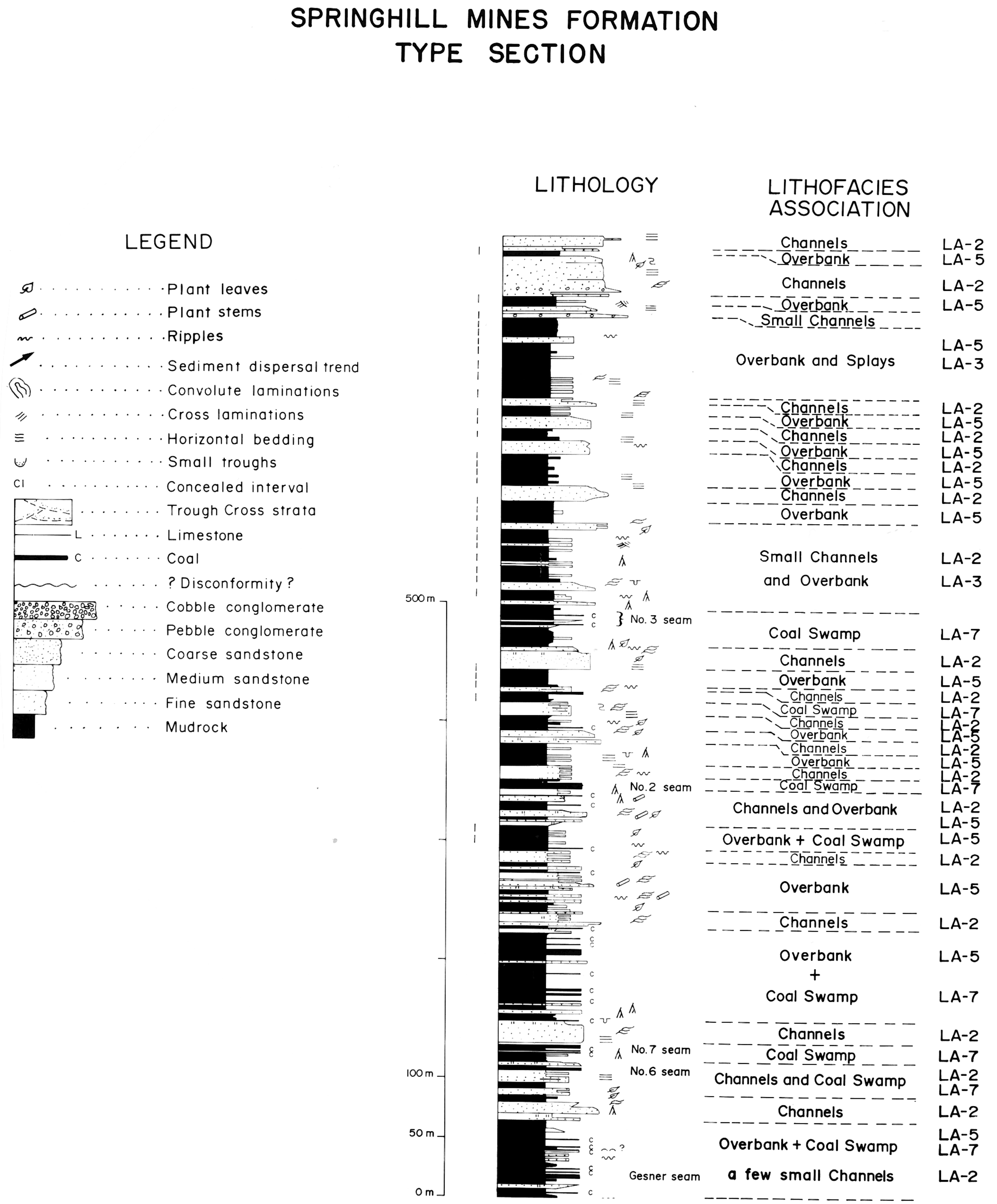


Figure 4-20. Lithofacies of the Springhill Mines Formation.

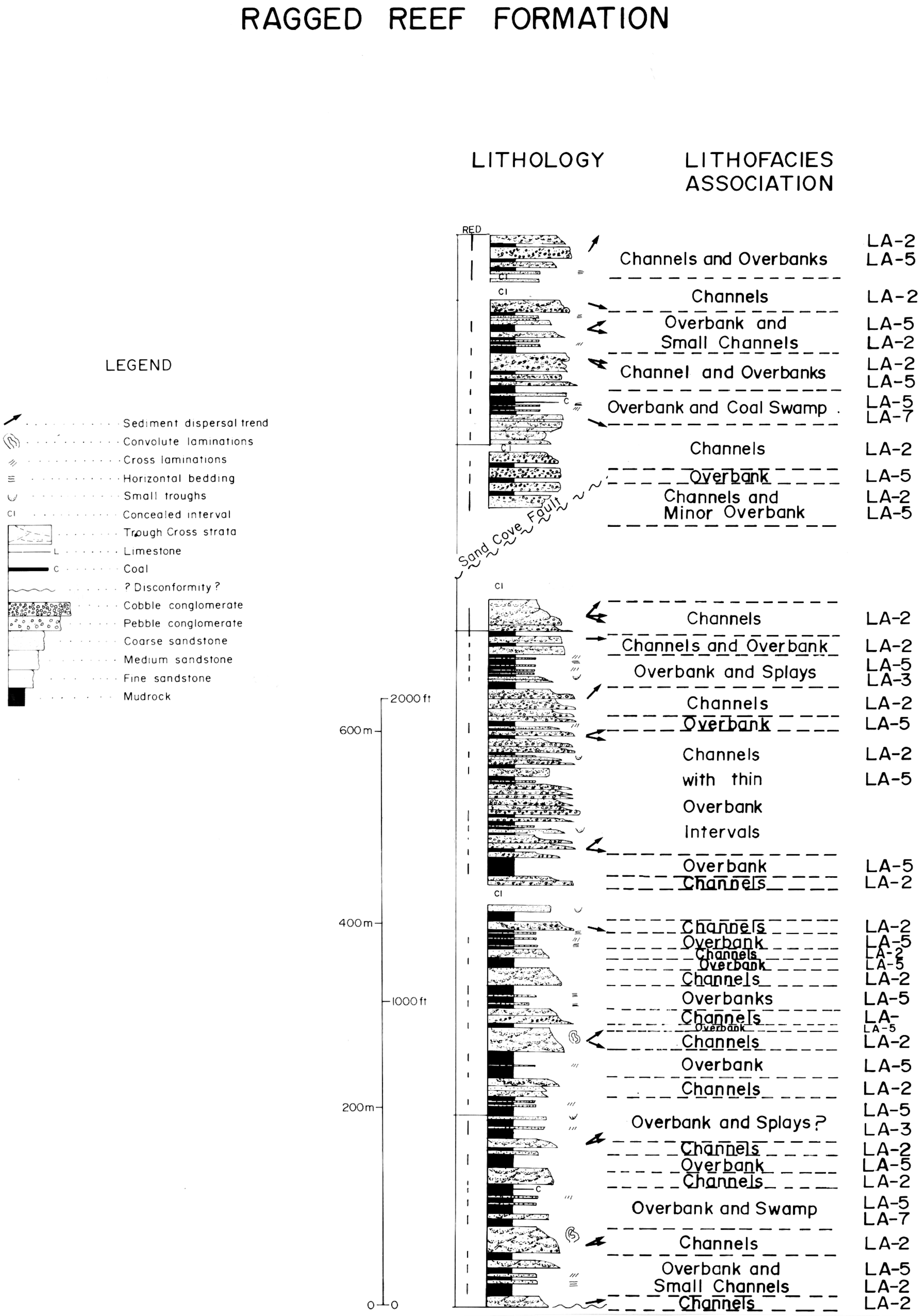


Figure 4-21. Lithofacies of the Ragged Reef Formation.

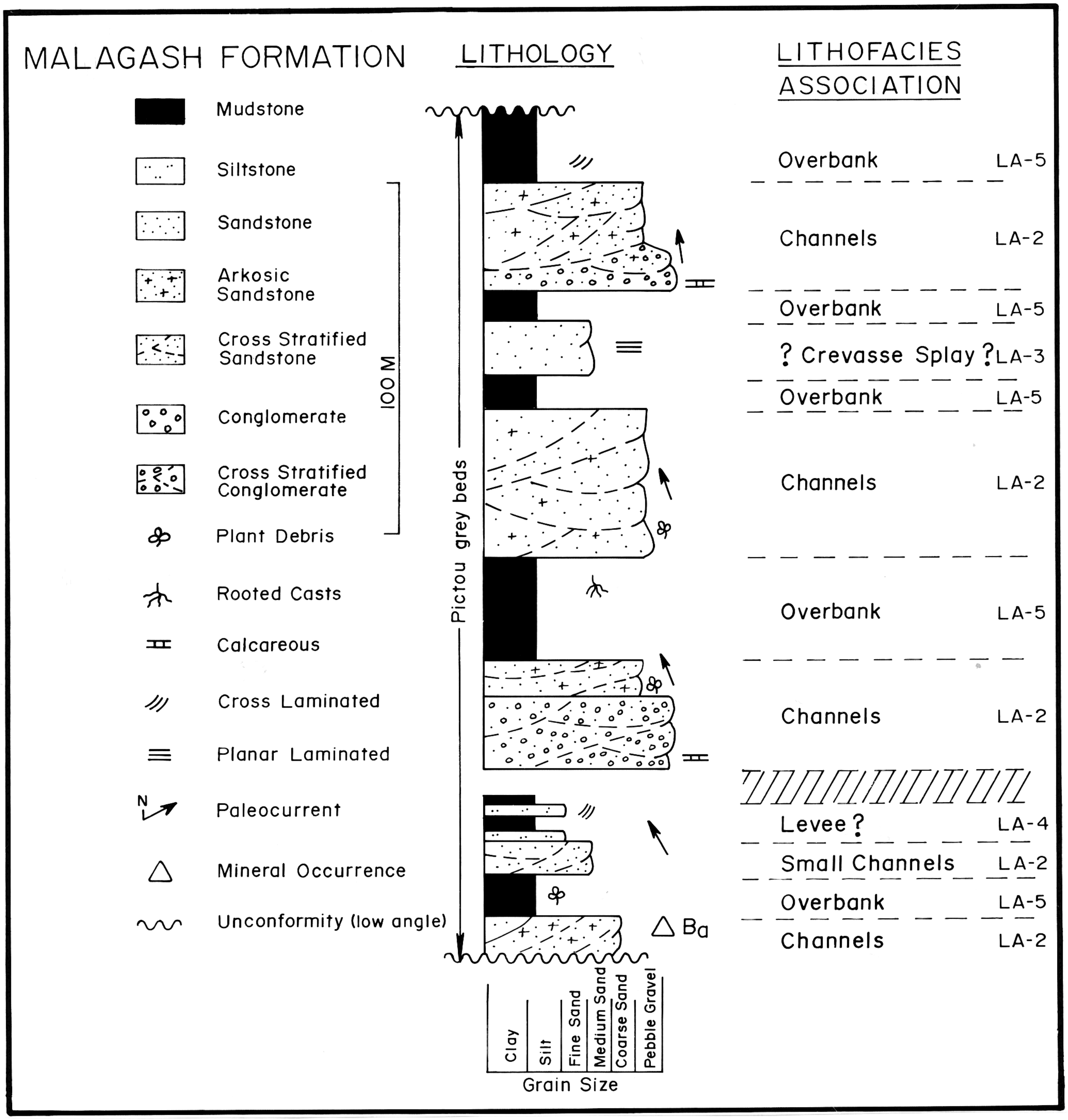


Figure 4-22. Lithofacies of the Malagash Formation.

ratio of sand bodies, and (5) an upward decrease in the scale of the sedimentary structures. The last two differences may not apply to mud-rich anastomosed streams as proposed by Galloway and Hobday (1983).

Model

Although the streams of the Balfron and the Tatamagouche formations can be classified as either meandering or anastomosing, there are differences that are significant and consistent throughout the study area. Many sedimentologists may feel that these differences are not significant enough to warrant the establishment of a separate fluvial facies model for these strata. However, in our attempt to better understand the sedimentation, we

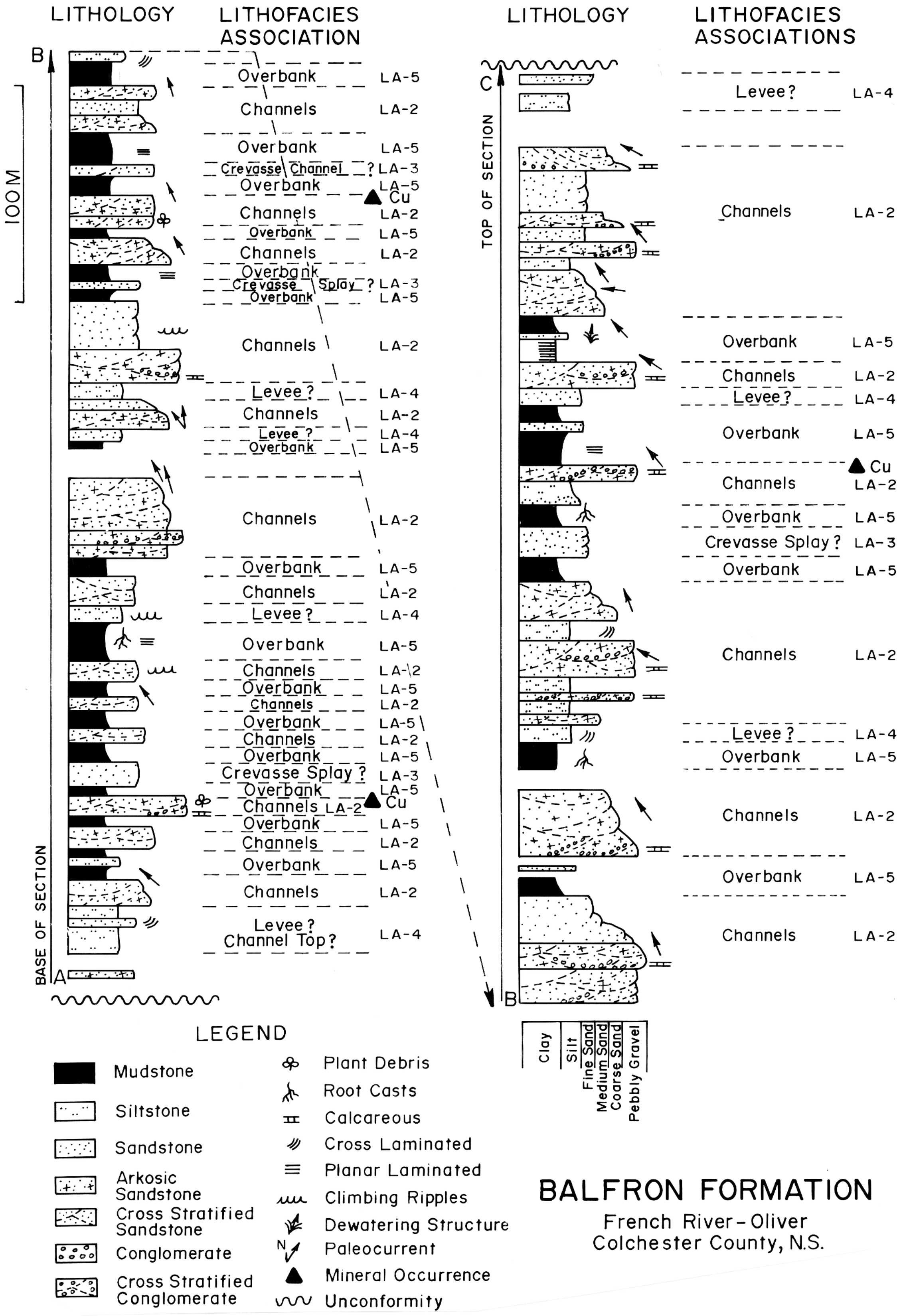


Figure 4-23. Lithofacies of the Balfron Formation.

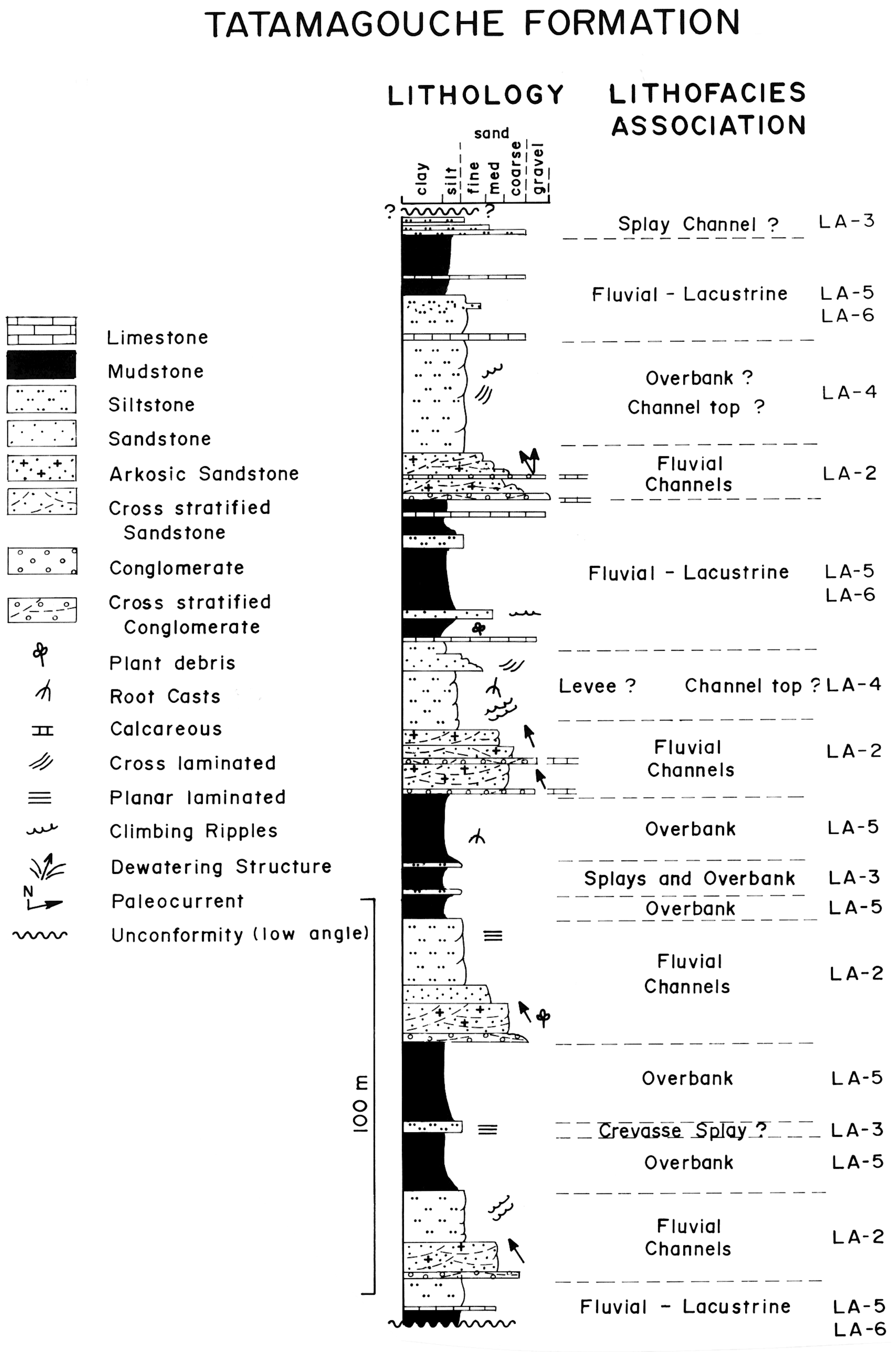


Figure 4-24. Lithofacies of the Tatamagouche Formation.

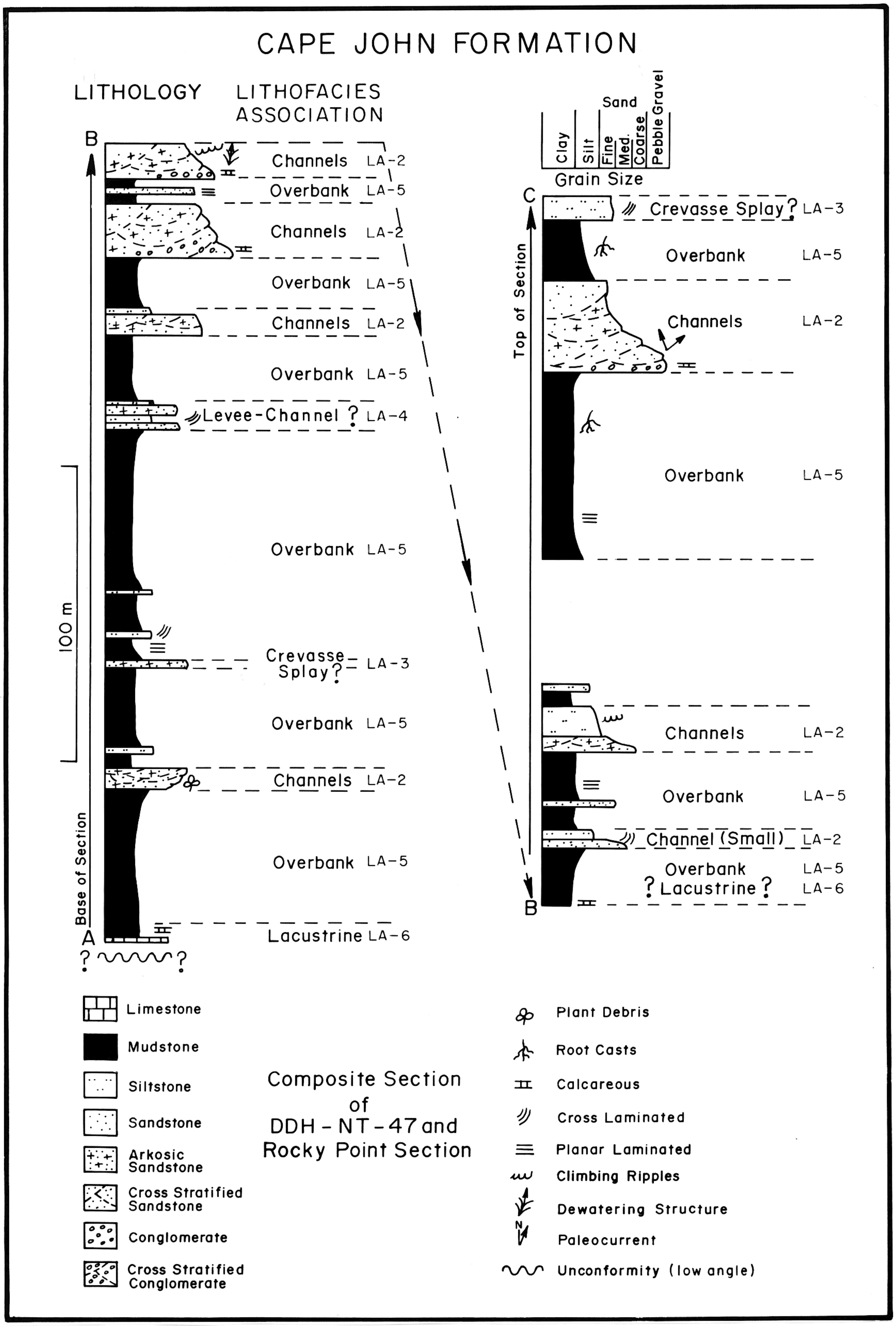


Figure 4-25. Lithofacies of the Cape John Formation.

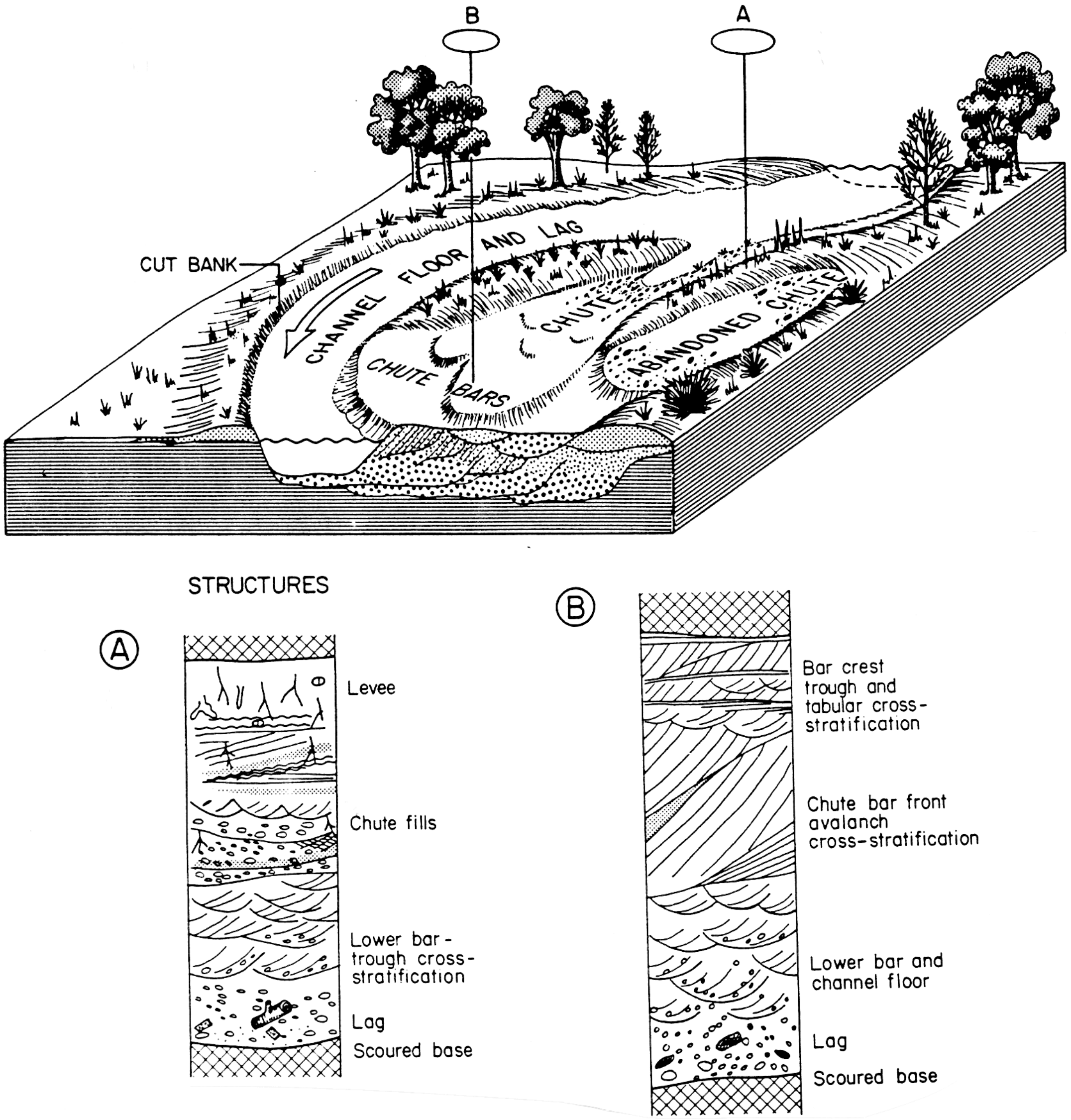


Figure 4-26. Model for anastomosing stream after Galloway and Hobday (1983).

felt that it was advantageous to examine the possibility of a new intermediate type of stream pattern. Cross-sections of diamond-drill holes were logged (Fig. 4-29), to aid in the development of a model for this stream channel pattern.

Section A-B (Fig. 4-30) represents a geological cross-section almost perpendicular to the dispersal trends. Sand bodies above limestone marker no. 1 (Fig. 4-30) are in the Cape John Formation and are interpreted as having been deposited in an anastomosing stream system, based on the multistoried sand bodies and other sedimentological features which are discussed in a succeeding section of this chapter. Channel sequences within the Balfron and Tatamagouche formations can be up to 50 m thick and can be correlated from drillhole to drillhole for distances of 20 km or more. The sand to silt ratio of this succession is estimated from the cross-section as being approximately 1:4. Sections C-D and E-F (Fig. 4-31) are approximately parallel to the sediment dispersal trends of the streams and perpendicular to section A-B (Fig. 4-30). The apparent south to north upward stratigraphic migration of the sheet-like sandstone bodies is to some extent exaggerated by the scale of the cross-sections. The cause and significance of this reversed depositional dip is not understood. Field observations, drillhole descriptions, and lithofacies transition matrices were combined to create a

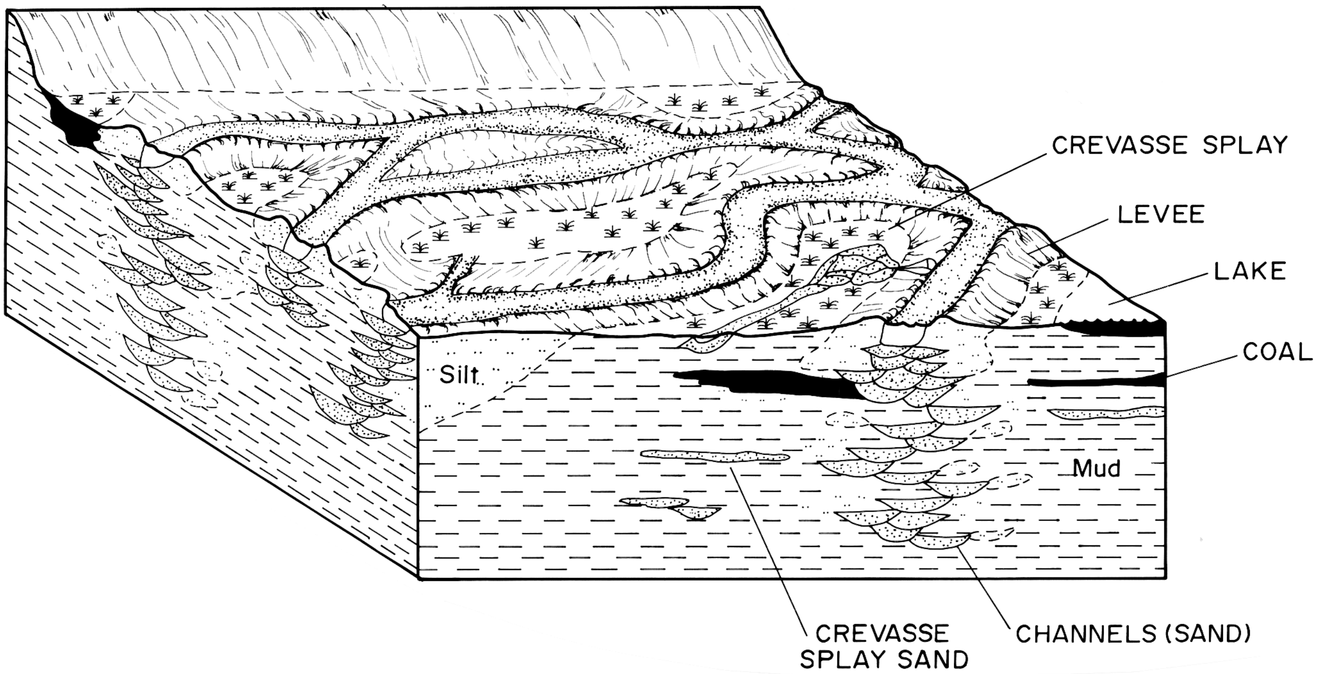


Figure 4-27. Revised anastomosing stream model after Smith and Smith (1980).

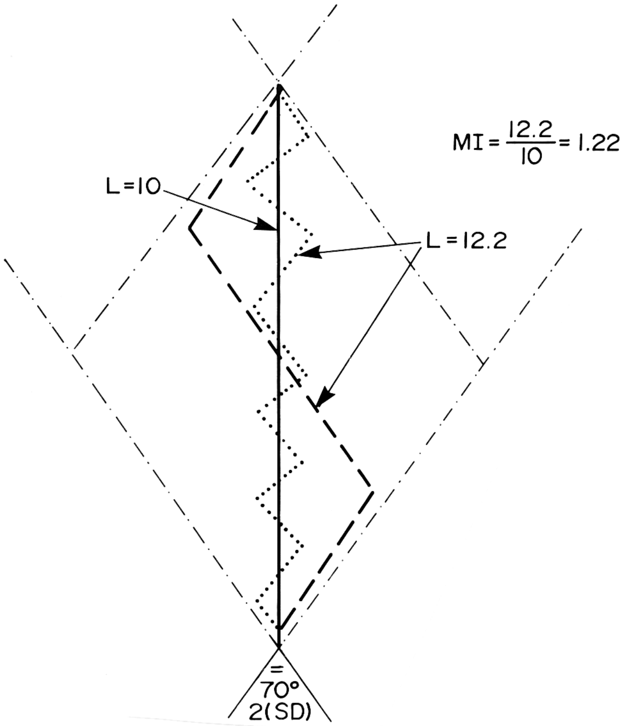


Figure 4-28. Graphic sinuosity index method (Ryan, 1986).

hypothetical fluvial cycle for the stream deposits of the strata (Fig. 4-32). This hypothetical profile is rarely completely preserved in the strata and thus caution should be exercised before drawing analogies on the basis of an idealized section. The idealized cycle fines upwards from a calcareous mud-chip conglomerate through medium to fine sandstone to laminated siltstone at the top and exhibits a concomitant decrease in the scale of sedimentary structures. The associated transition of sedimentary structures upwards is: (1) large scale troughs, (2) small scale troughs, (3) low-angle foresets, (4) ripple drift, and (5) planar laminated bedding.

Crevasse splays are common and represented by thin (less than 70 cm) tabular sandstone enveloped by the overbank mudstone and siltstone. Crevasse splay sandstone exhibits obscure coarsening-upward cycles, planar bedding, or more rarely, small scale trough cross-stratified beds.

Based on drillhole data and field observations, a three-dimensional model of the depositional environment may be constructed (Fig. 4-33). Although facies models are not usually drawn to scale, this one is.

The multilateral nature of the sand bodies is confusing, given the strongly unimodal paleocurrent data. Collinson (1978) suggests that sheet sandstone bodies similar to the ones here are usually attributed to low

Table 4-3. Summary of interpretations of channel morphology.

CHARACTERISTICS	BRAIDED	MEANDERING	ANASTOMOSING	COMPOSITE
Channel geometry	multistoried and multilateral	multilateral	multistoried	multilateral and multistoried
Sand vs. mud ratio	sand exceeds silt 2-10:1	silt exceeds sand 3-10:1	silt exceeds sand 5-8:1	silt exceeds sand 3-6:1
Channel bases	slightly concave to flat	flat	stepped	stepped to slighly concave
Paleocurrents	unimodal	polymodal	weakly unimodal	strongly unimodal
Grain size distribution	fining up & coarsening up	well developed fining up	locally fining up	well developed fining up
Crevasse splays	rare	common	abundant	abundant
Levees	rare & poorly developed	common and can laterally acerete over channel sands	common - sides of channels only	common to rare - sides of channels only
Lateral accretion beds	common on top of channel fill	abundant	rare	rare to absent
Horizontal strata	common	rare to common	rare	rare
Abandoned channels	rare (sand filled)	common - meander loops divergent from other channels	rare to common, approx. parallel to other channels	rare approx. parallel to other channels
Channel width vs. depth ratio	moderate	moderate to low	moderate to low	high to moderate
Upward decrease in scale of sedimentary structures	rare	abundant	rare	abundant

sinuosity streams because only low sinuosity channels migrate over the great distances required to form these sheets. He questions why such large scale migration does not occur in modern streams, implying that the interpretations may be incorrect. Collinson (1978) did not consider that the absence of sediment binding vegetation in the past may have resulted in a lack of modern analogues. Campbell (1976) suggested that lateral coalescence of lenticular sand bodies could form laterally continuous sheets of sand. Erosion surfaces are often visible within the sand bodies of the study area, suggesting that coalescence has occurred. Leeder (1978) suggested that low sinuosity streams display channel instability and this causes intermittent to continuous channel migration. Lateral continuity of sandstone sheets may be explained either as the result of coalescing of a multichannel system or perhaps as reflecting meander belts on such a large scale that it is rarely possible to recognize limits in the rock record where only local sections are available for study. But if large scale meandering occurred, why are there no lateral accretion beds or point bars present in the strata? It is possible that channel morphology in the study area reflects a combination of both mechanisms. Either way it would seem almost certain that coalescence of channels occurred in the study area. Abandonment of the stream channels may have been the result of inhomogeneous floodplain sequences. The presence of more erosion-resistant beds, such as limestone interbeds in the overbank mudrock sequence, may have forced channels to shift from one area to another. The presence of large logs and abundant plant detritus in some of the channels suggests that

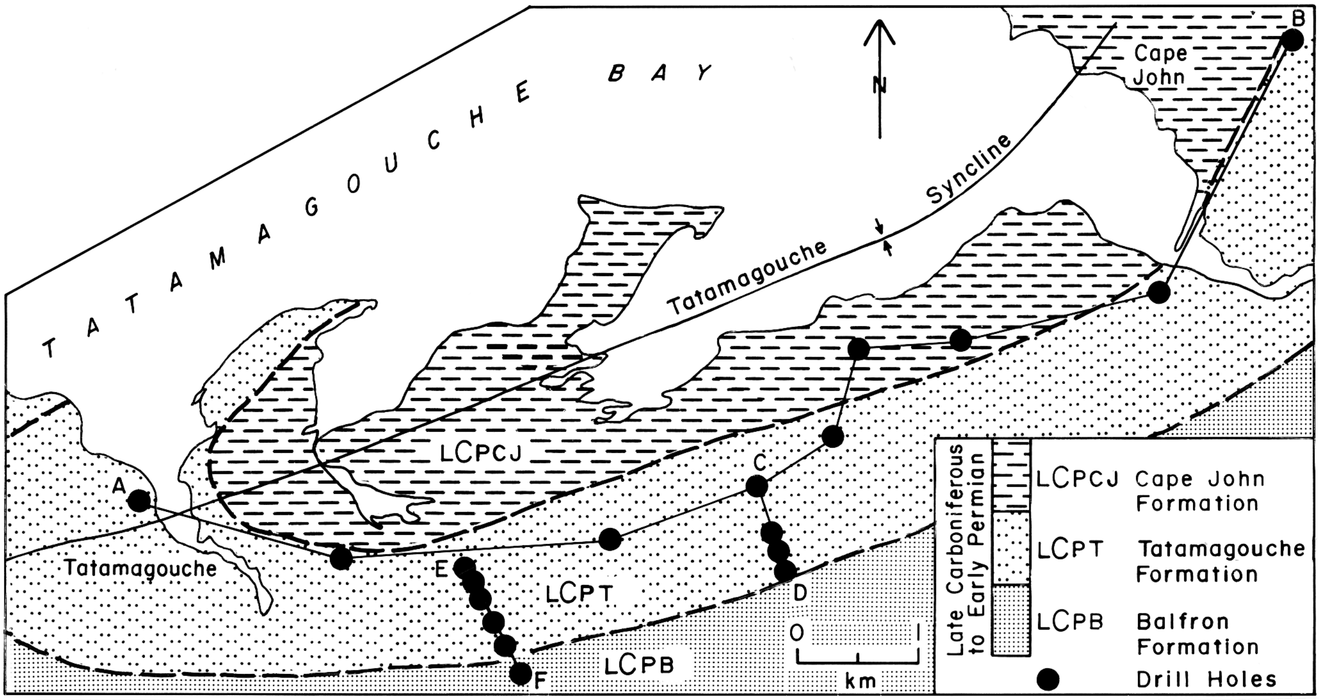


Figure 4-29. Drillhole and cross-section locations, Tatamagouche area, Nova Scotia.

blockage by organic debris (log jams) could have contributed to the abandonment mechanism (cf. Rust *et al.*, 1984).

The presence of laterally extensive, interbedded lacustrine limestone indicates that the enclosing floodplains of these streams must have had low gradients to facilitate the episodic establishment of relatively large inland lakes. Smith and Smith (1980) suggest that a variation in sea level (lake level) or damming of the streams may have been a significant controlling factor in the establishment of anastomosing patterns. A similar effect, perhaps triggered by a sudden basin subsidence which resulted in lake transgression, may have been operating in the Cumberland Basin to produce the composite stream pattern. Tectono-allocyclic events have been documented for megasequences occurring within the Maritimes Basin (Ryan *et al.*, 1987) and similar but smaller scale occurrences of episodic subsidence may account for lake transgression events.

Analogues

The best description of a sedimentary sequence similar to strata of the Tatamagouche Formation is the description by Campbell (1976) of the Westwater Canyon Member of the Morrison Formation (Jurassic) in northwestern New Mexico. Another similar sequence is the Moor Grit Member of the Scalby Formation (Jurassic) of Yorkshire, England (Nami and Leeder, 1978).

Campbell (1976) describes the Westwater Canyon Member as low sinuosity, multilateral, multistoried sheet sands up to 60 m thick. Strongly unimodal paleocurrents and the dominantly trough cross-stratified succession of lithofacies appear to be very similar to those of the study area. The sand to silt ratio is approximately 1:2 which differs slightly from the eastern Cumberland Basin; however, this difference may not be particularly significant when compared to the many similarities. Campbell (1976) suggests that the facies enclosing the Westwater Canyon Member were floodplain deposits below, and laterally equivalent to, downcurrent lake deposits. The presence of proximal lacustrine deposits in his example and in the Cumberland Basin area suggests that low gradient floodplains marginal to large inland lakes may be a preferred paleogeographic setting for composite stream sedimentation.

Nami and Leeder (1978) describe another similar sheet-sand sequence from the Scalby Formation in Yorkshire, England. At this locality a 12-20 m thick multilateral, multistoried sandstone sequence can be traced normal to the unimodal paleocurrent trend for a distance of 70 km. The lithofacies sequence within the sheet sand is almost identical to the examples from New

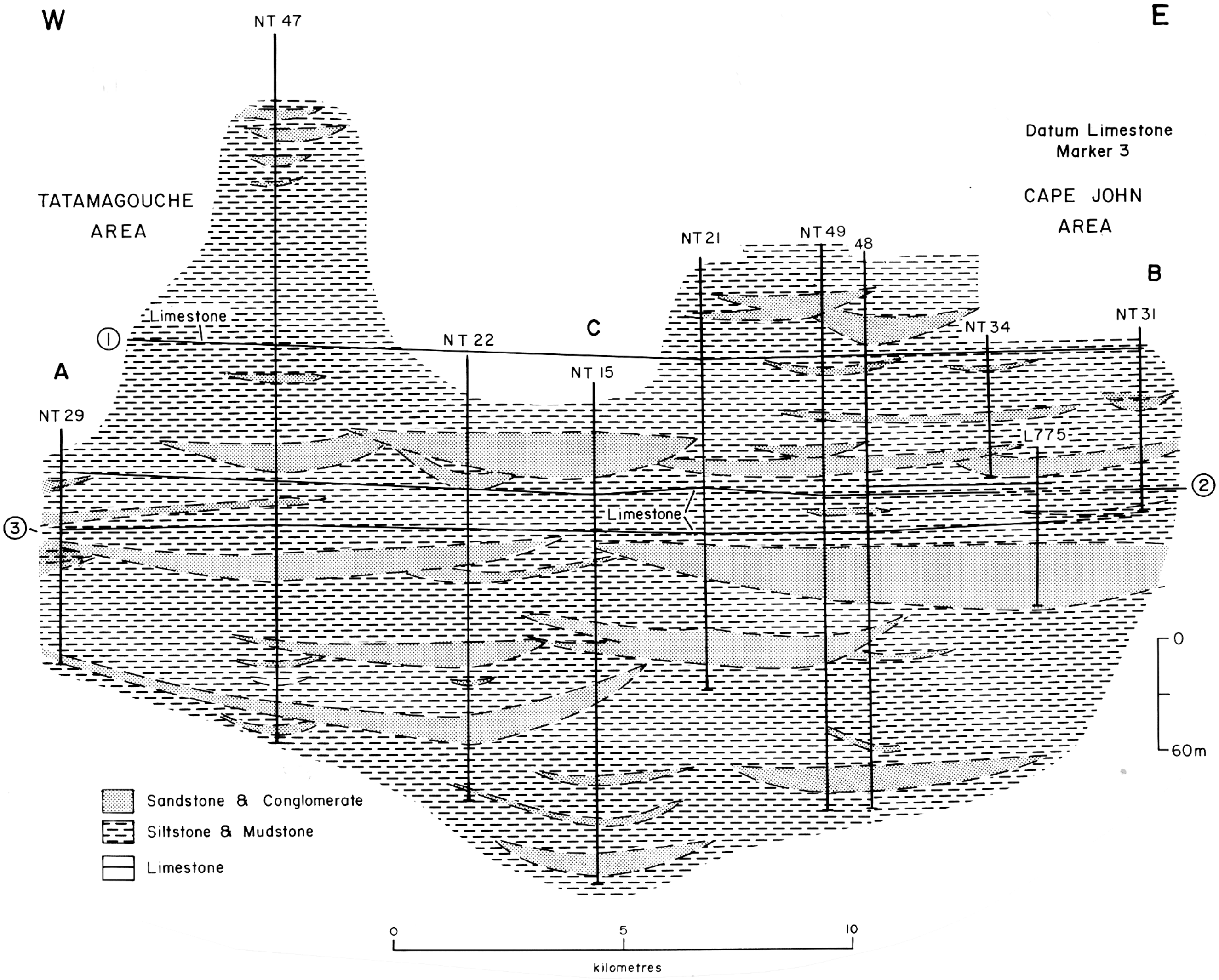


Figure 4-30. Cross-section A-B, perpendicular to sediment dispersal trends.

Mexico and the Cumberland Basin.

Alluvial Fan Facies Assemblage

Along the margins of the Cumberland Basin thick accumulations of polymictic conglomerate occur. The thickness of these strata decreases dramatically downflow (basinward), with a concomitant decrease of grain-size and bed thickness. The conglomerate also has a bedform transition from unstratified to crudely horizontal beds at the basin margin, to graded beds at 1 or 2 km from the margin, and finally to large scale trough cross-stratification basinward. The principle condition for alluvial fan development is a highland setting adjacent to a lowland. Heward (1978) summarizes the characteristics of alluvial fan sequences as having: (1) a decrease in grain size down-fan, (2) a decrease in bed thickness down-fan, (3) an increase in sorting down-fan, (4) changes in clast shape down-fan, (5) down-fan increase in channelization, (6) down-fan changes in transporting and depositional processes.

McGowan and Groat (1971) subdivide fans into three facies, proximal fan, mid-fan, and distal fan facies, which grade laterally into one another. The proximal fan facies is dominated by coarse boulder to pebble conglomerate which is massive to crudely bedded. The mid-fan facies is characterized by pebble to cobble conglomerate that has graded bedding and may be interbedded with trough cross-stratified pebbly sandstone. The distal fan facies is more varied, and is predominately composed of tabular to trough cross-stratified coarse-grained sandstone and pebble conglomerate (McGowan and Groat, 1971). McGowan (1979) suggested that the changes in sediment transport result from unconfined

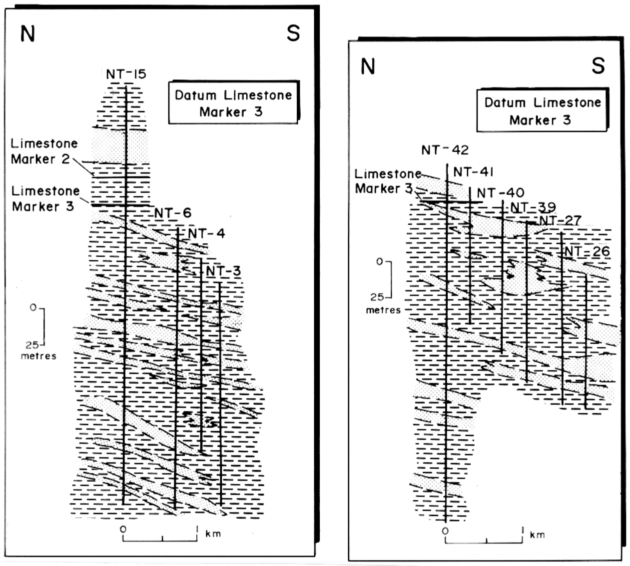


Figure 4-31. Cross-sections C-D, and E-F, parallel to dispersal trends.

sheet flow at the apex of the fan as opposed to wide braided patterns down-fan. Heward (1978) also points out debris flow deposits occur most often in the proximal to mid-fan positions. Nemec and Steel (1984) characterize these variable debris or mass flow deposits as being: (1) sheet-like beds with little basal erosion, (2) massive to graded beds, (3) without obvious stratification, (4) clast- to matrix-supported beds, and (5) beds often display a positive correlation between clast size and bed thickness.

The alluvial fan facies assemblage of the study area is composed of lithofacies associations LA-1 and LA-2 with LA-1 constituting the majority of the assemblage.

Lacustrine Facies Assemblage

The most important parameters of lake sedimentation are: (1) climate, (2) subsidence rates, and (3) basin tilting in response to faulting. For practical purposes, Reineck and Singh (1980) divided lakes into clastic and chemical lakes. Recognition of fine-grained clastic lake deposits occurring in overbank mudrocks is difficult. However, where limestone beds containing fresh water biota are encountered, recognition of lacustrine deposition is obvious. To determine the extent of clastic lake deposition above and below the limestone beds is less obvious, however. Close examination of the carbonate beds has shown that the major biological contributors to the lake beds were algae, ostracods and gastropods. Micritic lime mud, in which there are few recognizable skeletal remains, may be the result of chemical precipitation or disintegration of the remains of calcium carbonate supported algae.

Lacustrine facies assemblages found in the study area are similar to the inner mudflat to marginal limestone, shale, siltstone, and oil shale facies of the Green River Formation of Eocene age in Lake Gosiute area of the western United States (cf. Surdam and Stanley, 1979). Lithofacies associations that constitute this facies assemblage are LA-6 and LA-7, with LA-6 being more common.

Marine Evaporitic Facies Assemblage

Within the study area Windsor Group strata represent the only documented marine beds of the basin-fill sequence. The marine strata are typically composed of thick evaporite sequences with subordinate fine-grained clastics and carbonates. Thick salt beds that have undergone extensive remobilization into diapirs dominate the facies assemblage.

The interstratified halite and anhydrite represent shallow subaqueous deposition in a highly restricted environment characterized by excess evaporation and sustained connection to marine waters. Evolution to disconnected, isolated salt pans that were both mud-rich and salt-dominated with some degree of recycling of earlier evaporites is probable. The relatively thick, interstratified (deeper subaqueous) evaporites are typical of the regionally extensive Major Cycle 1 of the Windsor Group, and to a lesser extent the later cycles. Later cycles record repeated transgressive-regressive alternation between shallow normal marine environments, through subaqueous evaporitic marine to coastal sabkha environments and ultimately to isolated mud-rich and mud-poor saltpans and fluvial- (aeolian?) mudflats. The continental redbed mudflats are spatially related to local alluvial fan and distal (possibly terminal) braidplain deposits (i.e. Hopewell Group in southern New Brunswick).

Carbonates present are bioclastic sparite and micrite which have biota indicative of shallow marine, sublittoral, near wave-base environment of deposition. The mudstone, siltstone and fine sandstone interbedded with anhydrite, salt and carbonate rocks of the assemblage represent a complex of transgressive-regressive cycles. They represent the complicated interaction of ephemeral, episodically flooded fluvial processes in a stressed arid, to semi-arid hot (savannah-like to desert) climate with seasonal rainfall. Intermontane basins were invaded by marine transgressions juxtaposing marine to lagoonal stressed marine deposition with coastal to intermontane desert-salt

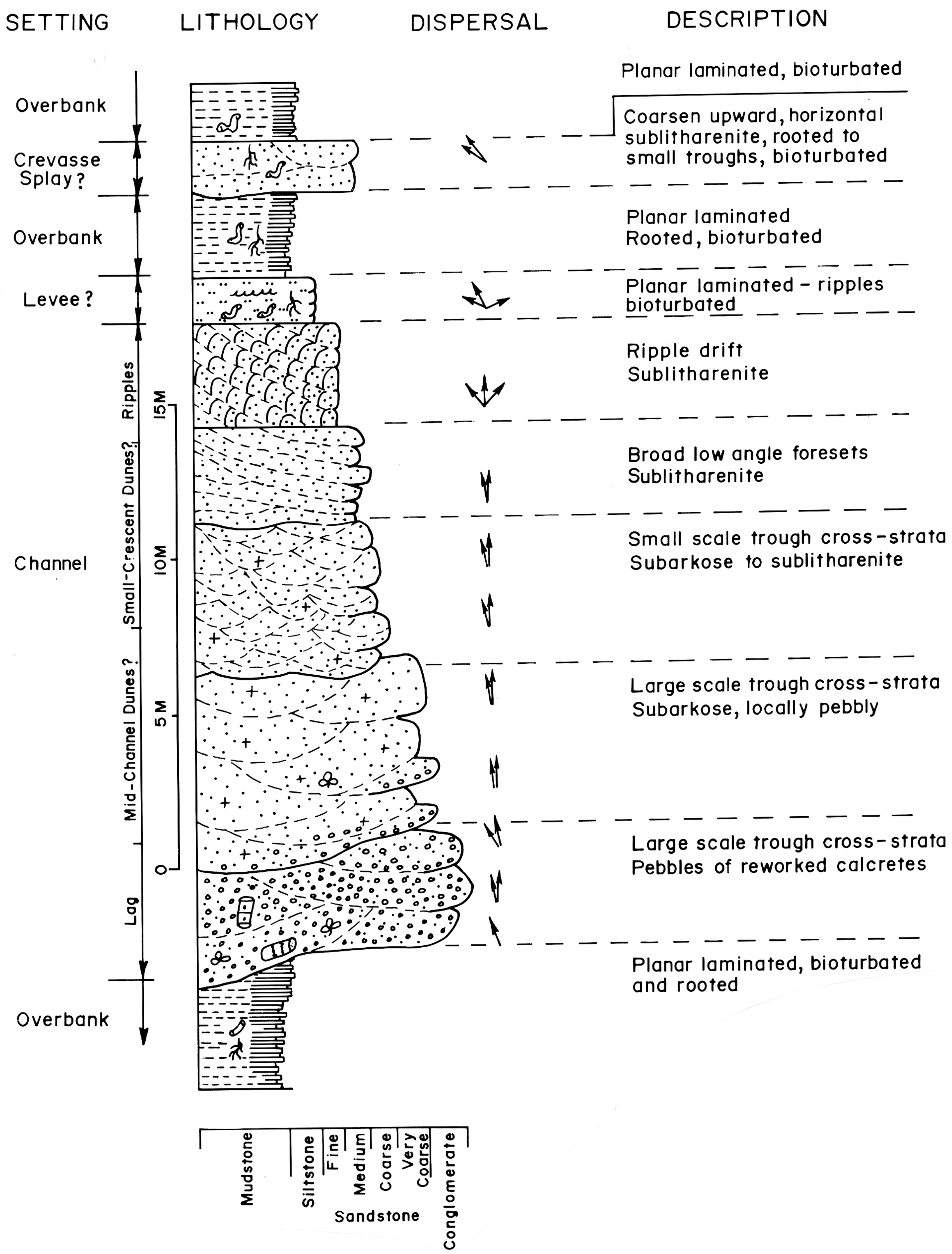


Figure 4-32. Composite(?) stream model, idealized section.

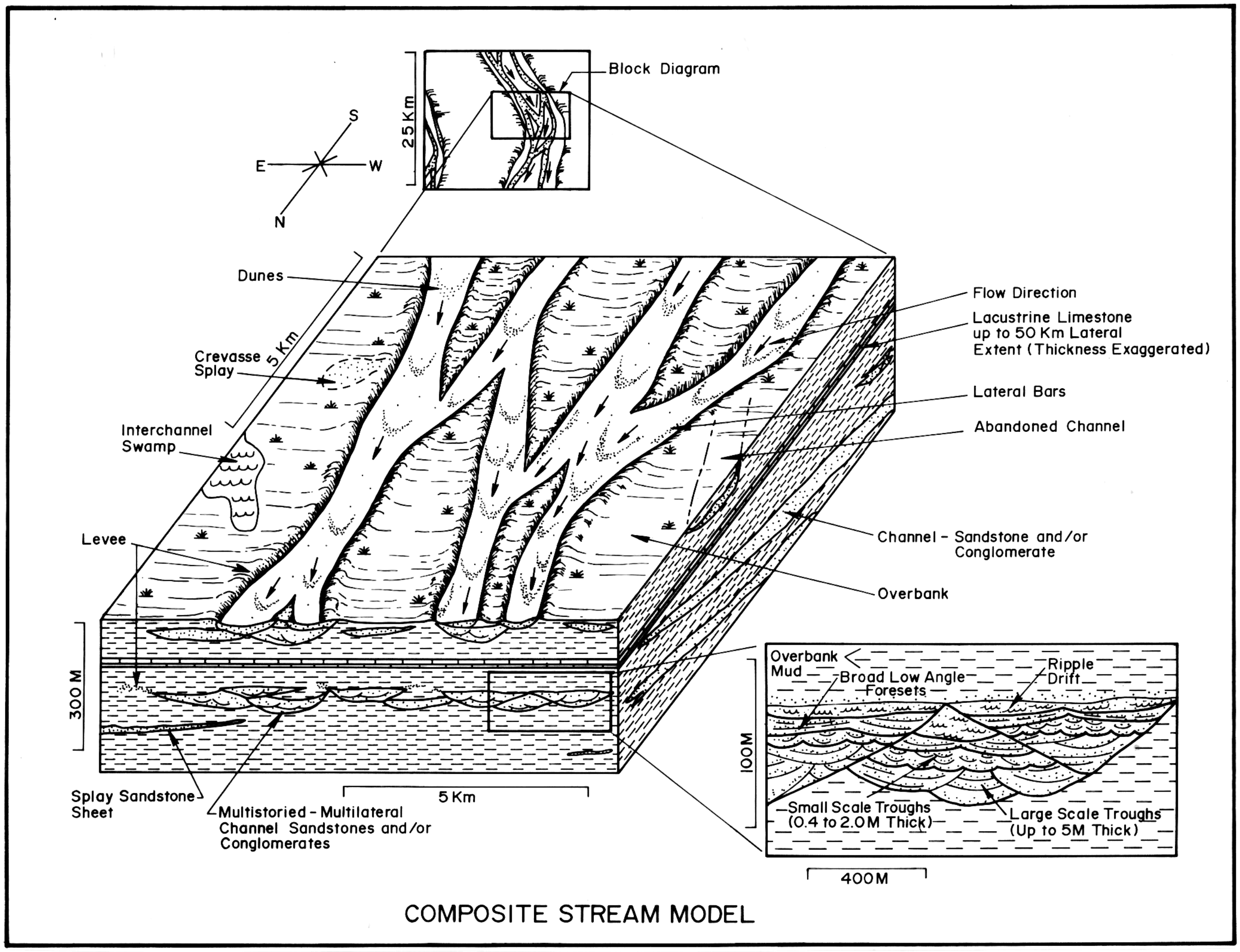


Figure 4-33. Composite stream model.

pan environments. Areas peripheral to marine shorelines, as well as the internally (closed) drained regions remnant during the regression, represent marginal marine to continental sabkhas with low relief mudflat, saline mudflat to playa-salt pan environments. The influence of fine-grained aeolian processes in this setting is suspected but unconfirmed.

Facies Assemblages of the Cumberland Basin

Windsor Group

The evaporites, carbonates and portions of the mudrock sections (grey and some redbeds) of the Windsor Group are grouped together for the purpose of this study into the marine facies assemblage. The exact depositional environment of the evaporite-dominated sequence is difficult to determine or identify close analogues. Evaporites represent a range from open marine to shallow subaqueous to subaerial continental origins. Carbonates of the Windsor Group, which are thin and interbedded with evaporites and clastics, were deposited in shallow water (subtidal to shoreline). The fauna and flora of the various carbonates studied within the Cumberland Basin all indicate deposition under stressed conditions (possibly hypersaline) at or near wave base.

Middleborough Formation

Strata of this formation are generally poorly exposed in the area which makes interpretation of depositional environments speculative. McCabe and Schenk (1982) suggest that most of the Middleborough (Maringouin) Formation was deposited on a floodplain during sheetfloods and within shallow ephemeral streams. The overall sequence of the formation is mostly composed of very fine-grained sandstone and mudrocks (Fig. 2-10) and generally represents extensive mudflat deposition. Fine-grained rocks commonly have pedogenic horizons as well as desiccation features. Rare lateral accretion beds can be found within the thicker sandstone units indicating that a few less seasonal streams also traversed the floodplain. In general the formation coarsens upward, perhaps as increased fluvial input in response to the transition from an arid paleoclimate at the base of the formation to a more humid paleoclimate at the top.

Shepody Formation

This formation is a sandstone-dominated sequence with subordinate fine-grained rocks. Sandstone bodies are usually single story at the base of the formation but rapidly develop upward into multistoried sequences. Unimodal paleocurrents predominate in the upper parts of the formation. Lateral accretion beds occur primarily in the lower parts of the formation although a few persist into the upper beds. This formation is interpreted to represent a transition from meandering streams at the base of the unit to a sandy braided system at the top (Fig. 4-34). The uppermost beds of the formation are interbedded with polymictic alluvial fan conglomerate of the Claremont Formation.

Claremont Formation

In the Cumberland Basin, alluvial fan deposition occurred during the Namurian. Alluvial fan deposition is recorded by the Claremont Formation which is characterized by poorly sorted boulder to pebble polymictic conglomerate. The presence of planar-bedded intervals indicates episodic deposition by sheet flow. Less commonly, conglomerate units are matrix supported and were probably formed by debris flows. The presence of alluvial fans is usually taken to indicate syndepositional tectonic activity, as they only develop in areas of relatively high relief (Davies, 1983). A similar link between tectonic movements and alluvial fan deposition in the Cumberland Basin has been proposed by various workers (Bell, 1944; Fralick and Schenk, 1981; Ryan *et al.*, 1987). The source for detritus that constitutes these conglomerates is the Cobequid Highlands Massif, although the Caledonia Highlands Massif to the northwest may also have contributed coarse detrital material. Both the thickness and the size of the clasts diminish to the north and the conglomerate units exposed at the axes of anticlines are commonly trough cross-stratified. Areas along the margin of the Cobequid Highlands Massif are interpreted as proximal fans whereas to the north, at the axis of the Claremont Anticline, the Claremont Formation was probably deposited in the mid-fan area (Fig. 4-35).

Boss Point Formation

The sandstone-dominated strata of this formation have strongly unimodal sediment dispersal trends. The sandstone and mud-chip conglomerate channel deposits are multistoried and multilateral, and have flat channel bases. On the basis of these criteria and the presence of horizontal stratification at the top of some of the channel sequences, the Boss Point Formation is interpreted as representing a braided stream facies assemblage. In addition, the interbedded relationship with alluvial fan polymictic conglomerate along the margin of the Cobequid Highlands Massif strongly suggests a braided stream environment.

Polly Brook Formation

This formation is made up of coarsening upward cycles of polymictic cobble to pebble conglomerate. There is a northward decrease in the total thickness of the unit as well as individual bed thickness and in clast size. Along the margin of the basin, adjacent to the Cobequid Highlands Massif, the conglomerate is very crudely horizontally stratified. Downflow, to the north, conglomerate exhibits trough and tabular cross-stratification and is interbedded with coarse-grained arkosic sandstone. The distribution, lithofacies assemblages, and lateral transitions of the Polly Brook Formation suggest deposition in proximal to distal alluvial fans which emanated from highland areas to the south.

Joggins Formation

Sandstone body configurations and sedimentary features suggest that the Joggins Formation sands were deposited in an anastomosing to meandering stream transition area. Rhythmites (alternating beds of 1 m thick sandstone, thicker mudrocks, and thin beds of coal and limestone) interbedded with channel sandstone suggest deltaic sedimentation may also have taken place (Walton and Duff, 1973). Walton and Duff (1973) suggested that sedimentation may have occurred on a large marine floodplain delta. Although the floodplain was broad there is no evidence of marine environments and the deltas must be related to large inland lakes. The abundance of lacustrine limestone interbedded with fine-grained rocks of the rhythmite sequences suggests deposition occurred marginal to a large (possibly several hundred km^2) inland lake system. Perhaps the depositional setting of the Joggins Formation strata was a flat floodplain or lacustrine delta plain, traversed by numerous small streams and positioned between the southern highlands with their adjacent alluvial fans and a large inland lake near the centre of the basin.

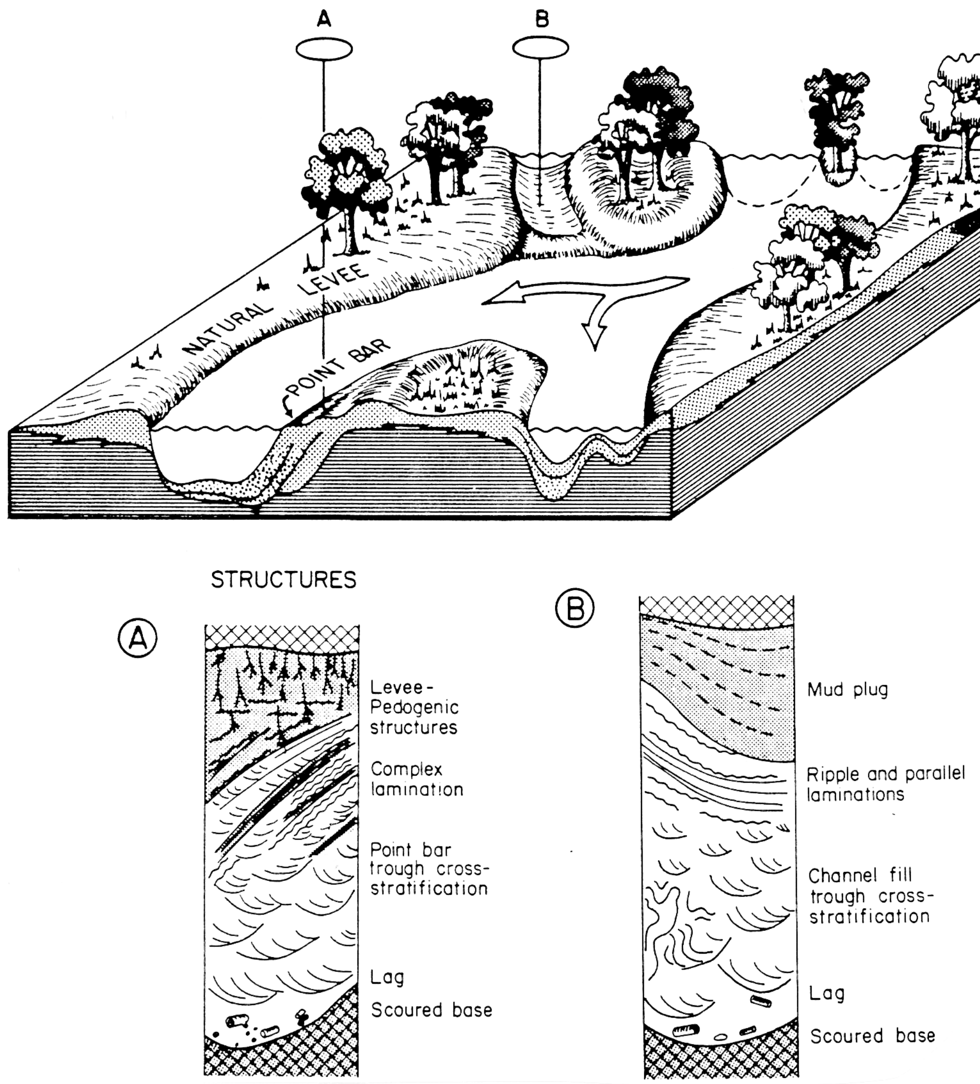


Figure 4-34. Braided stream model (Galloway and Hobday, 1983).

Springhill Mines Formation

Coal-bearing strata of the Springhill Mines Formation probably accumulated in an inland river valley setting bordering a mature piedmont of coalesced alluvial fans derived from the Cobequid Highlands Massif to the south. Streams of the northeasterly-trending trunk system differ in configuration from streams derived from the Cobequids. Multilateral channel sandstones occur within the formation and multistoried channels with stepped bases are very common. The trunk system has been interpreted as anastomosing where it is exposed at the Joggins Shore (Rust *et al.*, 1984). These streams exhibit moderate sinuosity in the Springhill area based on isopach analysis of drillhole data (Calder, 1984b). Ephemeral input from smaller streams entering the basin from the south merge into the larger trunk system. The presence of alluvial fans, which have built out for several kilometres into the basin, could possibly have contributed to damming of the trunk system, a rise in water table level, and subsequent peat accumulation and development of anastomosing stream patterns.

Ragged Reef Formation

The Ragged Reef Formation has two end members with dramatically different coarse to fine ratios. In the western Cumberland Basin and in the Roslin area north of Springhill the formation is composed primarily of cobble to pebble conglomerate and coarse sandstone with subordinate mudrocks. However, in the central part of the Athol Syncline the strata of this formation are much finer grained and only a few thin conglomeratic horizons occur (Deal, 1990). The coarse end member of the formation was clearly deposited by high gradient braided streams from the southwest. The finer-grained end

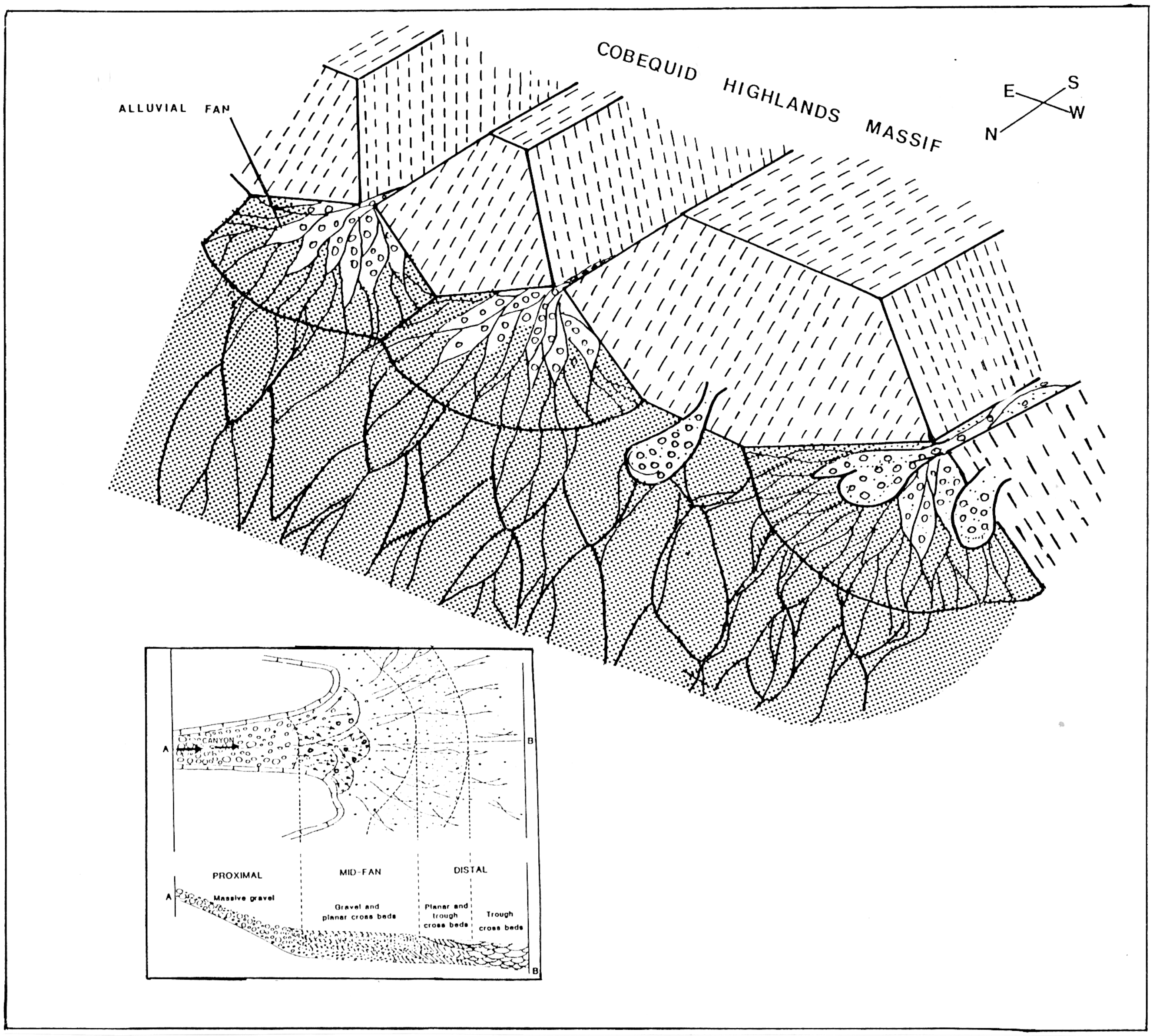


Figure 4-35. Alluvial fan model.

member of the Ragged Reef Formation was probably deposited in an area where the stream gradient was significantly reduced. At the top of the formation, both in the east and the west, there appears to be significant lacustrine influence which is recorded by the presence of thin coal seams and limestone beds. In the upper parts of the formation the coarser strata change over a short distance into a grey coal-bearing package. The Ragged Reef Formation, therefore, represents a transition from marginal braided streams to meandering streams (Fig. 4-36) marginal to lakes or ponds within the stable part of the basin. The facies relationships within the Ragged Reef Formation in the Athol Syncline have been the focus of thesis research by A. J. Deal and the reader is referred to his work for the details regarding stratigraphy and sedimentology (Deal, 1990).

Malagash Formation

The strata of this formation are composed of a sandstone-dominated sequence with a fine/coarse ratio of 0.5. Sandstone and mud-chip conglomerate channel deposits are multilateral and multistoried. Channel deposits show only a crude fining-upward trend and there is little evidence of an upward decrease in the scale of sedimentary structures. Paleocurrent directions are unimodal. Levee deposits are rare and splays are

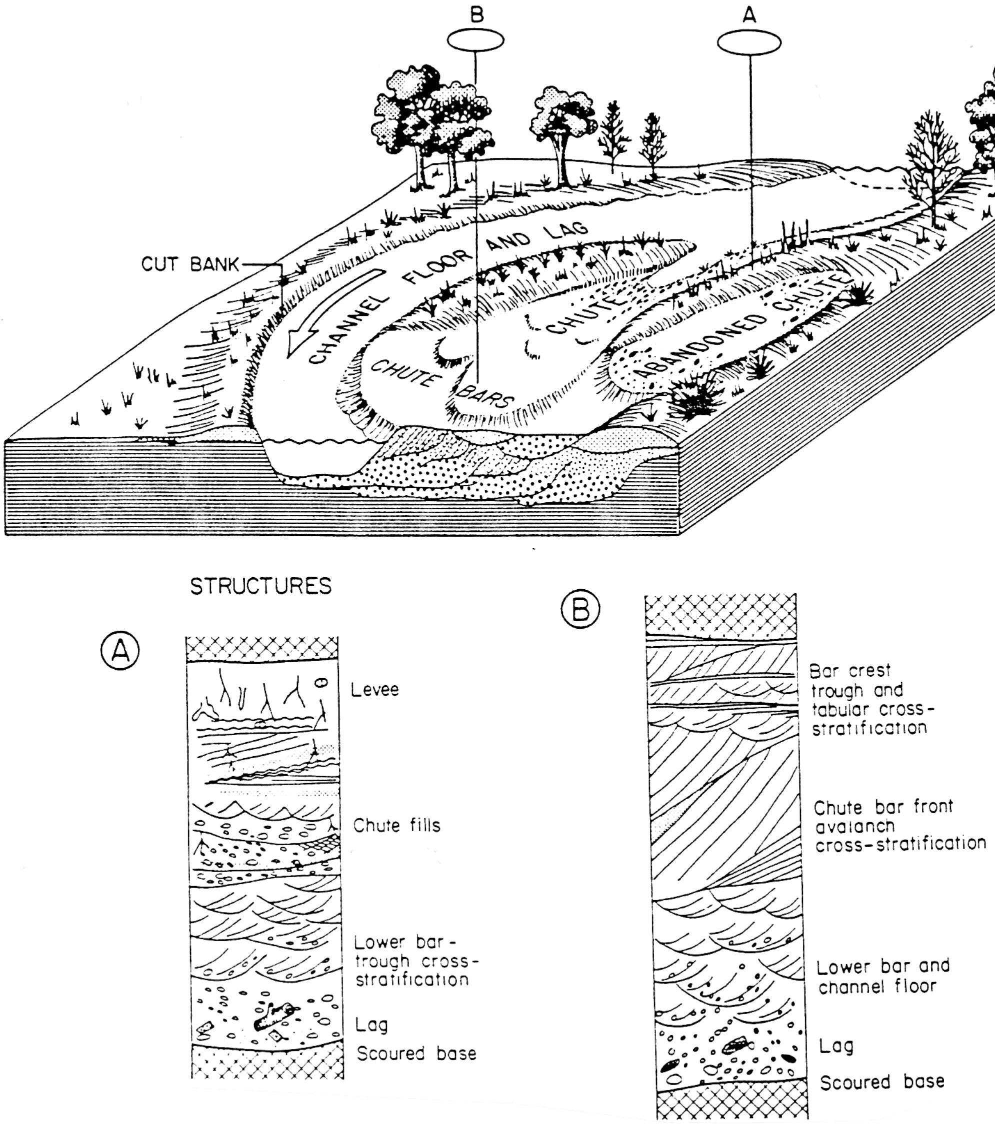


Figure 4-36. Meandering stream model.

common. Fresh water limestone is interbedded with the fine-grained overbank strata of this formation. Based on the biota present, these carbonates were deposited in shallow water near the edge of a lake. This formation is interpreted as a sandy braided stream facies assemblage with associated shallow lacustrine facies assemblages.

Balfron Formation and Tatamagouche Formation

These formations are well exposed in the study area and intersected by numerous drillholes. These data were used to reconstruct the composite stream model, discussed earlier in this chapter. Interbedded with the overbank mudrocks of these formations are shallow lacustrine facies assemblages which were deposited near the inner mudflat zone of large inland lakes. Fossil indications suggest that these inland lakes may have had some marine connection, however, this is highly speculative at this time. Deposition is therefore interpreted as taking place on a large floodplain traversed by relatively straight streams that drained into inland lakes with high variability in seasonal discharge.

Cape John Formation

Strata of the Cape John Formation are dominated by mudrocks interbedded with multistoried channel deposits. Bases of the channel deposits are commonly stepped and concave upward. The channel sequence has a poorly developed upward decrease in the scale of sedimentary structures and grain size fines upward. Crevasse splays are common and levees are more abundant than in the other units of the area. A few thin, shallow lacustrine carbonates occur within the mudrocks; however, they are not as laterally continuous as those of the Balfron and the Tatamagouche formations. Sediment dispersal is unimodal; however, changes of direction are much more common than in the older units. The strata of this formation probably represent mud-rich anastomosing stream facies assemblages (cf. Galloway and Hobday, 1983) interbedded with shallow lacustrine facies assemblages (Fig. 4-37).

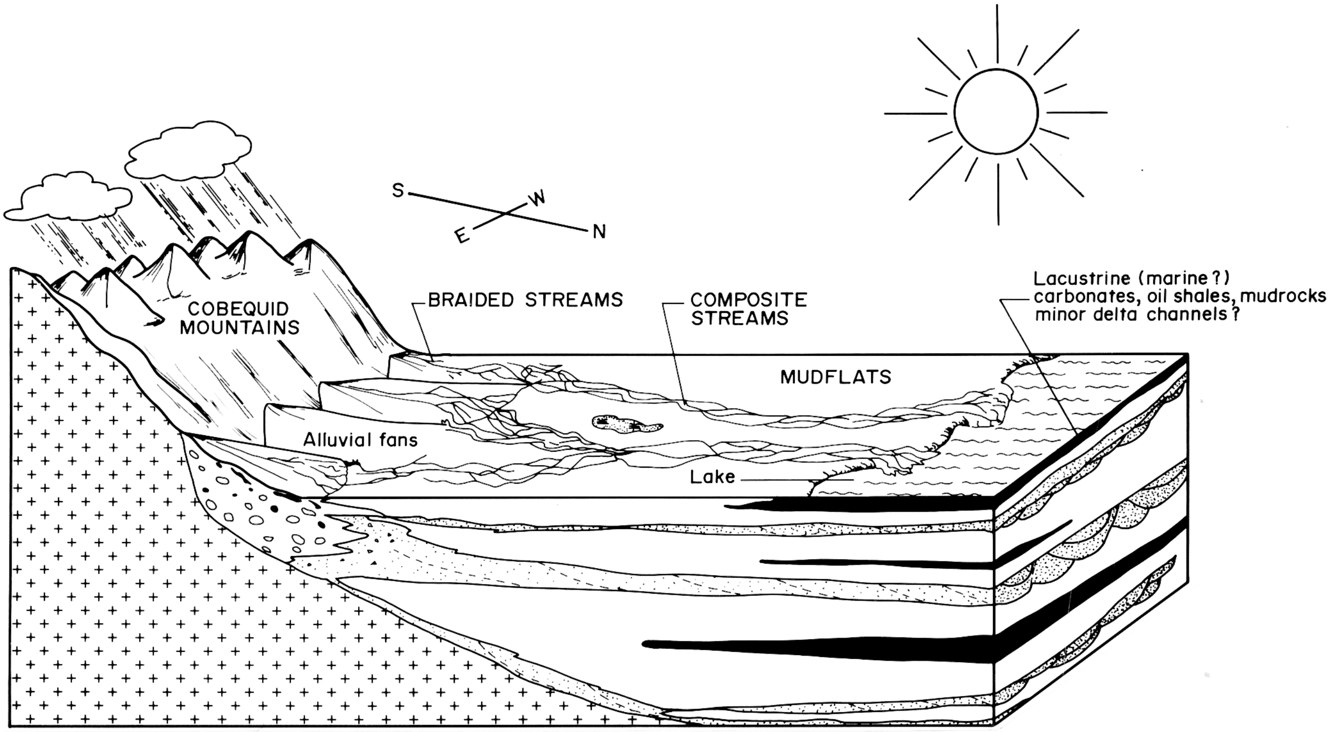


Figure 4-37. Diagrammatic representation of depositional environments for the Pictou Group. The elevation of the Cobequid Mountains is greatly exaggerated.