THE SEDIMENTOLOGY OF THE UPPER MORIEN GROUP (PENNSYLVANIAN) IN THE SYDNEY BASIN EAST OF SYDNEY HARBOUR, CAPE BRETON, NOVA SCOTIA

by

ARTHUR GUY MASSON

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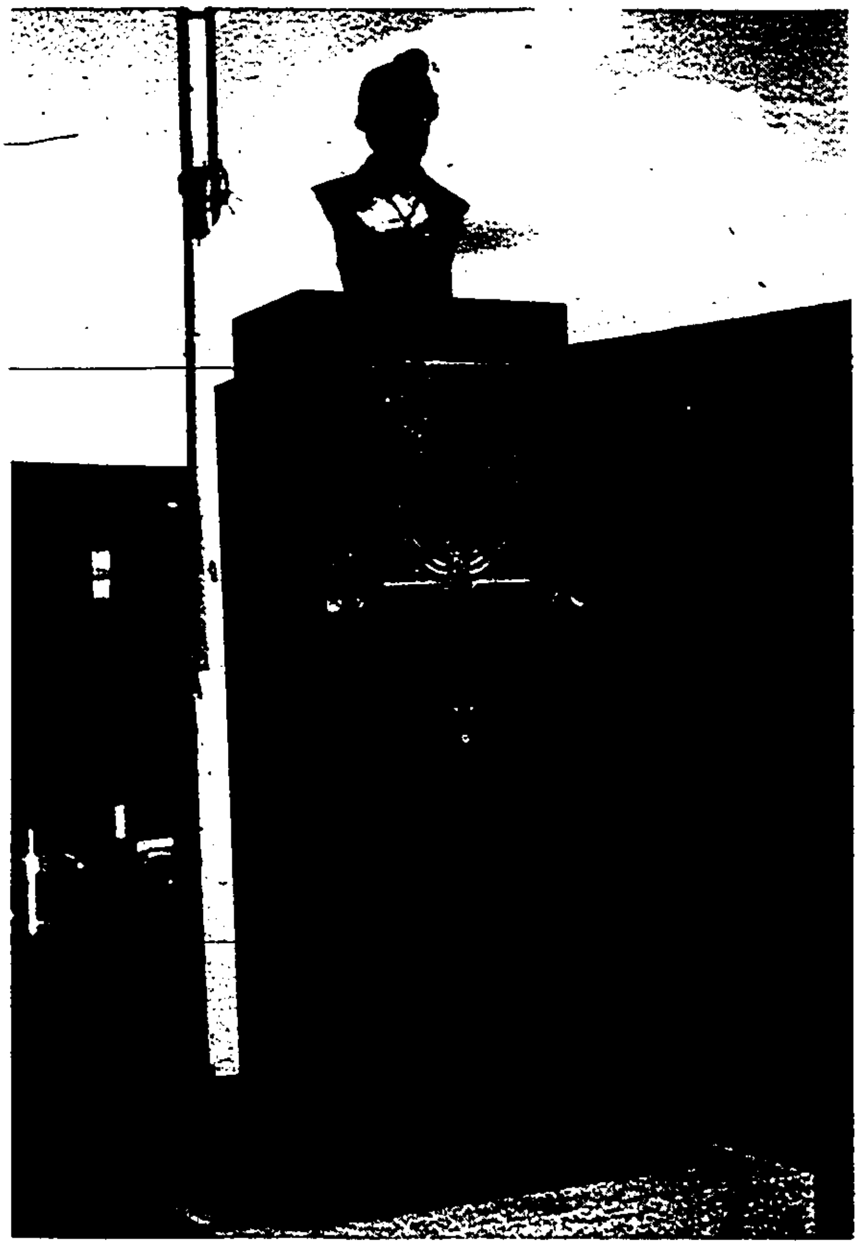
To the coal miners of Cape Breton Island.



ABSTRACT

The onshore part of the Sydney Basin, Nova Scotia, comprises a 1.8 km fining-upward succession of coal-bearing strata, extending from the Westphalian to post-Morien (Permian) Group. Facies analysis for the Sydney Mines Formation (upper Morien Group) shows a meandering fluvial plain depositional environment in which sandstones, siltstones and mudstones were deposited in channels and flood basins. A northeastward drainage was maintained throughout, and the basin records gradually decreasing slopes as source relief was worn down during a period of tectonic quiescence. The economic coals of the upper Morien are thick and extensive and formed under wet conditions in large flood basins between major meandering channels.

The main characteristics of the fluvial system and the controlling factors in the upper Morien Group (Sydney Mines Formation) are:

1) Deposition took place in low-gradient, low-energy streams.

2) These were mixed-load, high-sinuosity channels within a lesser sinuosity meander belt.

3) Point-bar, levee deposits are well developed and overbank deposition and floodplain deposits are widespread.

4) Epsilon cross-stratification is a characteristic structure in the best developed point-bars.

5) Cyclicity is autocyclic (channel migration and avulsion) in a steadily subsiding basin.

6) No deltaic-type marine incursions are present.

Stromatolitic limestone units in the Sydney Mines Formation occur within mudstones in repetitive fining-upward, coal-bearing sequences, interpreted as meandering-fluvial cyclothems. The fluvial association, the presence of a

nonmarine fauna and the lack of marine fossils indicate a lacustrine environment for the algal units. Horizontally laminated and domal forms are present, the latter encrusted on oncoids, which are attributed to moderate wave agitation. The stromatolites occupy a position analogous to the marine bands in paralic coal sequences and represent repetitive lacustrine development within the fluvial cyclothems of the Sydney Basin.

Algal limestones contain abundant fish fragments. A wide variety is present, including remains of bony fish, lungfish and xenacanthid sharks. Of these, the most significant environmentally are the lungfish and teeth and skeletal fragments from freshwater xenacanthid sharks. Their presence confirms the earlier diagnosis of nonmarine conditions derived from the nature of the sedimentary succession and the other biota present. Lithologic and faunal associations suggest that the xenacanthid sharks lived mainly in shallow, alga-bearing lakes on alluvial plains, whereas the bony fish were also tolerant of more restricted swampy environments marginal to the lakes.

Paleocurrent studies indicate consistent northeastward transport through space and time. There is little indication of basement influence at present basin margins, implying that the basin formerly extended further to the southwest. The basin records a period of increasing tectonic quiescence, as source relief inherited from earlier deformation was progressively worn down and slopes decreased with time.

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CHAPTER 1. INTRODUCTION

1.1 Introduction

Coal has long been one of the most important mineral products of Nova Scotia, with nearly 500 million metric tons extracted so far. During the top production years coal was extensively mined in eight separate fields, of which the largest (in terms of both available resources and size) at Sydney contributed 77% of the total (Hacquebard, 1983). Results of offshore drilling show that this field is much more important than previously thought. It is located in northeastern Cape Breton Island, Nova Scota, occupying a lowland zone along the Atlantic Ocean. The landward extent of this field is about 50 x 40 km (Fig. 1), but it is believed to extend seaward nearly to Newfoundland and occupy some 36,000 km^2. The existence and extent of the offshore basin was outlined by King and MacLean (1976) by shipboard seismic, acoustic and bottom sampling methods, showing that the onshore area represents only 3% of the projected region. Reserves have been estimated at nearly 21 million metric tons for the near-surface onshore deposits and at 1.6 billion metric tons of demonstrated coal for the offshore zone to a depth of 1220 m below sea level and approximately 11 km from shore (Hacquebard, 1983).

Mining History

Coal was first mined in 1720 in the Port Morien district by the French military of the Louisbourg Fortress. Mining of coal continued sporadically until the formation of the General Mining Association (GMA) in 1825, which began the systematic exploitation of coal of the Sydney coalfield in the Sydney Mines area. The mid-1940s witnessed the greatest prosperity, the most productive period, and the most mines working. In 1968 all remaining operations were taken over by the Cape Breton Development Corporation (Devco). By 1976 only three mines remained operating: the Prince (Point Aconi), the Lingan (New Waterford) and the Devco #26 (Glace Bay). Devco is now developing a new mine in the Donkin Reserve Area (source: Nova Scotia Dept. of Mines, 1978).

A wealth of information is available on the coal from the mined areas. Most of these data can be found in the numerous detailed reports on the various seams by Haites (1948, 1949a,b, 1950a,b, 1951) and by mine geologists in the files of Devco and in the various reports resulting from the work of P.A. Hacquebard and his collaborators (see p.4).

There are twelve major seams in the Sydney coalfield, all outcropping along the coast in broad open folds that trend northeasterly to easterly. The youngest is at Point Aconi (the Point Aconi seam) and the oldest (the Tracy) near False Bay (Fig. 1, Table 1). Their thickness varies from 1.2 to 3.0 m and eleven of the seams have been mined commercially or "bootlegged" (i.e., unauthorized mining by the local population) at some time. Each of the twelve seams has been given different names in different mining districts. To avoid confusion, a general name for each seam within the entire coalfield has been adopted (Table 1).

Generally speaking, all the Sydney coals are classified as high volatile A bituminous coal, but there are significant variations in their vitrinite reflectance (Hacquebard et al., 1967; Cameron, 1971). The ash content is low, averaging 6%; the sulphur content is variable, ranging from 1.5 to 5%, even within the same seam (Hacquebard, 1983).

1.2 History of geological investigations

Haliburton (1829) was the first to define the "Sydney Coalfield." He gave a broad classification of the rocks of Cape Breton and described the structural geology of the coal measures and the most prominent coal seams exposed along the coast. Brown (1871) divided the Carboniferous of Cape Breton into four distinct units:

- Productive Coal Measures
- Millstone Grit
- Carboniferous Limestone
- Conglomerate

This nomenclature was based on comparison with the European divisions of the Carboniferous and was adopted by later workers. Brown included a detailed section and description of the coal measures exposed on the north side of Sydney Harbour.

Dawson (1873) described fossil plants from the Middle and Upper coal formations of Nova Scotia and divided the coal measures into five units:

A) Upper Coal Beds - all seams from upper part of Morien Bay

B) Middle Coal Beds - Tracy seam and accompanying thinner seams

C) Lower Coal Beds - seam outcropping west of False Bay beach

D) Millstone Grit - below the lowest known coal seam

E) Lower Carboniferous - underlying strata

Dawson (1891) pointed out that the Sydney coal measures contain numerous beds with Naiadites, Cythere, Spirorbis worm tubes, fish scales, etc.

The earliest systematic geological field mapping of the Sydney coalfield was by Charles Robb, assisted by Hugh Fletcher of the Geological Survey of Canada in 1872-75. The results of this work, including two maps on a scale of one mile to one inch and several vertical sections of the strata at a scale of 400 feet to an inch, were published in GSC Reports of Progress for 1874-75. Fletcher revised and updated the geological data from 1895 to 1897, and an additional three maps were published. Robb and Fletcher's maps and reports have served as the basis for subsequent studies as well as the mining development of the coalfield.

The most significant contribution to our understanding of the subdivisions of the Carboniferous in the Maritimes and their correlation with the United States and Europe was made by Walter A. Bell. His contributions to the paleobotany (1938), stratigraphy and the invertebrate paleontology (1938, 1944) of the Carboniferous in eastern Canada remains unequaled. The maps by Hayes et al. (1938) and Bell and Goranson (1938a,b,c) are based to a large extent on his work.

Under the direction of P.A. Hacquebard and with the collaboration of numerous researchers invaluable information was gathered in the fields of coal petrography, coal sedimentology and Carboniferous palynology. Important contributions include the works by Hacquebard (1950, 1961, 1972, 1980, 1983), Hacquebard et al. (1965, 1967), Hacquebard and Donaldson (1969), Hacquebard and Avery (1982), Barss et al. (1963), Barss and Hacquebard (1967), and Cameron (1971).

1.3 Aim and scope of this study

This Ph.D. dissertation is part of a general geological study (including the sedimentology and stratigraphy) of Carboniferous rocks in the Sydney Basin, Cape Breton Island, Nova Scotia, initiated concurrently in 1981 by Dr. B.R. Rust of the University of Ottawa, the Nova Scotia Department of Mines and Energy and the Geological Survey of Canada as part of the Canada-Nova Scotia Co-Operative Mineral Program (CNSCMP).

The main object of this thesis is the detailed investigation of the stratigraphy and sedimentology of the coal-bearing upper Morien Group (Pennsylvanian) in that part of the Sydney Basin east of Sydney Harbour and comprising the sedimentary package between the Emery and the Hub seams (Fig. 1). This was achieved by the detailed mapping of coastal sections and by the examination of cores from nine boreholes from the offshore area. Locations of sections and boreholes are given in Fig. 1.

Other objectives of the present study include:

1) the outlining of new lithostratigraphic subdivisions of the upper Morien (Chapter 2);

2) the description and discussion of the petrography of all lithofacies present (Chapter 3);

3) the interpretation and definition of the environments of deposition (Chapters 4 and 5); and

4) some aspects of the diagenesis of the sandstone (Chapter 4) and some of the limestone present (Chapter 5).

CHAPTER 2. STRATIGRAPHY

2.1 Introduction and general stratigraphic setting

In ascending stratigraphic order the Carboniferous succession of the Sydney Basin comprises the Grantmire Formation, the Windsor Group, the Point Edward and Cape Dauphin Formations (Canso Group), the Morien Group and unnamed red beds, herein termed the post-Morien.. These rock units range (collectively) in age from Tournaisian to Stephanian. The post-Morien rocks also contain Permian strata (Belt, 1968a,b). Their stratigraphic relationship is shown schematically in Fig. 2, and their main characteristics were outlined by Giles (1983).

The Morien Group (Pennsylvanian) of eastern Cape Breton Island is correlated with the Pictou Group, which has a wide distribution in Maritime Canada (Bell, 1944; Hacquebard, 1972). It consists of approximately 1,850 m of variegated sandstones and mudrocks with minor conglomerates, limestones and coal seams. It overlaps older strata toward the northwest (Howie and Barss, 1975). In the onshore parts of the basin, rocks of the Morien Group have been assigned a Westphalian C and D age on the basis of the megaflora and spore florule (Bell, 1938; Hacquebard et al., 1965). The Morien Group extends into the Stephanian at Point Aconi (Hacquebard, 1983) and in the offshore areas.

The base of the Morien Group is exposed at Cape Dauphin and at Boularderie Island and comprises strata ranging from cobble conglomerate to pebbly sandstone and sandstone. However, the basal exposures are all limited in extent and are separated by considerable gaps from the extensive sections of higher parts of the succession. These major sections permit the recognition of two major lithostratigraphic subdivisions of the Morien Group throughout the basin, the boundary between them being diachronous on a regional scale (Giles, 1983).

The lower subdivision of the Morien Group is estimated to be 900 m and is dominated by grey sandstone, medium to thickly bedded, with minor, discontinuous units of grey shale and noneconomic coal occurrences near the top. Thin lensoid beds of conglomerate occur throughout and medium- to large-scale trough cross strata are characteristic (Rust et al., 1983; Gibling and Rust, 1984).

The upper subdivision of the Morien Group is approximately 600 m thick in the onshore areas and is probably much thicker offshore. Boehner (1984) recognises "unnamed redbeds" offshore, which are apparently post-Morien. The base is defined by the first appearance in the succession of thick, laterally continuous mudrocks, which are typically grey in colour. The upper boundary is presently undefined. Rocks characterising this subdivision include grey shales and silty mudstones with associated coal seams, several of which are of major economic importance. Variable sandstone bodies, mostly grey in colour, are interspersed throughout the succession.

These two major lithostratigraphic subdivisions of the Morien Group are independent of the three fossil megafloral assemblage zones (Table 2) recognised by Hayes et al. (1938), Bell (1938), Bell and Goranson (1938a,b,c), which Hacquebard (1983) and Barss and Hacquebard (1967) confirmed on the basis of spores. The basis of Bell's subdivision was biostratigraphic. The Morien Group, which is supposedly the time-stratigraphic equivalent in eastern Cape Breton Island of the Pictou Group (Bell, 1944), was subdivided by Bell (1938) into three megafloral assemblage zones. Adherence to this subdivision has required the placing of boundaries within the Morien Group where no lithological change is present. This has created much confusion and has led to units defined on biostratigraphical grounds being used as lithostratigraphic units.

Boundaries between these biostratigraphic zones were mapped across the Sydney Basin by Hayes et al. (1938) and Bell and Goranson (1938a,b,c). Hayes et al. (1938) drew the boundary between the lower (Lonchopteris) and middle (Linopteris obliqua) zones at the Tracy seam, and that between the middle and upper (Ptychocarpus unitus) zones at the Spencer or Emery seam. These authors did not indicate that any other lithostratigraphic criteria were taken into account in the subdivision. Zodrow and McCandlish (1978, 1980) have recently combined the upper two of Bell's zones into one zone (the Linopteris obliqua zone).

Geological studies of Carboniferous rocks in the Sydney Basin (Cape Breton Island, Nova Scotia) were initiated in May 1982 as part of the Canada-Nova Scotia Co-Operative Mineral Program (CNSCMP). Concurrently, Dr. Brian Rust, of the University of Ottawa, and several graduate students under his supervision undertook detailed sedimentological and stratigraphical analysis of the Morien Group. Preliminary results outlined in Rust et al. (1983) have permitted significant advances in the geological understanding of the Morien Group.

Continuation of the CNSCMP Program during 1983 has resulted in the collection of additional data permitting the tentative stratigraphic subdivision of the Morien Group into mappable formations. This new stratigraphic nomenclature, outlined by R.C. Boehner (1984), but as yet not formally proposed, is summarized in Figs. 2 and 3.

This scheme divides the existing Morien Group into the South Bar (SB) and the Sydney Mines Formation (SM). The latter corresponds to the alternating facies assemblage of Rust et al. (1983) and the former to the pebbly sandstone and sandstone assemblages of the same authors. A red bed unit between the SM and SB formations near Wadden Cove, outside the study area, is as yet undefined.

The proposed type section of the South Bar Formation is located on the east side of Sydney Harbour, from south of Liscomb Point to Victoria Mines. The basal part of the section is covered but the top is exposed and is in conformable contact with the basal part of the Sydney Mines Formation (i.e., Appendix A, Fig. 1, Victoria Mines section of the present study). The South Bar type section is virtually continuously exposed in cliffs and wave-cut platforms. It corresponds closely, but not exactly, to the lower subdivision of the Morien Group (Figs. 2 and 3 and Table 2, i.e., Lonchopteris and Linopteris zones of Bell).

The type section of the Sydney Mines Formation is located on the northwest side of Sydney Harbour, from Stubbert Point to the Point Aconi seam north of Cranberry Head. This section has been investigated by Margaret Best (Best, 1984). The type section was selected on the basis of continuity of exposure (70% exposure) and ease of access. All the coastal sections measured for this study are lateral equivalents to the type section for the Sydney Mines Formation. This formation is characterised by great lateral variation from section to section (see section 2.3). The base of the formation is just below the Emery seam and the top is located at the base of the red beds overlying the Point Aconi seam.

The Sydney Mines Formation does not correspond exactly to the fine coal-bearing upper subdivision of the Morien Group, or Ptychocarpus zone (Table 2). The present study further subdivides the Sydney Mines Formation into "informal mappable lithostratigraphic zones" and beds (Fig. 4 and section 2.3).

2.2 Definition of sections measured

The present study is concerned with measured sections of coastal cliff exposures of the Sydney Mines Formation between Sydney Harbour and Morien Bay. The locations of the measured sections and of the wells from which core was examined are shown in Fig. 1.

The rocks of the study area are shown on published geological maps 361-A (Bell and Goranson, 1938c) and 362-A (Hayes et al., 1938), compiled from the mapping by A.O. Hayes in 1917-19, W.A. Bell in 1921, 1930, 1931, and E.A. Goranson in 1930, 1931. The Sydney Mines Formation is the main coal-bearing unit and does not correspond exactly to the Ptychocarpus unitus zone of Bell (1938). The lower contact is located approximately 10 m below the Ptychocarpus unitus zone at the Victoria Mines section (Table 2).

The rocks studied consist essentially of interstratified sandstone, siltstone, mudstone-claystone, shale, limestone and coal. Their lithology and characteristics are described and discussed in Chapter 3. Fig. 5 gives the total thickness and the relative percentage of the main lithological groups for all sections measured. Continuity of measurable rock exposure varies greatly from section to section. This is a direct reflection of the high degree of coastal erosion taking place. For example, measurable exposure reaches a maximum of 280-285 m in the New Waterford and the Glace Bay West sections, whereas at Schooner Head it reaches only 60 m. Covered parts of sections were measured directly or by pace and compass method and incorporated into the sections. The thickness of covered sections exceeding 15 m was estimated from aerial photographs; lateral relationships between facies were also observed.

Detailed stratigraphic sections through the sedimentary package between the Emery and Hub seams (locations in Fig. 1) are given in Appendix A, Figs.

1-8. Stratigraphic correlations of these sections, using the main productive coal seams as datum lines, are given in Appendix B, Figs. 1-6.

Because of the economic importance of the coal beds, subsurface rocks of the Sydney Basin have been penetrated in many locations by offshore wells. Examination of core records from 9 of these wells (locations in Fig. 1) permitted lithofacies analysis and comparisons with coastal sections. Data from boreholes are too sparse to be included with the detailed coastal sections. However, the lithofacies observed in well cores are similar to those in the coastal sections, indicating that there are no significant sedimentological and stratigraphical changes, at least as far as well control goes, about 10 km offshore (Fig. 1). Lack of continuous core recovered (most vary from 5 to 40 m and only one exceeds 100 m) and uncertainty as to exact vertical location (mainly because of coal removal from core and/or poor recovery) make correlation with units from the coastal sections unfeasible in most cases.

2.3 Lithostratigraphic zonation of the upper Morien Group

A study of the detailed stratigraphic sections (Appendix A) and their correlations (Appendix B), as well as the data outlined in Fig. 5, suggest important modifications to the non-marine model advocated in the literature and briefly outlined previously in this study. The fine, coal-bearing upper Morien Group (Sydney Mines Formation) has many features characteristic of meandering river, alluvial-plain and related pond-lacustrine deposits. Rust and Masson (1981) enumerated such features for the Port Morien and Victoria Mines sections, but further work has shown that they are found in all sections measured in the upper Morien Group. The sedimentology and depositional environments of the upper Morien Group as well as detailed accounts of several examples of the most characteristic sedimentary bodies and their vertical and lateral relationship are discussed in detail in Chapters 4 and 5.

Correlation as defined in the North American Stratigraphic Code (NACSN-AAPG, 1983) is "the demonstration of correspondence between two geologic units in both some defined property and relative stratigraphic position." Lithocorrelations (linking units of similar lithology and stratigraphic position) of the measured coastal sections using the main productive coal seams or their covered equivalents as datum lines are plotted as columnar sections in Appendix B, Figs. 1 to 6. In general, the thicknesses of sedimentary columns for the correlated sections enclosed by any two datum lines do not show great variation. An important exception is the Morien North section, which is significantly thicker than the other sections to the west. Correlation with the other sections of similar stratigraphic position was not successful. This section, although illustrated in Appendix A, Fig. 8B, is not shown in Appendix B.

A lithostratigraphic unit is "a defined body of sedimentary, extrusive igneous, metasedimentary, or metavolcanic strata which is distinguished and delimited on the basis of lithic characteristics and stratigraphic position" (NACSN-AAPG, 1983). The term "zone" is an informal unit that "may include all or parts of a bed, a member, a formation or even a group" (NACSN-AAPG, 1983), and the term "member" is a formal unit next in rank below a formation, recognised as a named entity within a formation because it possesses characteristics distinguishing it from adjacent parts of the formation."

In the author's opinion, the lithostratigraphic subdivisions of the upper Morien are sufficiently distinct and laterally extensive to be assigned member status, but because the regional study to substantiate this is not completed, I refer to the units as "informal zones A to E succession" within the still-to-be-defined Sydney Mines Formation.

From the columnar sections (Appendix B, Figs. 1-6), five "informally designated mappable zones" have been recognised on the basis of similar lithology, stratigraphic position, and facies assemblages, in particular the vertical and lateral distribution of the channel sandstones, fine-clastic sediments, coals and carbonaceous shales and limestones (Fig. 4; Figs. 1-6 of Appendix B).

The criteria used for the subdivision are based on facies interpretation such as: abundance and predominance of channel sandstone, overbank sandstone and floodplain muds. The exact locations, the vertical and lateral extent, the lateral lithological variation and the selected boundaries for each zone are outlined in detail in the figures of Appendix B. Fig. 4 includes: thickness of each zone, cumulative thickness and exact position of contact of each zone using the New Waterford section thickness as reference; the distribution, lateral extent and coastal sections where the zone is exposed; relation of the main coal seams to each zone and the main lithological assemblage defining each zone.

The greatest usefulness of the criteria for subdivision lies in their correspondence to environment of deposition. Fig. 4 and Appendix B reveal that the zones reflect such changes. Thus the sequence from zones A to E represents a fining-upward megatrend, reflecting a vertical change from channel to floodplain dominance.

The following types of facies assemblages are defined:

A) fluvial-channel-dominated with floodplain (zones A and C);

B) fluvial-channel and floodplain dominated with local lacustrine limestone beds (zones B and D);

C) floodplain-dominated with minor secondary channels and lacustrine limestone beds (zone E).

These three main facies assemblages will be the basis of the sedimentology discussion of Chapters 4 and 5.

Coal development in the floodplain environments of the Sydney coalfield has been studied in considerable detail by Hacquebard and his collaborators. Hacquebard and Donaldson (1969) showed that entire seams or individual seam benches maintain nearly the same height of coal over a distance of some 40 km. Clastic parting in the coal is extensive at lateral margins of seams and is the result of the interaction between fluvial sedimentation and peat accumulation. A westward expansion in successive seams and a westward migration of the depositional center in successive seams was also observed. This is borne out by Hacquebard and Donaldson (1969, Plate 1). Within this depositional setting several parameters determine and control the potential for extensive peat formation:

1) botanical parent material;
2) climate;
3) detrital influx from fluvial source;
4) frequency of switching of fluvial source;
5) subsidence leading to pond or lacustrine conditions;
6) fluctuation in level of water table.

Each of these factors will in turn have a direct influence on the variability of the ash content and the mineralogical (maceral) composition of the peats.

Stratigraphic observations of the main productive seams from coastal sections (datum lines of Figs. 1 to 6 in Appendix B) are tenuous, mainly because of the discontinuity and/or poor quality of most seam exposures. In addition this study only deals with that part of the basin located east of Sydney Harbour. However, a few interesting observations can be made:

1) All major seams (except the Hub) occur in the floodplain deposits of fluvially influenced zones; the extent of the coals shows that peat persisted right across the floodplains.

2) More pronounced splitting, digitation and interstratification has been observed in exposures of the Emery, Phalen and Bouthillier seams, indicating stronger influence from fluvial sedimentation.

3) Lesser fluvial influence was apparent in exposures of the Backpit seam.

Observations 2 and 3 are in agreement with those of Hacquebard and Donaldson (1969).

The study of the columnar sections (Figs. 1-6 of Appendix B) shows that many seams other than the main productive ones exhibit lateral thinning, discontinuity and a high content of interstratified fine clastic material, making standard methods of correlation by stratigraphic intervals very difficult and in many cases impossible. The splitting, digitation and rejoining of these coals are caused by the distribution of the associated sedimentary rocks, especially crevasse-splay and channel-fill sandstones. These represent short-term input of crevasse-splay clastics or migration of fluvial channels into interdistributary peat swamps.

Some coal seams are laterally equivalent to lacustrine limestone bodies (e.g., Appendix B, Fig. 4, GBW 130 m), indicating that in places swamps were laterally transitional into shallow lakes.

CHAPTER 3. LITHOLOGY, PETROLOGY AND FOSSIL CONTENT

3.1 Introduction

The lithology of the sections studied was evaluated from the detailed study of 1026 hand samples, sedimentary structures and contacts between units. Nine lithofacies were recognised. The sandstones were named according to the classification of Mansfield and Ahlbrandt (1978), illustrated in Fig. 6. To simplify description and to avoid repetition, these lithofacies have been grouped under the following headings:

- Sandstone lithofacies:
  - conglomerate to very coarse quartzolithic and quartzosublithic sandstone
  - coarse-medium quartzolithic to lithisubquartzose sandstone
  - medium-fine quartzosublithic to lithisubquartzose sandstone
  - fine-very fine lithisubquartzose to lithiquartzose sandstone
- Fine-clastic lithofacies:
  - interstratified sandstone-siltstone and shale/mudstone
  - silty shale and/or mudstone-claystone
  - nodules and concretions
- Limestone and fossil content
- Coal

Miall's (1978) Depositional Facies scheme and Reineck and Singh's (1975, p.82-83) terminology for shapes and thickness of strata are used in the following discussion. Detailed description and discussion of the diagenetic features of these lithofacies will be presented in Chapters 4 and 5.

In this section, each lithofacies type is described in detail, followed by an environmental interpretation. Because individual rock types in the sequence have certain similarities in geometry, internal structures, grain size and composition, an attempt is made in Chapter 4 to relate sedimentary structures, lithofacies types and depositional facies.

3.2 Sandstone lithofacies

In most cases the main component of the sandstones is moderately subrounded to angular quartz (20 to 80%). Quartz grains are strained and/or unstrained and in the coarser fractions are much more angular. Chert grains are locally present. Metamorphic quartz fragments are locally common and are more prominent than igneous fragments. Other minerals include variable percentages of micas (muscovite and biotite), chlorite and altered and non-altered ferromagnesian minerals (hornblende, pyroxene), minor localised plagioclase, alkali-feldspar and a few grains of tourmaline, epidote, apatite, sphene and zircon. Organic fragments and mud intraclasts are important components (10 to 50%) and extensive hematite cement is locally abundant. The principal rock fragments are sedimentary in origin, mainly the various types of mudrocks, limestones, ironstones and sandstones found within the succession; metamorphic fragments are locally common, whereas igneous fragments are uncommon. Lithic fragments decrease from 80% in the coarsest lithofacies to less than 10% in the finer lithofacies. Clay matrix may form up to 30% of some poorly sorted sandstones. Silica cement and/or calcite cement amounts to 25% in some sandstones. Extensive intermixing of clay and silica and/or calcite cements is common in the medium to very fine fractions of the sandstones.

3.2.1 Conglomeratic to very coarse quartzolithic and quartzosublithic sandstone

This lithofacies is genetically related to the coarse-medium quartzolithic to lithisubquartzose sandstone lithofacies, both forming channel lag deposits. The clasts vary greatly in size, shape and composition (Plate 1). They range in size from a few millimeters to tens of centimeters and, depending on the type of material, can be subrounded, angular, flattened or elongated. Various types of shale and mud clasts (i.e., grey, black, purple, mottled), finer sandstone clasts, extraformational quartz, sideritic nodules, limestone fragments, metamorphic rock fragments, igneous rock fragments, organic and plant fragments (and in some units layered tree trunks) are commonly observed as clasts in this lithofacies. These fragments can form up to 60% of the units and usually occur with the coarse-medium quartzolithic sandstone. Generally speaking, the lower surface of this unit is sharp and in most cases erosional.

Besides forming channel lag deposits (Plate 2), this lithofacies also forms beds of variable thicknesses (several cm to 1.5 m) in the following environments:

- basal lag in thicker trough cross-bedded units from lowermost part of channel fills;
- tabular beds representing sand waves or rip-up intraclastic units;
- lower part of fining-upward point-bar sequences;
- basal part of coarser tabular bodies and rippled bodies from levees and marginal channel environments.

3.2.2 Coarse-medium quartzolithic and lithisubquartzose sandstone

This lithofacies is a "salt and pepper" unit with 20 to 40% of its components in the coarse sand size fraction (Plate 3A). The quartz content ranges from 40 to 75%, as subangular to angular grains. Angular and platy mica flakes (5 to 20%), mostly muscovite but also some biotite and chlorite, occur as laminated concentrations or as coarse to medium randomly scattered grains. Variable but generally minor amounts (1-7%) of angular to subrounded chert, feldspar (plagioclase exceeding K-spar), opaque minerals and pyrite grains are present in some cases. Organic matter and plant debris is abundant in some units (up to 30%) commonly in association with mica flakes. Angular to subangular clasts of shale, mudstone, sideritic or hematitic mudstone, silty sandstone, fine to very fine hematitic sandstone and coal-bearing carbonaceous shale and metamorphic rocks are also present in this lithofacies. A few grains of tourmaline, hornblende, apatite and sphene are present locally. In general, detrital calcite crystals and calcareous cements are not prominent and are very localised. Clay content is variable (5-20%) and cement is principally siliceous, both as material intermixed with the clay and as solution silica welding the quartz grains at their points of contact. Porosity varies from 5 to 10% and is intergranular to vuggy in nature. Burrows are present locally in the finer units of this facies.

Stratification is highly variable and can be summarized as follows in order of decreasing importance:

- bedding thicker than 1.5 cm and up to 15 cm with a faint to well-defined trough-shaped base enhanced by greater concentration of mica and/or by extensive organic coatings. No internal laminations are observable and large clasts may be present at the base of the thicker beds.

- rippled (locally climbing) sets less than 1.5 cm thick, building up into beds several cm thick. The internal laminations are very thin to medium, discontinuous to continuous, wavy to uneven, parallel to even parallel (Plate 3A).

- homogeneous, horizontal beds (1.5-3.0 cm thick). In some samples individual laminations a few mm thick are present. These can be faint to well defined and range in shape from continuous-even parallel to discontinuous-uneven non-parallel.

- burrows are present locally.

This lithofacies is attributed to deposition in the following environments:

- as trough cross-bedded units forming channel fills and lower and coarser units of fining upward point-bar sequences;

- as the basal part or complete units of coarser tabular and rippled bodies formed in marginal channel environments, such as levees and crevasse-splays;

- as the upper part of calcareous-cemented, coarsening-upward sandstones forming lacustrine delta and crevasse-splay sequence.

3.2.3 Medium-fine quartzosublithic to lithisubquartzose sandstone

This lithofacies is the most extensive of the sandstone lithofacies and is poorly to moderately well sorted (Plate 3B). It exhibits the greatest range in mica, silt, clay and cement (type) content. The proportion of lithic clasts is much less (10-20%) than in the previously described facies, and calcareous components show a sharp increase. Ferromagnesian minerals and organic matter remain high. Because it is formed in a great variety of environments, this lithofacies exhibits a wide range of colour variations, commonly salt-and-pepper (speckled black/white) or greyish (N7 to N4 and 5Y5/1).

Quartz content is high (35 to 75%), with the coarse quartz fractions ranging from 1 to 7%. Quartz grains are generally angular to subrounded, with monocrystalline grains greatly exceeding the composite types. Well-developed local solution welding contacts and corrosion of grain borders are also important features. Chert and hematite are generally minor (1-7%), but locally hematite cement intermixed with grains as staining and mottling may form up to 40% of the unit. Chert and hematite grains are usually subangular to angular and disseminated. Feldspar (subrounded highly weathered plagioclose and K-spars) and mica (platy and broken flakes of muscovite and biotite exhibiting variable weathering) commonly vary between 2-7%, but mica is 20% in local concentrations. Organic material is present in almost every sample (5-10%), ranging from well-developed plant imprints, to coarse or very coarse twigs and wisps, to fine to very fine disarticulated carbonaceous debris, showing various degrees of coalification. Lithic fragments and clasts are generally less than 20%, but can reach 50% locally, most being subangular to subrounded and ranging in size from 5 mm to 2 cm. Most are of sedimentary origin (very fine sandstone, shale, mudstone, coaly-carbonaceous, sideritic mudstone and fine-grined carbonate clasts), but numerous metamorphic rock clasts (mostly low grade) are also present. Many of the softer clasts are flattened as a result of compaction. Individual grains of pyrite, hornblende, epidote, tourmaline and unidentified opaques are present as traces. Clay content is variable (5-25%) and occurs as intercrystalline material within the cement, or in fine laminations. Although silica cement is again the dominant type, there is a general increase in calcareous cement over previously described lithofacies.

The commonest stratification types are, in decreasing order:

- homogeneous to very faintly laminated units exhibiting variations in amount of quartz, mica, clay, hematite and/or organic material;

- very thin to medium horizontally laminated (i.e., continuous to discontinuous, even, parallel) sets several mm to 3 cm thick. These laminations usually show a higher percentage of micaceous and/or organic material (up to 40%);

- trough-based rippled units up to 3 cm thick with discontinuous to continuous, wavy, parallel to non-parallel laminations;

- climbing-ripple sets exhibiting erosional bases (Plate 3B). The cross-laminations are mostly of the wavy-gently wavy, discontinuous, non-even parallel to non-parallel types.

In addition, soft sediment deformation and bioturbation by burrows and roots are important local features.

This lithofacies mostly occurs as:

- the middle and upper part of fining-upward point-bar sequences and lateral-accretionary channel fill;

- the major component of tabular splay deposits;

- the coarser material of the tabular sand bodies alternating with finer clastic tabular bodies in the floodplain environment;

- interstratified with calcareous mudstones in the coarsening-upward sequence representing lacustrine deltas and lacustrine crevasse-splay deposition.

3.2.4 Fine to very fine lithisubquartzose to lithiquartzose sandstone

Most of the characteristics of the fine to very fine lithisubquartzose to lithiquartzose sandstone are similar to those of the previously described facies. The most important differences are a better sorting (moderately good), decrease in lithic fragments (25-30%) and feldspars (trace), increase of clay (5-35%) and silt (5-30%), increase of interlamination with siltstone, shale/mudstone and increase of calcareous content both as cement and as detrital grains.

All types of rippled cross-lamination are present (every style of wavy to slightly wavy, continuous to discontinuous, even to uneven, parallel to non-parallel). Erosional relationships between rippled sets are common. Horizontal stratification is also prominent. The greatest percentage of sideritic/ankeritic nodules and root systems in the succession occur in this lithofacies and in the genetically linked interstratified sandstone, siltstone and shale/mudstone lithofacies. Soft sediment deformation, burrows and mottling are also important features.

The great variety in stratification in this facies attests to the highly variable character of currents in the floodplain environment in which it was deposited.

Some of the subenvironments in which this lithofacies accumulated were:

- uppermost part of trough cross-stratified cosets and rippled units of fining-upward point-bar sequences;
- basal part of coarsening-upward sand sequences;
- as intermixed and interstratified material in marginal channel, floodplain and sandy lacustrine bodies.

3.3 Fine-clastic lithofacies

3.3.1 Interstratified sandstone-siltstone-shale/mudstone

This lithofacies is genetically related to the fine to very fine lithisubquartzose and lithiquartzose sandstone lithofacies. It is an intricate and complex intermixture of material from the previously described finer grained sand lithofacies with a highly variable content (20-80%) of siltstone-shale/mudstone as interlaminations (2-10 mm) and interbeds (10 mm-6 cm). This lithofacies is characterised by abrupt alternations and common cross-cutting of strata on the scale of a few cm of mostly varicoloured medium to very-fine sandstone, siltstone and finer clastic material. Layers exhibit almost the entire range of shapes from parallel/continuous to discontinuous wavy laminations and small-scale cross lamination. Loading is common in coarser layers. Parallel lamination is also a characteristic internal structure. The complex interstratification indicates periodic and variable influxes of sediment into standing water bodies and floodplain areas. This conclusion is also supported by the presence of desiccation cracks, soft-sediment deformation, bioturbation (burrows and roots) and sideritic concretions.

Fluvial environments, especially in or near levees and floodplain tabular splay deposits, are usually composed of such interbedded lithofacies (Elliott, 1974). In addition to the environments listed in the previous lithofacies, the sand-siltstone-shale/mudstone lithofacies is common in alternating assemblages occurring above channel sandstones in fining-upward cycles and in some units underlying and in most units overlying coal seams.

3.3.2 Silty shale and/or mudstone-claystone

This lithofacies is characterised by various fine-clastic rock types exhibiting wide ranges of colour and composition. Colours vary from black to red-purple. In this report "mudstone" defines all massive mudrocks (Fm) that are composed mostly of clay-sized particles but also contain variable silt and sand particles (Miall, 1977b). The term "shale" is used for laminated (facies Fl) and fissile mudrocks. Claystone, as used in this text, describes rocks that are composed almost entirely of clay minerals and become soft and plastic when moistened. Carbonate minerals are common impurities (marlstone). This lithofacies is usually associated with limestone and coal as underclay deposits. Some dark shales exhibit a highly bituminous content.

The silty shale and/or mudstone-claystone lithofacies occurs as homogeneous beds of variable thickness (several cm to several m). The silt content is highly variable (2-40%) and is usually very minor in carbonaceous shale. Gradation to muddy siltstone is difficult to observe in the field, since both are commonly intermixed. Locally the mudstones are highly hematitic (red-purple type), calcareous (marlstone), or micaceous. Very little organic debris is found in the mudstones (0-10%) compared with the darker shales (10-70%) and the seatearth claystones in which root features are quite prominent.

Pyritic grains, coatings and nodules, coal fragments and plant remains are abundant in numerous shaly sections, especially in the shales overlying coal seams. Lycopods, Calamites, Pecopteris, Sphenophyllum and Asterophyllites, as well as a great diversity of unidentifiable fern imprints and fragments have been recognised. Slickensides, desiccation cracks and sideritic concretions are characteristic features of mudstones.

The red-purplish-green mottled mudstone and red micaceous shales commonly alternate with hematitic sandstone. This assemblage is particularly abundant between the Bouthillier and the Harbour seams in the Port Morien section. The mudstone is a dense, opaque, hematitic rock with 5-20% subangular to angular, fine sand to silt size quartz grains. The purplish-red colour is caused by the presence of hematite, and the green mottling results from the local reduction to ferrous oxide. Microscopic study of the shaly variety disclosed a close association between a red material, identified by X-ray diffraction as hematite, and micaceous minerals, which by X-ray analysis are mostly muscovite and illite, probably originating from alteration of biotite. The hematite occurs between the lamellae of the micas and fills the interstices and makes up the bulk of this red shale.

Generally, quartz is more abundant in mudstone than in claystone. Locally both mudstone and claystone are calcareous and in places may contain sideritic-ironstone and/or limestone nodules. The calcareous mudstone commonly grades into thick (up to several m) deposits of silty marlstone, particularly in limestone-bearing sequences. The mineral composition of 25 mudrock samples from the study area was determined by X-ray diffraction (Table 3) and is, in order of decreasing abundance: clay minerals, quartz, muscovite, hematite, siderite, calcite and ankerite. The clay minerals, in order of decreasing abundance, are kaolinite, illite and chlorite and minor amounts of mixed illite-chlorite. Kaolinite is by far the most abundant (Table 3).

The geometry of the mudstone and claystone units is less easily defined than that of the shales with good fissility. This is mainly because both types of rock weather rapidly and are soon covered by weathered rubble. The claystones commonly occur as lenses thinning laterally, but as thin underclays they are sheetlike units that cover large areas. The mudstones and shales are generally larger lens-shaped bodies, some of which are as much as 10 m thick. Mudstone and shale are commonly interbedded, grading laterally or vertically into siltstone.

Most shale, mudstone and claystone bodies are stratified. Claystone commonly occurs in single units ranging in thickness from a few mm to a few m. The strata are almost invariably destroyed by weathering because of the plasticity of the material. Shale is finely laminated, mostly horizontal-slightly wavy - discontinuous even/noneven - parallel, and in addition to muddy interlaminations commonly encloses upright tree trunks. Other mudstone bodies are massive, nondescript units breaking down upon weathering into irregular-shaped fragments. Shales (both organic and hematitic) are stratified with both single and compound units ranging in thickness from a few mm to 1.5 m. The laminations are well defined and are of the horizontal-slightly wavy, continuous-discontinuous, even-noneven, parallel type. Marlstones and calcareous mudstones are usually crumbly with few structures preserved.

3.3.3 Nodules and concretions

The presence of nodules and concretions in the mudrocks is one of the most striking features of the upper Morien Group. They occur in a great variety of sizes and shapes, generally appearing as minor segregations within their host rock. They range in size from a few cm to 50 cm in the longest dimension in the elongate type. Shapes vary from spherical to oblate to elongate (cylindrical) and may also occur as flattened, thin bands parallel to bedding. Concretions also coalesce laterally to form thin bands and beds (2-5 cm) and continuous layers (Plate 4A). Two main types are present (Table 4):

- sideritic (iron-carbonate) concretions;
- calcitic septarian nodules.

There are many descriptions of sideritic (iron-carbonate) concretions in the literature. They include the siderite and calcite-bearing concretions in the Lias of Yorkshire (Hallam, 1967), the sideritic nodules in Pennsylvanian shales from the Allegheny Group of Western Pennsylvania (Weber et al., 1964); the siderite concretions in the Upper Cretaceous Cardium Formation of Alberta, Canada (Griffith, 1980); and the sideritic concretions in the Francis Creek Shale (Pennsylvanian) of Northeastern Illinois (Woodland and Stenstrom, 1979). In the Sydney Basin the sideritic concretions occur mostly in the lower part of the organic shales and mudstones underlying coal seams (Plate 4A). They are also present as disseminated concretions within some of the finer rippled sandstones and argillaceous-fine clastic units from floodplain deposits, and as lag material in channels (Plate 2). They tend to be spheroidal, ellipsoidal or flattened and they range in length from 3 to 30 cm. In the non-weathered state they are light to bluish grey, but they develop a reddish brown colour upon weathering as a result of the oxidation of siderite. Bending of lamination around the concretions is very prominent locally.

The homogeneous-patchy texture of the rock is that of muddy micritic to microsparitic material. Petrographic examination reveals a fine mosaic of carbonate crystals (up to about 20 μ in diameter) with local irregular patches of smaller crystals (up to 6 μ). Detrital quartz of silt to fine sand size is present in amounts up to 7%. Very fine crystals of hematite and pyrite occur in variable quantities (hematite: 3--15%, pyrite: trace to 2%) in the samples exhibiting iron staining. Skeletal debris is absent from the samples studied. Kaolinite is the main clay mineral in the sideritic nodules, with illite present in subordinate quantities (Table 4).

The proportions of siderite and calcite in each sample were determined by X-ray diffraction (Table 4), and the distribution of these two minerals was studied by staining technique that distinguished calcite, ferroan calcite and siderite (Dickson, 1965). The X-ray diffraction results revealed the following combinations in order of decreasing importance: siderite with clay; siderite with minor ankerite; siderite with minor calcite (or silica); ankerite with minor siderite. The only other minerals present in nodules in any significant quantity apart from quartz (and hematite locally) are kaolinite, illite, mica and minor ferroan dolomite. Textural study revealed that siderite occurs as uniformly spaced micritic patches, within a matrix of ferroan calcite microsparite and/or microcrystalline silica.

Calcite-bearing septarian nodules are large (5-30 cm), oblate to slightly oval, and characterised by an internal network of radiating fractures that widen toward the centre of the nodule and narrow or die out at its margin (Plate 4B). Although not as numerous as the sideritic concretions, several occurrences have been observed in the upper Morien Group. They mostly occur as disseminated groupings of concretions in calcareous argillaceous bodies enclosed in mudrocks as part of floodplain sequences. X-ray diffraction (Table 4) shows that the fractures are mostly filled by crystalline calcite but that microcrystalline silica and clay minerals (kaolinite and illite) also occur in some samples. The matrix is usually clayey with variable amounts of iron-carbonate (mostly siderite) and/or silica cements, having a texture very similar to the sideritic (iron-carbonate) concretions.

The origin of both types of concretions results directly from a diagenetic environment with a reducing condition.

Special conditions are necessary for siderite formation. These conditions are low Eh, high pCO_2, a pH of about 6-8, negligible sulfide ions present, and an Fe^{++} ion concentration much higher than seawater. Such conditions are usually only developed in nonmarine environments, and siderite is normally found only in freshwater sediments. The low Eh can be related to the presence of organic matter and its anaerobic decay. Freshwater environments have much lower sulfate concentrations, and rapid burial by sediments may also inhibit sulfate diffusion, or the reduction of sulfate to sulfide, a necessary requisite for the deposition of siderite (Brounslow, 1979).

3.4 Limestone lithofacies

Limestones are widespread and highly variable in the sections studied, forming on average 16% of the sedimentary package (Fig. 5). This figure includes calcareous cemented sandstones, calcareous-marly mudrocks and the local calcareous interstratifications observed in the sandstone/mudstone interstratified lithofacies.

The limestone bodies can be subdivided into five main sublithofacies. These are, in order of decreasing importance:

- algal laminites and stromatolites (i.e., horizontally algal laminated and domal stromatolites and oncolites);
- interstratifed mudstone to packstone;
- nodular calcrete;
- conglomeratic/breccia limestone;
- massive microgranular limestones.

The location, thickness and distribution of some beds from these subfacies are given in Table 5.

Most of the limestone units in the Sydney area are tabular and extensive, but others are more lenticular and of local extent. They range in thickness from 10 cm to several m. Individual limestone bodies grade laterally into and/or intertongue with other rock types (especially the finer clastic lithofacies). Limestone bodies exhibit sharp to gradational lower contacts. The upper contact is commonly sharp. The intergradational relationship with the underlying rock is indicated by the presence in many limestone units of a nodular basal bed (or beds). Limestones underlying coal seams are usually separated from the coal by a rooted underclay whose basal part is commonly calcareous. Limestone interbedded with or overlying coal seams is carbonaceous and commonly highly fossiliferous (ostracods, Naiadites, minor fish fragments).

The limestone units comprise from 1 to 20 individual beds, ranging in thickness from several cm to 1.0 m and averaging 20-40 cm. The beds are separated by thin units (1-10 cm) of marlstone, mudstone or claystone. Some of the limestone bodies have been correlated through several sections, but correlation of individual beds is not possible.

Structures within limestone bodies commonly differ from bed to bed. A single bed may be in part structureless, laminated or both. Lamination is the most common structure present, with a great variety of types and shapes observed, including horizontal, slightly wavy to wavy, irregular and continuous to discontinuous. Small-scale microfractures, some offsetting laminations, bioturbation, burrows and pellets are the other common structures present.

The fabric of most limestones is a combination of a microcrystalline calcite matrix (micrite) and varying amounts of particles (skeletal, mud clasts, organic, etc.) that range from clay size to rock fragments up to several cm in diameter. Totally crystalline limestone, although present, is of lesser importance, while conglomeratic beds are locally prominent.

The carbonate rocks of the Sydney area are combinations of calcite, minor dolomitic rhombs and a variety of detrital minerals and rock fragments. A study of 133 limestone samples representing each of the subfacies units listed shows that micrite and clay-sized calcareous content varies from 20 to 50% and dolomite from a trace to 5%. Dolomite content increases upward within limestone units, in which middle and basal beds commonly show very little to no trace of dolomite. Phosphatic material (fish scales and bone fragments) is important locally and will be discussed in section 3.4.6 and in Chapter 5.

The fine to very fine sandy and silt-sized detrital particles are largely quartz, but include pyrite, feldspar, mica, and carbonaceous material. The general mineral composition of the clay-sized fraction, as determined by X-ray diffraction, comprises in order of decreasing abundance quartz, mica, kaolinite, illite, chlorite, pyrite and minor amounts of plagioclase and potash feldspar. Siderite and hematite were identified in the more ferruginous (red-purple stain) samples. Other mineral substances found in small amounts are calcium sulphates and organic matter in various stages of degradation.

The sedimentology and environment of deposition for each of the subfacies and fossil content will be discussed in Chapter 5.

3.4.1 Algal laminites and stromatolitic limestones

Algal limestones occur at various stratigraphic levels in all sections measured around the coast, with the exception of the Schooner Head and the South and North Morien sections, in the easternmost part of the basin (Masson and Rust, 1983). Two types were recognised: horizontally laminated units and laterally linked domal stromatolites with local oncolites. The first type occurs preferentially as tabular sheet-like interbeds capping coal seams but also as interbeds within tabular bodies enclosed by marlstones and mudstones. The latter type occurs as encrustations on oncolitic units and was observed only in unit NW-73 of the New Waterford section (Appendix A, Fig. 2B-179 m and Fig. 4 of Masson and Rust, 1983). The two types distinguished on the basis of these gross morphological characteristics have similar microstructures, but the horizontal forms contain a more abundant shelly fauna than the domal stromatolites. A variant of the horizontally laminated type has isolated domes within an otherwise horizontally laminated unit.

• Horizontally algal-laminated limestone: These algal units have a prominent subhorizontal layering that varies in thickness from 0.2 mm to a little over 1 cm (Plate 5A). The tabular-sheet individual beds range in thickness from several cm to 40 cm. Separated by very thin to thin beds of muddy material, they can form limestone bodies up to 1.5-2.0 m thick. The laminae vary in sharpness of definition and show no obvious cyclicity. Their algal origin is indicated by the presence of variably preserved filaments, disrupted algal remnants and rolled-up algal mud lumps. Variable algal growth rates and differential diagenetic calcification are probably the main factors in the development and preservation of lamination and filaments. The laminae are mostly composed of micrite and exhibit varying degrees of calcification and recrystallization, as indicated by sparite and microsparite contents. They are commonly horizontal, but gently wavy forms are also prominent, and contortion due to compaction and diagenesis is locally distinct. Quartz silt, very fine sand, local pyrite and hematite commonly are concentrated within specific layers, varying individually in abundance from 1 to 7%.

Fossiliferous material varies greatly in abundance. Some layers are composed almost entirely of fossil material, mainly thin-shelled ostracods, but also algal remnants, thin-shelled gastropods, serpulid worm tubes, bivalves, fish fragments, pellets, and burrows. Organic material is extensive and comprises much of the interlaminations present. The high degree of compaction hinders identification of the ostracods, but they are probably the species Carbonita inflata and C. scalpellus, identified by Copeland (1957) from the upper Morien Group in the Sydney Basin. Ostracods of this genus are known to characterise non-marine deposits in the Carboniferous of North America and Europe (Bless and Pollard, 1972; Bless and Massa, 1982). Other non-marine elements in the biota are teeth, scales, and bone fragments of freshwater sharks (pleuracanths) and fishes, acanthodians, and palaeoniscids, thin-shelled gastropods and bivalves, and acritarchs. They clearly indicate that the limestones were deposited in a freshwater, not a marine, environment (Masson and Rust, 1984).

Ostracod abundance tends to increase upward within individual algal units of the Sydney Basin, whereas gastropod and bivalve contents are more localised, showing no general trend. Grazing of algae by ostracods (Osborne et al., 1982, p.58) was probably a factor in establishing their periodic increase in abundance. The paleoecologic balance was modified from time to time by localised but abrupt molluscan incursions. These faunal changes must have influenced the types of carbonate grains embedded in the algal mats, as did other environmental factors such as turbulence.

• Domal stromatolites and oncolites: The domal stromatolites from unit NW-73 (Appendix A, Fig. 2, 177-180 m) in the New Waterford section occur as encrustations on oncolites. The domes are mostly symmetrical, vary in diameter from 1 to 10 cm, and are up to 5 cm high. They have a columnar internal structure (Plate 5B), with individual columns rarely exceeding a few mm in diameter and several cm in length. Most are vertical, but a few are slightly inclined. They contain crinkled laminae in which the principal convexities are in the growth direction. The shapes of the laminae are reflected in the shape of the outer surface of the entire algal body. The shelly fossils in the domal stromatolites are the same as those in the algal laminites but are much less abundant; they are limited to a few fragments in the cores of some of the domes and serve as interdomal fillings. Algal fragments are also present. Most are too "sparitized" to be identified, but forms resembling Girvanella, Garwoodia, and Ortonella were identified among those responsible for the algal build-up (B. Mamet, personal communication 1983).

The domal stromatolites in the New Waterford section closely resemble the blue-green alga Gouldina (Johnson, 1963). This genus is characterised by rounded colonies consisting of laminae that are gently domed and undulating in the basal portion. The morphology becomes increasingly irregular with greater size, forming mammillary projections in the outer area. In most cases these projections show a well-defined external bulbous shape but little or no microstructure.

Most oncoids underlying the domal stromatolites are nearly spherical, but some approximate flattened spheroids (Plate 5C). Individually they range from several mm up to 5 cm in diameter but they also occur as larger composite clusters. They have been subjected to disruption and compaction, as evidenced by flattening and tilting, so that the long axes of some are vertical. Internally, the oncoids display smooth concentric laminae, which become more crinkled, less well defined, and thicker toward the outside. The laminae enclose a nucleus of rock and/or shell fragments, mud clasts, and hematitic grains, some with coarse-grained calcite cement.

Microscopically, the stromatolites show extensive sparitization, especially of laminae within the domes, in which all features except the laminae have been destroyed or altered by diagenesis. Dolomite rhombs are scattered randomly within the laminae. Carbonate intraclasts, penecontemporaneous dolomite rhombs, isolated ooliths, pelleted mud lumps, ostracod and gastropod shells, acritarchs and fish fragments are contained within the sparry calcite cement filling the interdomal areas. These ooliths range from 0.25 to 1.5 mm in diameter and show a nucleus of variable nature (shell fragments, quartz grains, peloids, etc.) surrounded by several concentric layers. Staining shows that they are formed almost entirely of calcite.

The domal forms are separated from the oncoids by a thin zone of irregular, wavy micritic laminae with a high-hematite content. Hematite replacement does not occur in the stromatolites but is extensive in the oncoids, entirely replacing several of the concentric laminae and in some cases acting as a nucleus for other oncoids. Hematite replacement was probably caused by reaction with iron-rich waters in an oxidizing freshwater environment, whereas in the reducing coal-swamp environment, similar waters precipitated siderite nodules.

The occurrence of the domal stromatolites as encrustations on oncolites is similar to those described by Schäfer and Stapf (1978) from the Permian Saar-Nahe Basin and ascribed to lacustrine deposition. Other similarities are the intense sparitization and the size and form of the domal stromatolites, although the Saar-Nahe oncoids are somewhat smaller than those of the Sydney Basin.

In Walker Lake, Nevada, modern domal stromatolites form on algal-encrusted pebbles (Osborne et al., 1982). Pebbles are abundant in this lake, and once encrusted, they act as a suitable substrate for upward growth of domal forms, playing a role equivalent to the oncoids in the Sydney and Saar-Nahe basins.

3.4.2 Interstratified mudstone to packstone

The horizontally laminated mudstone to packstone subfacies is characterised by prominent layering, with thickness ranging from a few mm to a few cm (Plate 6). Interstratification of well- (to moderately well-) defined individual beds of alternating calcareous mudstone, wackestone and/or packstone with well-defined individual laminae of different composition (mainly carbonaceous shales or silty mudstones and shales) is the most characteristic feature of this subfacies. The absence of algal remnants is a major difference from the algal laminite subfacies. In thicker sequences both are locally interbedded.

The laminae are generally composed of micritic mud exhibiting various degrees of calcification and variable percentages of recrystallization (i.e., microsparite to sparite content). Some layers are almost entirely composed of skeletal debris, which is totally absent from others. Stratification is mostly horizontally continuous to discontinuous, uneven parallel to slightly wavy to wavy, or discontinuous-uneven parallel to non-parallel. Strata vary in thickness from a few mm to 40 cm. These complexly interstratified units exhibit no apparent cyclicity. Locally they are highly contorted and disrupted by compaction. Microfractures (with pyritic, calcitic or organic filling), stylolites and "cone-in-cone structures" are also present.

The percentage of mud and skeletal material varies from 10 to 80% and their relationship is roughly inversely proportional. Quartz content, in the form of silt or disseminated fine to very fine sand grains, ranges from 1 to 7% and is usually concentrated in specific layers. Mica, hematite and disseminated dolomite rhombs are also present. The coarser detrital material comprises, in order of decreasing importance, skeletal debris; roots, woody and plant material; mud clast pellets and burrows in the more muddy units and teeth, scales and bone fragments of freshwater sharks (pleuracanths) and acanthodian and paleoniscid fishes (Masson and Rust, 1984).

The associated fauna is similar to that described for the algal laminites. It is particularly rich in ostracods, but bivalves, thin-shelled gastropods and serpulid worm tubes are locally important. Packstone beds are mostly composed of ostracod shells with variable amounts of gastropods and coarse bivalve debris subjected to a high degree of compaction, deformation, dissolution and cementation. As in the algal laminite subfacies, upward variation in the skeletal content suggests local infestation by ostracods modified by occasional abrupt mollusk incursions.

3.4.3 Nodular calcrete

Paleosols containing horizons of pedogenic calcium carbonate are numerous in the Sydney coalfield. They are important for paleoclimatic and paleogeomorphic reconstructions (Allen, 1974; Hubert, 1978; Wright, 1980).

The units are mostly enclosed by, and grade laterally into, mudstones locally associated with laminated siltstones and rarely with sandstones. They form tabular beds (lenticular when laterally persistent), ranging in thickness from 50 cm to 2.5 m (Plate 7A). The lower contacts are gradational, whereas the upper contacts are sharp. The beds comprise scarce to common, irregular shaped to rounded nodules (i.e., glaebules of Allen, 1974) scattered through a clayey-mud matrix (Plate 7A). The nodules constitute up to 80% by volume of the units in which they occur but are commonly 20-60%. The highest nodule densities usually occur in the middle and toward the top of the beds. There is a gradual upward increase in the size and density of the nodules and a corresponding decrease in the amount of the host matrix. The individual nodules vary from a few mm up to 5 cm across and most have sharp boundaries with the host material (Plate 7B). Larger nodules formed by coalescing and compounding of several smaller nodules generally show a faint elongation normal to bedding. X-ray diffraction shows that they are chiefly composed of calcite (locally a mixture of calcite, siderite/ankerite and dolomite), with kaolinite and minor illite, siderite, quartz and hematite (Table 4).

The internal fabric is a complex network of branching and cross-cutting tubes several mm in diameter and several cm long. Some are infilled with silt, others with sparry calcite or a mixture of calcite and disseminated dolorhombs (Plate 7B). The clay matrix is soft and exhibits great variation in colours (light greenish-grey to mottled reddish-purple-green to brownish-grey). The clays contain quartz silt (5-35%) and hematite (up to 20%) in the mottled purple type.

3.4.4 Conglomeratic/breccia limestone

Beds of this subfacies range in thickness from 60 cm to 2.0 m and are composed of a chaotic assemblage of large brecciated clasts in a mudstone matrix. The units commonly wedge laterally into non-conglomeratic fine-clastic units. Where laterally continuous they form tabular bodies locally exhibiting greater concentration of coarser-size clasts lacking internal stratification. All beds are poorly sorted but locally a slight coarsening upward trend is present (Plate 8A).

The contacts between the conglomeratic and the enclosing non-conglomeratic units are commonly irregular in outline. In most cases the lower contact is sharp and erosional and the upper contact is sharp, with an abrupt drop in the coarse clast content.

The fragments are subrounded to angular, range in length from 1 mm to 10 cm, and comprise 30 to 80% of the units, the remainder being a host mud matrix exhibiting variation in silt and calcareous content (Plate 8A,B). The more rounded fragments (Plate 8B) probably were transported a greater distance from their source. The lithic fragments are almost entirely of limestone and most can be matched with limestone in underlying and/or laterally adjacent parts of the bed. Preferred clast orientation is lacking (Plate 8A).

Besides microfractures filled with microcrystalline silica or clay cement (Plate 8A), very few structural features are present in this subfacies.

3.4.5 Massive, microgranular limestone

The massive, microgranular limestone subfacies is less common than the other subfacies. It occurs as massive, tabular, laterally continuous beds (5-40 cm thick), exhibiting sharp lower and upper contacts. It is composed of 90-100% microcrystalline-microgranular calcareous mud and is highly recrystallized. Other components are localised and slightly shaly, silty and/or carbonaceous interlaminations and minor concentrations of compacted but well-preserved ostracod shells or calcareous mud clasts (subrounded, less than 5 mm in diameter). Besides the faint discontinuous horizontal laminae and irregular late diagenetic microfractures, this subfacies is structureless.

3.4.6 Fossil content

In addition to the fossil assemblages previously described with the individual lithofacies, one indicator of nonmarine origin is the presence in the limestones of teeth and skeletal fragments of freshwater sharks (xenacanthids) and of various associated fish remains. Samples (approximately 1200 g each) from the Sydney Mines Formation east of Sydney Harbour were collected from the limestone beds located at Victoria Mines section, interval 2-3 m, and at the New Waterford section, intervals 108-110 m, 128-130 m and 178-180 m (oncolitic beds). The locations where these units crop out on the coast are all within the floral zone of Ptychocarpus unitus (Bell, 1938). The samples were digested in dilute acetic acid; this yielded a fauna whose distribution is given for each limestone unit in Table 6, indicating that interunit differences are not significant. Systematic measurements for the purposes of taxonomic definition were not made.

The fish remains occur in two lithologies. The first is a black to dark grey, carbonaceous, calcareous shale or siltstone closely associated with coal. Units of this lithology contain relatively few elasmobranch remains, generally less than 1-2%, but in some cases up to 5%. In contrast, they have abundant bone fragments, scales, teeth, and spines of osteichthyan (bony) fishes, in a few cases filled or coated with pyrite. These bony fish fragments occur with coprolitic material, ostracods (Carbonicella type), nonmarine bivalves, and Spirorbis tubes.

The second fish-bearing lithology is massive limestone, interbedded with algal laminites, and in one case with a domal stromatolite-oncolite unit (Masson and Rust, 1983). Units of this lithology contain abundant bony fish fragments and are the most productive, both in amount and diversity, of shark remains. The associated invertebrate fauna is widespread, of low diversity and of a nonmarine nature. Ostracods (Carbonita inflata and C. scalpellus) are particularly abundant. Nonmarine bivalves (Naiadites) and thin-shelled gastropods are also present. Algal remains, serpulid worm tubes, pellets, burrows and woody plant material also characterize these limestones.

The relative paucity of shark fragments in the carbonaceous units is attributed to paleoecological rather than sedimentary factors. There is little or no reason to suppose that wave or current action could discriminate between shark and bony fish fragments, and in any case the shallow depth would have minimized current and wave energy. It is concluded that the virtual exclusion of shark remains from carbonaceous remains is due to the sharks' preference for the environment in which massive limestone was deposited.

Description of fish microfauna

• Xenacanthid teeth - Most of the xenacanthid teeth collected are well preserved. Each consists of two lateral and a smaller central cusp, set on a basal tubercle (Plate 9, Figs. 1-3). In most cases the base of the tooth is intact; but one or all of the terminal parts of the cusps are damaged. The teeth differ in minor details, including absolute or overall size, but have similar ornamentation labially and anteriorly. The basal width and the height from the basal tubercle to the end of the lateral cusps range from 0.3 to 3.5 mm.

The principal cusps are commonly rounded or compressed in section and have smooth surfaces (Plate 9, Figs. 1-3). These surfaces are parallel and rise nearly straight from the base, diverging slightly upward and outward from the root (Plate 9, Fig. 3). In some specimens the cusps have a more pronounced curvature and some degree of compression in the basal part (the "compressus" type). In all cases where central cusps are present they are smaller and more slender than lateral cusps and are best preserved in the smaller teeth. Their length exceeds one-third the length of the lateral cusps in smaller teeth, generally increasing in relative size in larger teeth to half that of the lateral cusps (Plate 9, Fig. 3).

• Scales and dermal denticles (elasmobranch) - Dermal denticles and scales are the most abundant of the elasmobranch shark materials obtained (Table 6). Several examples belonging to the xenacanthid, ctenacanthid and hybodontid families were recognised, with xenacanthid fragments by far the most numerous. Numerous mucous membrane denticles were also recovered (Plate 9, Fig. 4).

The denticles and scales can be divided into two groups, the cuspidate and the crown-platform (Reif, 1978). Generally, in the cuspidate group a long central cusp is curved in a dorsal posterior direction and exhibits strong to moderate ribbing (Plate 9, Fig. 7). These ribs are curved backward and may exhibit secondary cusps, also ribbed, which are commonly shorter than the main central cusp (Plate 9, Fig. 7). A neck region separates the base from the cusps. The cusp assemblage is either single or compound, that is, associated with similar cusps attached to a common ridgelike base (Plate 9, Fig. 8). The cuspidate tooth is more prominent in the xenacanthid and hybodontid families (Reif, 1978).

In the platform group the crown forms a flat surface, with ribs at its lateral margin. The crown is thin, with basal-apical ridges on its anterior side and a smooth posterior side. A well-developed neck region is commonly present, as is a thin, strongly concave basal plate. The platform group is more characteristic of the ctenacanthids than of other families (Reif, 1978).

- Acanthodian fragments - Acanthodian remains are mostly spine fragments, with scales and pieces of dermal material also present.
- Osteichthyan fragments - Fragments of bony fish are the most abundant in Sydney Mines Formation limestones (Table 6) and show the greatest diversity. They are the most difficult to identify because the diagnostic parts are commonly fragmented. A great variety of individual teeth (with or without preserved bases), bone fragments, scales and dermal plates (with preserved internal network) are abundant in each unit studied. Tentative identification and classification are based on the most complete and best preserved specimens.

Several small jaw fragments of the genus Sagenodus were recovered. They have rows of denticles on a simple, flat bony plate with a well-developed central ridge. Each row consists of three to five cusps, each being almost double the size of the denticle mesial to it. Fragments of jaws from small lungfish of the genus Monongahela have been found in each unit (Plate 9, Fig. 5). These jaw elements vary in width from 1 to 3 mm and have flattened cusps numbering three to six along the axes of several ridges. The ridges, of which there are usually less than three per fragment, show a growth pattern in which all the ridges radiate from a common point (Plate 9, Fig. 5).

Tiny vomerine teeth, also attributed to the genus Monongahela (Plate 9, Fig. 6) have been found in each unit. They are bladelike, slightly convex anteriorly, and grew laterally by addition of successively larger cusps, which are serrated along their mesial edges.

3.5 Coal lithofacies

The sequence of the main seams in the upper Morien Group, as well as their average thicknesses, are shown in Table 1. The main coal seams vary in thickness, where exposed, from 1.0 to 4.5 m. In addition there are numerous minor coals (i.e., carbonaceous shale to shaly coal bands) throughout the basin. Because of physical and chemical weathering by sea water, coal from coastal seam exposures is not suitable for petrographic and chemical analysis of the coal components. Abandoned mine workings and bootlegging of numerous seams by the local population makes a coastal study of the lateral variation of the main seams unfeasible. Fortunately, Hacquebard and Donaldson's (1969) data based on mine sampling can fill this deficiency.

3.5.1 Coal seams in coastal exposures

Careful examination of the coastal coal exposures, when cleared of surficial weathering products, reveals most of the characteristics observed underground. Most seams consist of normal-banded (bright-dull alternations) humic coals (Plate 10A,B) in which most of the megascopic coal types are present in greatly varying proportions. The predominant lithotype relation appears to be that of clarain with interstratified vitrain bands. Bands of durain and clarodurain are recognisable but are considerably less abundant.

Fusain is more prominent in the minor seams. In the main seams, fusain appears to be a variable component of minor importance.

Horizontal and vertical cleats (Plate 10B) coated with mineral matter are one of the most important and widespread physical characteristics. The visible mineral matter consists mostly of pyrite, clay minerals and quartz grains. With the exception of pyrite, the mineral constituents occur in minor amounts and only reach higher percentages in roof and bench coal and in the more detrital thin layers of splint or coal-bearing shale. The presence of thin to very thin clay layers (Plate 10B) (composed mostly of kaolinite with variable silt content) can be attributed to transport of kaolinite into the coal basin from supply areas, or to diagenetic conversion of detrital hydromicas to kaolinite. The low silt and ash content (4.5-11.5%, Hacquebard and Donaldson, 1969) suggests that little detrital material entered the peat swamps.

The diagnostic petrographic features of coal (including relative abundance of the macerals, their mode of preservation and the distribution of mineral matter) are summarized in Table 7, from Hacquebard and Donaldson (1969). Vitrinite predominates and inertinite and fusinite are lower and variable. Rank of the coal is "high volatile bituminous A." The coal has moderate fluidity characteristics and an average reflectance, R_o max., of 0.83%.

The amount of sulphur (mostly pyrite) varies considerably (trace to 15%) within each seam both vertically and laterally. In general, the greatest concentrations occur in the bench and roof coals and where cleating is best developed. Regional variation in the sulphur content of seams continuous through several sections has also been observed. Pyrite is present as fine to very fine disseminated grains in coal and in some cases in the associated kaolinite and as coating of the cleated surfaces. Hacquebard and Avery (1982) showed that pyritic sulphur in the Harbour Seam in the Donkin Reserve area is the main contributor to the total sulphur content, composing from 62 to 92% of the total amount. Residual sulphur (total sulphur - pyritic sulphur) is mostly organic sulphur, but it also includes sulphate sulphur and at least some pyritic sulphur derived from extremely finely divided pyrite (particles ≤ 1 micron in size).

Table 8 lists the location of all the measured coal sections greater than 40 cm thick and the nature of the underlying and overlying units.

3.5.2 Seatearths

The literature abounds in descriptions of seatearths or underclays. Table 8 shows that the units underlying coals in the Sydney coalfield are, in order of decreasing importance: 1)shaly carbonaceous rooted zones; 2)rooted zones with sideritic nodules at the base; 3)tabular interstratified sandstone/siltstone; 4)rippled sandstone and siltstone; and 5)siliceous "ganister" type bodies. It is important to note that even in the case of 3, 4 and 5 a very thin to thin (1-6 cm thick) rooted layer separates these units from the coal.

The underclays of the upper Morien Group are typically grey in colour, fine-grained, and traversed by abundant carbonaceous-coated fossil rootlets (rhizoliths of Klappa, 1980) and slickensided surfaces (Plate 11A). They occur as irregular lenses forming discontinuous beds. The shape of these clay deposits is indicative of swamp accumulation. Silty to very fine sandy, isolated calcite cemented pockets are present locally (Plate 11B).

The rhizoliths of the upper Morien Group are commonly cylindrical and vary in length from a few cm to 1.5 m. The best preserved fossil roots are compressed into very thin carbonaceous ribbons cutting the rocks at all angles, but they commonly occur as vertical, isolated or branching structures or as ramifying horizontal networks. In some cases the carbonaceous film has been lost and only obscure impressions remain (Plate 11A). Where underlain by sandy units, the roots invariably disturb the upper part of these beds.

The lack of bedding in the underclays is chiefly due to churning of the substratum by plant roots (Plate 11A,B). Compression of stigmarian roots results in a reduction in volume of more than 80% (Huddle and Patterson, 1961). That this is at least a contributing factor to the unbedded character of seatearths is indicated by the downward gradation from unbedded to slightly bedded material. Deformation due to loading and compaction due to dewatering can also erase traces of bedding (Huddle and Patterson, 1961).

In addition to these carbonaceous root imprints, two other basic types of rhizoliths are recognised in the Sydney Basin. These are root casts and rhizocretions. These forms commonly occur in various combinations or as individuals. Root casts are fillings of root moulds, either by sediment or cement or both. Most of the time the filling sediment is fine-clastic material but siderite, calcite and/or microcrystalline silica cement are also important locally. The term rhizocretion is used here to describe pedodiagenetic accumulations of mineral matter around roots, commonly calcite and siderite. Some rhizoconcretions are well defined, but most are loosely cemented pockets rather than well-defined nodular features (Plate 11B). Fibrous roots, together with weakly cemented sand-sized grains or lithoclasts, commonly occupy the central or axial part of the rhizocretion.

Imprints and ridges marking the position of earlier roots are also imprinted on some concretions.

The geological significance and origin of seatearths have been variously explained. The autochthonous theory, most completely documented by Huddle and Patterson (1961), holds that seatearths acquired their characteristics in a water-logged swamp environment. Plant roots and long-continued leaching by acid swamp waters were the major modifying influences on the previously unaltered sediment. The allochthonous theory, proposed by Grim and Allen (1938) and Schultz (1958), suggests that seatearths are made up of materials that have been altered but originated outside the depositional basin.

Acceptable evidence for the pedogenic nature of seatearths includes the presence of fossil roots, concentration of iron and calcium in concretions (rhizocretions) or cracks near the base, and a mineralogy resembling modern water-logged soil (Huddle and Patterson, 1961). Lack of bedding and slickensides are suggestive but not conclusive evidence; the latter may be due to compaction resulting from various causes. The presence of fossil roots and other forms of rhizoliths in the seatearths of the upper Morien Group provide diagnostic criteria that indicate terrestrial conditions (paleosols) related to a water-logged swamp environment. This is strong evidence for the autochthonous origin of the overlying coals.

Fine, even grained, seatearth sandstones consisting of closely packed, subangular quartz grains cemented by silica and containing abundant traces of rootlets are a minor feature in the upper Morien Group but have nevertheless been observed at several locations (Table 8). Siliceous sandstones of this type have been termed "ganisters" by several workers (Huddle and Patterson, 1961; Hemingway, 1968; Retallack, 1976; Percival, 1983). These authors concluded that ganisters form by silica enrichment due to leaching in a paleosol profile, and the term has attained genetic significance. Williamson (1967), Smale (1973), Watts (1978) and Percival (1983) state that to classify as a ganister the sandstone should consist of at least 95% quartz. Ganisters are differentiated from silcrete by a lack of abundant opaline or cryptocrystalline silica cement, a fine to medium grain size and moderately well-sorted grain-supported fabric and a lack of evidence for near-surface cementation.

The Sydney quartz arenites have most of the criteria characteristic of ganisters. These are:

1) The presence in the upper part of roots and rootlets, which decrease in abundance with depth.

2) The presence of moderately well-developed paleosol profiles in which the quartz arenite exhibits a carbonaceous top that is commonly overlain by a thin coal bed. The quartz arenite is underlain by a clayey zone.

3) A sharp to moderately transitional basal contact of the quartz arenite. This contact is usually irregular in outline, but not as a result of loading.

4) Absence of sedimentary structures, due to destruction by root bioturbation and leaching.

5) The quartz arenite units are commonly thin, less than 80 cm, but up to 1.5 m at one location.

6) Lateral variations in the thickness of the quartz arenite horizons are due to the irregular basal contact.

7) The absence of any marine fauna in the quartz arenite.

8) Lack of features indicative of high energy reworking such as well-rounded and well-sorted grains.

In the Sydney Basin each quartz arenite unit is underlain by a clayey zone. The vertical and lateral changes in the lithology of the quartzose unit due to variations in leaching were not investigated because of the general weathering on the outcrop.

The lack of sedimentary structures, the presence of rootlets and an irregular basal contact, the ≥ 95% fine medium size quartz content, and the absence of features indicative of silcretes are sufficient to diagnose a pedogenic origin and classify these rocks as ganisters (Percival, 1983).

3.5.3 Units overlying coals (roof rocks)

Roof rocks in the upper Morien Group (listed in Table 8) exhibit greater diversity than do seatearths. In order of decreasing importance they are:

• Carbonaceous shale interstratified with coal, silty shale and/or muddy material (Plate 12A), forms 45% of the roof rocks. Commonly rich in plant imprints and fragments, this lithology is also characterised by an increase in sand and silt content, as well as gentle rippling, upward and away from the coal. This represents fluctuation and periodic influx of sediments over the swamp environment transported by more oxygenated water. The upward increase of detrital material indicates return to fluvial influence on the floodplain.

• Interstratified skeletal (mostly ostracod), carbonaceous limestones and variable calcareous to non-calcareous carbonaceous shaly units, form 20% of the roof rocks. Plant fragments are locally abundant, but silty and sandy material is of minor importance. These units represent the establishment of shallow water bodies (possibly ponds), with fluctuating water conditions, in the swamp environment.

• Coarsening upward, horizontally laminated and rippled, very fine to medium, micaceous sandstone, forms 20% of the roof rocks (Plate 12B). The sandstones are interstratified with silty shale or mudstone and are attributed to migration over the swamp of crevasse-splay bodies related to a return of fluvially influenced conditions.

• Coarse to medium sandstone fining upward to fine to very fine silty sandstone, forms 15% of the roof rock units. Structures change upward from trough cross-bedded at the bottom to trough cross-laminated at the top (Plate 12C). These strata represent filling of paleochannels that migrated into the swamp environment, eroding all material overlying the coal seams. The coal seams were not affected, because of the high resistance to erosion of fibrous peat.

3.5.4 Fossil content

Plant material is widespread and abundant in all the roof rocks listed above, attesting to the prodigious plant growth that took place. The greatest concentration and diversity of plant material occur in the carbonaceous shale with coal, silty shale and/or mudrock interstratifications. Most are unidentifiable fragments of partially coalified leaves, stems, branches and roots but tilted and upright tree trunks (Plate 13A,B) are also present in the sandy units. Partially identifiable debris included:

• upright and flattened trunks of *Sigillaria* (Plate 13A), *Lepidodendron* and *Calamites* (Plate 13B), with variable preservation of surficial bark imprint;

• unsorted fragments from pinnae, pinnules and stems from the following trees, plants and roots: *Asterophyllites*, *Alethopteris*, *Calamites*, *Cordaites*, *Lepidodendron*, Lycopods, *Neuropteris*, *Pecopteris*, *Ptychocarpus*, *Sphenophyllum*, *Stigmaria*;

• megaspores from Alethopteris, Calamites, Neuropteris and Lepidodendron.

In general, the coal seams were formed mainly by lycopods (Lepidodendron, Sigillaria), with Cordaites (gymnospermous trees) and Calamites (horsetails, e.g., Asterophyllites). Most of the overshale floras are rich in foliage of tree ferns (e.g., Alethopteris, Linopteris, Neuropteris, Odontopteris, Pecopteris, Ptychocarpus and Sphenopteris). Their exact provenance and derivation, in terms of location in swamp environment, is highly speculative and subjective (i.e., depending entirely on the interpretation of the coal-swamp depositional environment) and will not be attempted here. Relationships between coal types and swamp environments have been well demonstrated by the studies of Teichmuller and Teichmuller (1966), Hacquebard et al. (1965) and Hacquebard and Donaldson (1969). The ecology of coal measure floras and plant assemblages has received wide attention in the literature by numerous authors (Murchison and Westoll, 1968; Krassilov, 1969; Peppers and Pfefferkorn, 1970; Peppers and Phillips, 1972; Phillips et al., 1974; and Scott, 1977, 1978, 1979). A review and discussion of their findings is beyond the scope of this study.

No pollen work was undertaken as part of this study, but extensive palynological studies of coal and clastic sediments by Hacquebard (1961), Barss et al. (1963) and Barss and Hacquebard (1967) in the Pictou Group of the Maritime Provinces have shown the presence of five zones, each characterised by a distinctive assemblage of miospores. These zones -- the Vittatina, Potonieisporites, Thymospora, Torispora, and Vestispora zones -- represent Lower Permian, Stephanian and Westphalian C-D ages. Barss and Hacquebard (1967) recognised the lower three of these spore zones in the Morien Group (Table 2).

3.6 Summary: environmental interpretation

The facies assemblage of the upper Morien Group can be grouped into or assigned to deposition on an alluvial plain. From time to time, particularly toward the end of Morien Group deposition, depressions on the floodplain gave rise to extensive peat swamps or to lakes (depending on subsidence rate) in which algal stromatolites, ostracods and other organisms flourished. Locally, lacustrine delta lobe deposits were formed in those lakes. The sedimentological aspects of the alluvial plain and of the related lacustrine environments will be discussed in detail in Chapters 4 and 5.

Sydney coals originated from autochthonous plant accumulations in extensive peat swamps. Coal seams of autochthonous (in situ) origin are derived from peat, which was formed and buried where the vegetation grew. The most likely accumulation areas are the alluvial plain, with generally contributary channels. The main arguments presented in the literature (Moore, 1940; Fisk, 1960; Bennett, 1964; Hacquebard et al., 1965; and Hacquebard and Donaldson, 1969) in support of the autochthonous deposition of coal are in accord with the features observed in the coastal exposures of seams in the upper Morien Group. These features are:

1) all seams are underlain by seatearths exhibiting roots of Carboniferous plants (i.e., Stigmaria);

2) the occurrence of upright and rooted fossil trees;

3) the preservation of delicate plant debris and fragments, such as leaves and fern fronds in the overshales of many seams;

4) the wide distribution of most of the seams;

5) the relatively uniform thickness of individual coal seams over large areas;

6) the relatively minor fluctuations in ash content within and between seams (Hacquebard and Donaldson, 1969);

7) the megascopic and microscopic composition of the coal (Hacquebard and Donaldson, 1969).

CHAPTER 4. SEDIMENTOLOGY: THE ALLUVIAL-PLAIN ENVIRONMENT

4.1 Definition of depositional facies (and significance of the sedimentary structures)

From the detailed petrographic study of hand samples, thin sections and field data, eleven depositional facies have been recognised and designated as in the system outlined by Miall (1978). Their relationship with the lithofacies outlined in Chapter 3 is given in Table 9. The numerous sedimentary structures observed in the Sydney Mines Formation show great diversity and are listed with their associated depositional facies in Table 10.

The depositional facies observed in the field have roughly the same characteristics as the lithofacies and may be formally defined and summarised as follows. Examples are included in section 4.2.

The massive or crudely horizontally bedded gravel (facies Gm) is the depositional facies corresponding to the conglomeratic to very coarse quartzolithic and quartzosublithic sandstone lithofacies. This facies comprises lenticular beds of massive to crudely stratified conglomerates with a coarse sandstone matrix, which in some cases is present in sufficient quantity to produce a matrix-supported texture. The lower contact is always erosional. Included in this facies are the lag gravel deposits formed on channel floors and high-discharge, scour-and-fill deposits. This facies incorporates a great variety of non-imbricated intraformational debris (i.e., tree trunks, peat mats, plant material; intraclasts of sandstone, mudstone and shale; siderite nodules and siderite-replaced root tubes). Basal flute and groove casts can be observed at a few locations but are not a major feature of this facies. At a few locations (i.e., Donkin West and Port Morien sections) facies Gm forms local tabular units exhibiting sharp erosional contacts and slight upward-fining grading. Interstratification with thinner tabular sandy units suggests deposition during waning or fluctuating stages of flood episodes.

Facies Gm commonly grades upward into the coarse-medium quartzolithic to lithisubquartzose sandstone lithofacies. This sand is mostly trough cross stratified (facies St), mainly as medium- to coarse-grained, locally pebbly, solitary or (more commonly) grouped trough sets, up to 2 to 3 m wide, and up to 70 cm thick, but mostly less than 40 cm (Plate 14A). The base of facies St is commonly an erosional surface, and the troughs show cross-cutting relationships (Plate 14A). The bases of grouped sets (and some solitary sets) commonly have moderately well-sorted intraclast or plant lags (usually less than 5 cm). This facies commonly overlies facies Se (erosional surface) and fines upward into the medium to fine sandstone lithofacies, which is the dominant element in the smaller-sized trough cross-stratified (most commonly 10-20 cm thick) units.

The cross-stratified beds are interpreted as resulting from the migration of sinuous-crested dunes in channels under low flow regime conditions. Asymmetric downcurrent fining of foresets and the presence of regressive rippled sets locally indicate a suspended load. Small trough cross-laminated sets associated with silt layers in the upper part of some trough cross-stratified units may have been formed by minor flood currents flowing over the bar top. Isolated trough cross-stratal sets probably formed as a result of vertical flow expansion at the bar front.

Planar-tabular cross-stratified sandstone (facies Sp) is relatively uncommon in the sections studied. It occurs mostly within trough cross-stratified packages as solitary or grouped sets a few decimeters to less than one meter thick. The cross-strata are mostly composed of medium-fine quartzosublithic to lithisubquartzose sandstone capped by interstratified sandstone-siltstone and shale/mudstone. Locally the grain size can be medium to very coarse, especially at the base of the thicker Sp cosets. This facies is the result of the migration of sand waves and/or transverse bars under lower flow regime conditions. Although it is most common in sandy braided rivers, it also occurs in some parts of the meandering river environment (Walker and Cant, 1984; Bridge, 1985).

Ripple cross-laminated sandstone (Sr) is the dominant facies of the upper part of the Morien Group (zone Ptychocarpus unitus of Bell, 1938). This depositional facies comprises several of the lithofacies recognised in sections. These include an appreciable percentage of the medium-fine quartzosublithic to lithisubquartzose sandstone, most of the fine-very fine lithisubquartzose to lithiquartzose sandstone, and part of the sandstone-siltstone-shale/mudstone interstratified lithofacies.

The ripples are asymmetric, current-formed types, showing variation in size, cross-sectional shape, crestal pattern, internal structure, and vertical sequence. Most are of the small, asymmetrical current types (Reineck and Singh, 1975) and have lengths of 4-35 cm and heights up to 5 cm (i.e., Ripple Index from 5-15, but mostly 8-12). The crests are mostly undulatory, but straight and linguoid-cuspate types are locally present. Small-scale cross-stratification results from the migration of ripples (Harms et al., 1963) under lower flow regime conditions (Harms and Fahnestock, 1965). The undulatory small-scale ripples represent a transitional form between the low-energy straight-crested type and the higher-energy linguoid-cuspate type. Their crests are generally out of phase (Plate 15A), but locally in-phase undulations (Plate 15B) have been observed. Locally both types, including transitional stages, are present. The units produce cross-bedded cosets of trough shape (i.e., festoon shape) that are commonly associated with parallel horizontal lamination and primary current lineation. The tongue-shaped linguoid small ripples observed are mostly out of phase, but the in-phase cuspate variety occurs at a few locations.

These cross-stratified units resulting from the migration of small-scale current ripples (i.e., the small-ripple bedding of Reineck and Singh, 1975) commonly exhibit an erosional surface in their lower bounding surfaces. Form-concordant, form-discordant, and climbing ripples have all been observed in the upper Morien Group. Types 1 and 2 ripple-drift are locally very well developed, and related transitional forms and in-phase ripple laminae are also present locally (Jopling and Walker, 1968). Internal shapes of the laminae vary greatly, and all styles from even-continuous parallel to curved-discontinuous non-parallel are present.

Small-ripple bedding is formed under conditions where relatively little sediment is available and reworking is stronger (Reineck and Singh, 1975). In the fluvial environment this corresponds to the upper part of point bars, levees and proximal crevasse-splays. In contrast, the development of climbing-ripple lamination from ripples necessitates continual availability of supply and abundance of sediment and is favoured in environments of periodic rapid sediment accumulation (Allen, 1963; Walker, 1963; Ashley et al., 1982). The change from ripple laminae in phase to those out of phase (or a transition from straight-crested to linguoid ripples) indicates a slight but regular, progressive increase in current velocity with a decrease in depth (McKee, 1965). Jopling and Walker (1968) have interpreted the change from type 1 into type 2 as the result of a decrease in suspended-load/bed-load ratio.

The complexity of facies Sr is indicative of the fluctuation of current strengths affecting the sediments and of the wide variety of depositional settings. In the Sydney Mines Formation the following are the most notable:

1) low-energy bar tops and levees as beds interstratified with horizontally laminated siltstones and mudstones;

2) waning-flood deposits of floodplain and crevasse-splays as flat-based, tabular beds;

3) crevasse-splays as upper part of tabular coarsening-upward sequence;

4) floodplain channel deposits, as thin, sheet-like beds enclosed in floodplain sediments.

The most commonly associated sedimentary features include: vertical rootlets, convolute lamination, load structures, small vertical burrows up to 5 cm in length, and rare mottled, brown, pedogenic horizons.

Soft-sediment deformation occurs predominantly by loading of coarse-silt to fine-sand-size ranges of terrigenous floodplain (crevasse-splay) or lacustrine deposits. They are deposited contemporaneously with or follow deposition of muddy water-saturated sediments. Such structures also result from rapid deposition, liquefaction and loss of cohesion due to near surface alteration (Blatt et al., 1980; Anketell et al., 1970; and Mills, 1983). Load casts, ball-and-pillows, convolute lamination and clastic dikes have all been observed in the Sydney Mines Formation. Mills (1983) has shown that these structures and their processes of formation are not environment specific, so their diagnostic value resides mainly in defining hydrodynamic conditions, as discussed later in this chapter.

Trace fossils in the Sydney Mines Formation occur most commonly in the fine/very fine sand-mud couplets of facies Sr, Sh and Fl. Most are moderately to poorly preserved cylindrical/tabular vertical to inclined feeding burrows and trails, up to 10 mm in diameter and several cm in length, with or without clay linings and almost invariably filled with fine sand. These features are most abundant in the upper parts of fining-upward tabular beds, decreasing in abundance toward the basal part of the sets. They are rarely present in the underlying thick-bedded sandstone facies. No body fossils are preserved, but their local association with fossil root systems and floral assemblages indicates a dominantly continental assemblage (possibly similar to the modern freshwater continental assemblage comprising gastropods, bivalves, crayfish, earthworms and certain insects) (Frey, 1975).

Horizontally stratified sandstone (facies Sh) occurs sporadically throughout the sections but is abundant only locally (Plate 14B). It is composed of a wide range of sandstone and finer clastic material, and it can occur in any of the sandstone lithofacies previously described. Horizontal stratification, parting lineation and local bioturbation disrupting or destroying internal laminations are characteristic of this depositional facies. It commonly bears primary current lineation, unless bioturbated. Its well-developed parallel lamination produces a distinctive weathering character.

Three main types of horizontally laminated sandstone occur in facies Sh. These are:

1) Laminated sandstone beds exhibiting primary current lineation and occurring in association with facies Sr (Plate 14B). This suggests deposition under plane bed conditions in the upper flow regime (Harms and Fahnestock, 1965) and/or by suspension after channel abandonment or dramatic decrease of flow (Allen, 1965a).

2) Continuous laminated sandstone beds grading laterally into rippled laminated or cross-stratified sandstones and exhibiting primary current lineation and groove and tool marks on bedding surfaces (Plate 16A). The presence of these features suggests upper flow regime conditions (Allen, 1964).

3) Flat-tabular to low angle bedded and laminated to massive very fine to coarse sandstone usually ≤ 40 cm thick and bounded by siltstone and mudstone (Plate 16B). Contacts are abrupt, with the lower contact usually being planar but occasionally slightly channeled. Soft sediment deformation, bioturbation, high organic debris and mica flakes on bedding surfaces are common features. Locally, paleosols can form in the upper parts of these beds. The beds represent deposition on a floodplain. In coarsening-upward tabular sequence they are part of prograding crevasse-splay lobes. A low angle of bedding reflects unconfined sheet-flood sedimentation on a floodplain.

Facies Se is characterised by medium- to coarse-grained sandstone with a high percentage of pebbly-gravelly lithic intraclasts and organic debris including tree trunks and logs. It forms massive to crudely stratified beds forming lenticular units less than 1.5 m thick. The lower contact is always an erosional surface and it usually occurs beneath or interbedded with Gm and the coarser fraction of St facies. Internally, thin lenses (≤20 cm) of conglomeratic material are common.

This facies is formed as basal lags within fluvial channels. The erosional lower surface and the crude and massive stratification indicates rapid deposition of intraclasts and organic debris derived from eroded banks.

Siltstone, shale/mudstone interstratified with minor very fine to fine sandstone (facies Fl) is abundant in the Sydney Mines Formation. The finer-grained lithofacies (Table 9, lithofacies 4, 5 and 6) form the main components of this facies. It is usually gradational and interbedded with massive strata of similar grain size (facies Fm).

Most layers form complex sets that are interstratified on a fine scale. The sets result from migration of very small-scale ripple marks (i.e., ripple heights ⩽ 3 cm and laterally continuous up to 10 m), mostly generating wavy to broken-wavy, continuous to discontinuous, fine to very fine cross laminations. Apart from the original stratification rootlets, burrows and desiccation features are the most common features of this facies. Small burrows are usually the only evidence of animal life. Well-preserved fragments of plant stems and isolated pinnules are very rare. Finely micaceous sedimentary surfaces with comminuted plant debris, sideritic lenses, nodules and layers are widespread. Calcrete nodules and often pedogenic deposits were observed in several sections of this facies.

Facies Fl is attributed to deposition in topographically low parts of the floodplain. Facies Fl has also been observed as the filling of abandoned channels. In the present study the Fl facies definition has been enlarged to include the laminated but homogeneous shale and/or mudstone observed locally in the sections.

Most of the comments on and characteristics of facies Fl apply to facies Fm. As defined by Miall (1978), this facies occurs typically as a mudstone or siltstone covering of underlying beds, its lower surface conforming to the shape of any underlying bedform, such as a ripple train. Facies Fm usually occurs as massive mud or silt lenticles a few mm to a few cm thick. In the sections studied it is closely related to facies Fl and occurs mostly interstratified and grading into sandstone-siltstone-shale/mudstone and in the silty shale and/or mudstone-claystone lithofacies, essentially involving the silt and mud fractions of these facies. It is often located immediately below a seatearth and it may overlie most facies. Facies Fm may form sequences several meters thick.

Lamination in facies Fm is usually difficult to recognise or is absent, but it may be distinct in some layers such as muddy layers with concentration of plant material or in sandstone-rich layers affected by deformation. Ferruginous patches, grey-green and red-green mottling, dispersed sideritic features, plant rootlets and debris and desiccation cracks are common and locally well developed. Relatively structureless siltstones of variable grade form the more massive siltstone fraction of this facies. In some cases the massive nature is due to destruction of lamination by bioturbation. It is in this facies that the best preserved pinnules and fronds of Neuropteris, Alethopteris and other fern-like genera are found. Upright Lycopod trunks, standing on an underlying coal bed, have been buried and remain relatively undeformed at several locations (Plate 13).

Facies Fm is taken to represent periods of ponded water stagnation following a drop in flood-stage water level, and although it is more common in overbank floodplain deposits, it also represents deposition in well-drained and well-vegetated interdistributary (backswamp) environments (Coleman, 1966; Johnson, 1984). The thick and laterally continuous calcareous siltstone/mudstone beds, locally containing freshwater faunal debris, are lacustrine in origin.

Coal and/or carbonaceous shale (facies C) occurs throughout the upper Morien Group. It includes coal seams and associated carbonaceous shales. This depositional facies commonly overlies a rooted seatearth and is attributed to swamp deposition. The main characteristics and interpretation of this facies are discussed in section 4.7.

Non-pedogenic and fossiliferous limestone units, for which there is no suitable facies code in Miall's (1978) nomenclature, are present in the upper part of the Morien Group. They vary from essentially massive micritic limestones to well-laminated fossiliferous limestones to stromatolitic limestones. They are collectively grouped under the fossiliferous limestone depositional facies (facies Ls-f) on the basis of fossil content. This facies comprises the algal laminite and stromatolitic limestone and the mudstone-packstone interstratified limestone sublithofacies. Also included in this facies is the massive, microgranular limestone subfacies. The fossils and stromatolites are of freshwater type and the units are interpreted as pond or lake deposits.

The nodular calcrete (section 3.4.3) and the conglomeratic/breccia limestone (section 3.4.4) sublithofacies form the non-fossiliferous limestone depositional facies (facies Ls-m). This facies shows features characteristic of subaerial and/or pedogenic origin. In some cases nodules are associated with in situ alteration around plant roots (rhizoliths: Klappa, 1980), while in others they were reworked following subaerial exposure.

The main characteristics and environmental significance of features in the limestone sublithofacies (facies Ls-f and Ls-m) are discussed in section 3.4 and Chapter 5.

4.2 Selected examples of alluvial plain deposits

4.2.1 Introduction

The differentiation of alluvial sediments between vertical and lateral accretion deposits is accepted by the majority of sedimentary geologists (e.g., Fisk, 1947; Leopold and Wolman, 1957; Allen, 1965a,b). As defined by

Allen (1965a), "...lateral accretion deposits are those formed of stream bed load materials in the active channel and as the result of the lateral migration of the channel...vertical accretion deposits are all those formed on the floodplain beyond the active channel, largely through settlement from overbank floods."

Because vertical and lateral accretion processes are closely related, difficulties are encountered in a discussion totally separating the two processes (Jackson, 1975, 1978; Bridge, 1985). Examples of alluvial sediments and overbank deposits from the Sydney Mines Formation are discussed on the basis of their depositional processes and environmental relationship as observed in the typical modern meandering fluvial/floodplain model. Deposits representing four major depositional environments have been recognised and will be the basis for this discussion.

Discussion of related examples will follow the outline below:

1) Channel sandstone deposits

- point-bar fining-upward sequence
- lateral filling of channel with epsilon cross-strata
- homogeneous vertical filling of channels
- pebbly-granular sand waves/transverse bar deposit
- channel abandonment filling
    - gradual abandonment (chute cutoff)
    - abrupt abandonment (neck cutoff)

2) Overbank deposits (proximal)

- channel margin and levee deposits
- pebbly sheet splay deposits
- crevasse-splays with distributary channels

3) Floodplain deposits (well to poorly drained swamps and coals)

Each example will be described and discussed in detail following a concise and standard format including: location, setting, lithological and sedimentary structure changes and associations, accessories present, paleocurrent significance, and environmental interpretation, followed by additional comments on mechanism of formation.

Examples of limestone deposition are discussed in Chapter 5.

4.2.2 Channel sandstone deposits

The definitions of channel parameters and morphology used in this study are outlined in section 4.3.1. The channel morphology and types as well as a broad outline of the lateral extent of the channel deposits observed in the major depositional environments of the Sydney Mines Formation are discussed in section 4.3.2. In addition, the main characteristics of those streams are summarised in Table 11, values of parameters of some significant sand bodies in the New Waterford section in Table 12, and the most significant lateral extent correlations (observed in Appendix B, Figs. 1-6) in Table 13. The significance of the width/depth ratio and the parameters and influence on the stream channel system of the factors controlling these parameters are discussed in section 4.5.

The purpose of the present section is to describe in detail some examples of significant channel-fill and lateral accretion deposits observed in the Sydney Mines Formation.

4.2.2A Example 1. Point-bar fining-upward sequence

Location: Donkin West section, interval 24-28 m.

Illustrations: Appendix A, Fig. 5, interval 24-28 m; Plate 17 and Fig. 7.

Setting: total thickness of sequence is approximately 3.5-4.0 m and is laterally continuous for > 150 m as a sheet deposit formed by point-bar migration; upper contact is covered and underlying unit is a silty shale.

Lithology: sequence is 75% sandstone and 25% shale and comprises fining-upward units. Each unit ranges from 1-2 m thick and exhibits the following upward gradation:

• Basal strata have lag deposits: large-scale troughs composed of very coarse to medium quartzose sandstone with 15% lithic clasts (sedimentary and metamorphic) and 5% micaceous flakes. Cement is a mixture of clay matrix (mostly kaolinite) and locally calcareous material.

• Upper-middle strata are micaceous, fine-grained silty (salt-pepper) sandstone with organic debris and mostly kaolinitic clay (interstitial) matrix.

• Uppermost strata consist of interstratified VF-F sandstone, mudshale and clay laminations.

Structures: the most significant characteristic of this sequence is the bedform migration of units exhibiting vertical fining of even-stratal sets from trough cross-bedded in the basal unit to trough cross-laminated and finally into rippled sets upward into the middle and uppermost units. The characteristics of these various sets are from bottom to top:

• Trough cross-bedded sets: 60 cm to 1 m thick/3.5 m wide, most 60 cm thick and 1.5-2.0 m wide.

• Trough cross-laminated sets: most are 30-35 cm thick and 1.5-1.0 m wide.

• Rippled sets: ≤ 20 cm thick and composed of out-of-phase even-continuous-discontinuous wavy laminations.

Paleocurrents: toward 080° in Fig. 7 in bottom sets with variation of 030° to 050° upward into the rippled units. The dip of lateral accretion sets ranges from 7 to 10° and averages 8° in an easterly direction.

Accessories: ball-and-pillow structures, clastic dykes, small-scale faulting and micro-fracturing are observed locally in the last unit of uppermost finer material.

Interpretation: the main features of this example are the lateral migration of bedforms, the fining-upward of lithology and structures, the presence of one major erosional surface and of other minor ones and the gradational tops. These features are attributed to point-bar deposition and migration in a meandering channel in which the thalweg is overridden by point-bar deposits.

In modern point-bars, grain size decreases through the length of the bar, as does facies distribution (Jackson, 1976, 1978). The type and the scale of sedimentary structures present in this channel are a reflection of the influence of changes in hydraulic factors (which control width, depth and dip of slope) (Jackson, 1975, 1978). Presumably this example represents the downstream part of the point-bar, where the fining-upward is fully developed.

Comments: other locations at which similar point-bar sequences (analysed in similar detail but not described in this text) were observed in the Sydney Mines Formation (Appendix A) include:

Victoria Mines section, interval 38-45 m;

New Waterford section, interval 114-135 m;

New Waterford section, interval 163-174 m;

New Waterford section, interval 203-211 m;

New Waterford section, interval 256-260 m;

Glace Bay West section, interval 205-210 m;

Donkin West section, interval 114-120 m.

4.2.2B Example 2. Point-bar sequences exhibiting lateral migration and trough cross-strata with 180° divergence of direction

Location: Donkin East section, interval 72-77 m.

Illustration: Appendix A, Fig. 6, interval 72-77 m; Fig. 8.

Setting: the sequence was deposited by a laterally migrating point-bar 5 m thick and laterally continuous for 50 m. The underlying unit is covered and the overlying unit is the partially covered remnants of a (secondary) rider seam from the Backpit Seam. The entire sequence is exposed along the axis of the migration direction (west toward east) and dips into the ocean at roughly 8 to 10°. At the point where it disappears into the water it is exposed as a cross-section of trough cross-laminated sets corresponding to the topmost fining-upward sequence observed.

Lithology: the sequence is composed of 75% sandstone and 25% fine clastics and shale and is composed of several stacked fining-upward units averaging 1.5 m in thickness.

- The sandstone is mostly a light-medium grey, salt and pepper, gritty, micaceous coarse sandstone with kaolinitic matrix.

- Well-developed lag deposits (10-15 cm thick) are present in the basal troughs of each of the fining-upward beds and sets. These deposits are complex alternations of very coarse/coarse sandstone with sideritic and lithic (mostly mudclasts 2-4 cm in diameter) clasts and nodules. Sharp erosional contacts separate each of these deposits.

- The basal sandstone grades upward into horizontally bedded coarse-medium sandstone with abundant coal debris and micaceous flakes on parting planes. This unit and the previous lag deposits represent the remnant of thalweg deposition.

• The sandstone fines to medium-fine and fine-very fine in the uppermost part of the sequence (i.e., uppermost tabular rippled beds).

Structures: changes in sedimentary structures are related to grain size. In the coarser sandstone channelling and larger scale cross-bedding and horizontal bedding predominate.

A typical complete sandstone unit begins with an erosion surface containing lithic clasts followed in ascending order by large-scale cross-bedding - horizontal bedding - rippled sets - climbing ripple lamination and mud layers.

The entire sequence from bottom to top is as follows (Fig. 8):

First fining-upward cycle -

• large-scale trough cross-bedded sets 30-50 cm thick/1.5-2.0 m wide;

• horizontally bedded, homogeneous, coarse-medium sandstone bed 15-20 cm thick;

• lag deposits (15 cm thick) with lower erosional surface;

• horizontally bedded, coarse-medium sandstone 50 cm thick;

• horizontally laminated medium-fine sandstone, 20 cm thick;

Second fining-upward cycle -

• large-scale trough cross-bedded unit 20-30 cm thick with lower erosional contacts and lag deposits;

• trough cross-stratified set 50 cm thick with trough axis direction opposite to main migration direction with dip of foresets of 10-15°;

• horizontally laminated medium-fine sandstone, 30 cm thick;

• uppermost 1-1.5 m variegated rippled units: climbing in phase to slightly climbing out of phase; the transition between rippled-laminated sand

and mud layers is abrupt or gradational passing up into wavy laminated and streaked muds.

Paleocurrents: paleocurrents of fining-upward sequences are:

- basal trough cross-bedded units of first cycle: 030-210°;
- basal trough cross-bedded units of second cycle below reversed set: 045-225° with a range of 025-205° to 065-245° for the overlying trough cross-laminated units;
- trough cross-bedded units stratified reversed unit: 225-045°;
- sequence above the reversed unit: trend 050-230°.

Interpretation: the main features of this sequence are similar to those of example 1 and therefore a similar interpretation is proposed. Two major differences are: 1)the presence of horizontal strata, and 2)reversal of direction of trough cross-strata. Horizontal bedding with parting lineation is characterisitic of an upper flow regime. It is formed most commonly in shallow water, especially across the top of point-bars, where increasing flow velocities are prominent. The horizontal bedding present in this example may have formed during the flood stage with the erosional base. Deposition of upper-flow-regime horizontal beds at the falling stage (Allen, 1965a,b) followed.

The origin of the reverse-oriented trough cross-stratified set can be explained in one of two ways: 1)channel meandered across the area with 180° opposed directions; or 2)eddies occurring in the stream during an abrupt change of velocity. Either of these alternatives is possible but (1) seems to be the most likely in this example, given the wide variation in paleocurrents observed.

4.2.2C Example 3. Lateral filling of channel with epsilon cross-bedded sets.

Location: Donkin West section, interval 75-83.5 m.

Illustration: Appendix A, Fig. 5, interval 75-83.5 m; Fig. 9.

Setting: this example is an upward-fining sandstone channel body 100 m wide (exposed lateral continuity > 100 m and 9 m thick. The channel is laterally filled by trough cross-beds and exhibits well-developed epsilon cross-strata (dipping 6-12°) in the lower 1/3 to middle part of the channel. The underlying bed is a minor coal seam on a seatearth. The lower contact of the channel lies directly on the seam but does not erode into it.

Lithology: the trough cross-beds of the basal part of the channel (thalweg deposition) are formed of coarse-medium, subangular sandstone with abundant pebble-sized lithoclasts distributed throughout the lower part of the individual sets. The epsilon cross-beds are 1.5 m thick and formed by thin beds 10-20 cm thick of medium-fine sand, normally slightly rippled and separated by silty argillaceous thin beds 2-5 cm thick. An upward-fining trend is observed in the individual sets but also in the entire sequence. This is manifested by 1) decrease in mean grain size, and 2) upward increase in silt and clay content and in shaly thin beds and partings.

Structures and laminations: the sets of epsilon cross-strata average 1.5 m in thickness with dips averaging 6-12° toward 340°. In exposures roughly parallel to the dip direction of the epsilon cross-beds, the major surfaces are planar from the top to the base, and the base of each sand bed is usually sharp with signs of local erosion. The epsilon cross-beds are sigmoidal and are filled with laminae 3-7 mm thick. Mica is commonly present on bedding planes. The basal third of each epsilon sandstone unit is structureless or shows current ripples up to 5 cm thick. The dominating structure observed in the upper part of the set is cross-lamination ranging from 5-20 mm thick.

The sandstone portions of the epsilon units grade, over a few mm to 1 cm, into overlying mud parting composed of finely laminated greyish silt to silty clay with much organic debris and plant remnants. Fine tubular burrows (≤5 mm) are present locally in the silty fraction of the uppermost part of the epsilon cross-sets.

The lowermost trough cross-beds in the channel sequence transitionally grade into the overlying epsilon cross-set. These basal troughs are 60 cm to 1 m wide and 20-35 cm thick. The beds overlying the epsilon cross-beds are partially characterised by trough cross-laminated sandstone but are dominated by rippled sand similar lithologically to that in the sandstone of the epsilon cross-sets. Horizontal laminated sandstones are also present in the transition zones between these facies.

Accessories: fine plant debris and imprints, coalified fragments and fine clasts and mica on parting planes.

Paleocurrents: the channel direction (representing the thalweg channel) is 020° to 040°, while epsilon sets dip roughly 350° to 340°. Directional data from outcrop measurements of ripple foresets in the epsilon cross-set facies as well as in the underlying trough axes indicate a moderately well-defined pattern and show current direction ranging from 015-195° to 75-255°. The main river trend is roughly in a northeast direction.

Interpretation: The described sequence is believed to have originated as a result of several successive migrations of a meandering belt with avulsion taking place at 76.5 m (Fig. 9). The underlying trough cross-bedded sands were deposited contemporaneously in the basal part of the channel (thalweg). Lateral-accretion sets are commonly preserved in channel sandstones containing silty alternations and are much less common in homogeneous sandstone bodies (see Example 4).

4.2.2D Example 4. Homogeneous channel fill deposit

Location: Morien North section, interval 50-57 m.

Illustration: Appendix A, Fig. 8B, interval 50-57 m; Fig. 10 and Plate 18.

Setting: Individual channel (5 m thick and laterally continuous for > 50 m) homogeneously filled by trough cross-bedded sandstone; overlain by floodplain package and underlain by one major sequence of channel margin (ES) and tabular levee deposits; Fig. 10: interval 47-51 m and paleocurrents of level 1 and 2.

Lithology: generally fining-upward of sediments:

base of channel -- coarse to medium quartzose sandstone, salt and pepper with very coarse organic clasts and plant debris lag deposits (clasts generally ≤ 1 cm in diameter;

upward into (lower third of channel) -- medium to fine quartzose sandstone, salt and pepper, with 5 mm diameter organic fragments at the base of sets;

uppermost unit -- interlaminated fine-clastics and mudstone.

Sedimentary structures: homogeneous trough cross-bedded filling of channel exhibiting general decline upward in the scale of the cross beds and in the grain size of sandstone and no epsilon cross-strata.

- The lower 2/3 of channel (3.5 m thick) is formed of thicker and more massive trough cross-bedded units. Troughs at base are 30-50 cm thick and 2-3 m wide with lag deposits averaging 20 cm thick. These troughs form sequences averaging 1.5 m thick.

- The upper 1/3 of channel (1.5 m thick) is formed of thinner, lenticular smaller scale (20-30 cm thick, 1-2 m wide) trough cross-stratified beds with five lag deposits a few cm thick.

• The unit overlying the channel fill sequence is a series of interstratified rippled to horizontally laminated siltstone and crumbly mudstone (locally purple) beds 10-25 cm thick, representing floodplain deposition.

Paleocurrents: measurements from levels 1 and 2 of Fig. 10 represent directions from trough cross-bed axes and they range from bottom to top as follows: trough axis from base of channel 050° (northeast direction) progressively upward into trough cross-laminated sets 020° (north-northeasterly direction).

Other example: The example from the New Waterford section, interval 202-211.5 m (Plate 18B) exhibits similar type of channel fill as that in Plate 18A, but here the channel fill is entirely homogeneous with the scale of the trough cross-beds declining upward as one uninterrupted sequence.

Interpretation: This grouped trough cross-stratification is interpreted as the filling of channels by the migration of trains of dunes or megaripples in the deeper parts of the thalweg channel with decline of scale related to decline in flow strength related to avulsion. In very sinuous rivers with relatively finer sediments the scale of the cross-beds and grain size of sands decline upward (Walker and Cant, 1984), but Jackson (1976, 1978) and Bridge (1985) have also demonstrated that fluvial channels with coarser sediment and less mud deposition (which is the case here) generate a sequence without the well-defined fining-upward trend found in classical point-bar sequences. The rarity of lateral-accretion sets in homogeneous channel sandstones is attributed to the obscuring effect of dunes migrating across the point bar and to a lack of lithological contrast (Gibling and Rust, 1984). This rarity has also been observed in anastomosed and distributary channels in the Paleocene (Bridge, 1985; Belt, personal communication).

4.2.2E Example 5. Pebbly-granular sand wave deposit

Location: Donkin West section, interval 14-20 m.

Illustration: Appendix A, Fig. 5, interval 14-20 m; Fig. 11.

Setting: lenticular curved to sinuous ridge of pebbly-conglomeratic granular material (1.5 m thick and 12 m wide) located in the basal part of the lowermost channel (beach level) of a series of erosively based channels. The topmost of these channels exhibits gradational abandonment. The sequence is overlain by overbank deposits.

Description of sequence (unit numbers correspond to those of Fig. 11):

1) Pebbly-granular sand wave: composed of 50-60% intraclasts (shale, mudstone, calcareous mudstone) in a coarse-medium sandstone matrix with little mud content. Clasts show no imbrication. No internal cross-stratification is apparent and the entire sequence is formed of four fining-upward beds (30-40 cm thick) separated by three thin beds (2-8 cm thick) of silty mudstone to muddy siltstone. Direction is oblique to the main channel direction (i.e., in a direction toward the left of the figure and out of the page).

2) Main channel: sand wave forms the lowermost unit of this channel. Fining-upward from coarse to medium sandstone and upward from trough cross-bedded to trough cross-laminated to horizontally laminated, this channel appears to erode into the lateral floodplain package and is scoured by channel (3). The axis of the channel is roughly 350° in direction.

3) Second channel: erodes into the finer sandy rippled sediments of channel (2). The uppermost part shows vertical accretion of muddy material. The axis shifts in direction to 010°.

4) Third channel shows chute cutoff abandonment: eroding into finer sediments of (3) and showing the characteristic features of gradual

abandonment channel fill, fining-upward of sequence and upward waning of flow. No significant paleocurrent measurements were available.

5) Overlying overbank/floodplain deposits: interstratified tabular to lenticular beds (20-30 cm thick) consisting of small-scale rippled and horizontally laminated very fine silty sandstone to sandy siltstone and thinly bedded (5-15 cm) mudstone and shale.

Interpretation: this example represents the deposition of a bar on the lower lateral accretion face of the main channel. The bar was oriented obliquely to the direction of the stream flow with slip face directed inward toward the meander lobe. It was probably deposited during moderate flows in which pebbles accumulated. The small amount of mud present as matrix probably was washed into the gravel after deposition. The sequence of three channels is believed to illustrate lateral shifting related to gradual filling and abandonment of the main channel.

4.2.2F Example 6. Channel abandonment filling: gradual abandonment (chute cutoff deposit)

Location: Morien North section, interval 14-17.5 m.

Illustration: Appendix A, Fig. 8B, interval 14-17.5 m; Fig. 12A.

Setting: gradually abandoned channel 2.5 m thick and laterally exposed for > 10 m. In cross section the fill deposit is triangular to slightly U-shaped and is bounded by a partly erosional surface and enclosed in a floodplain sequence.

Lithology: fining-upward sequence from coarse-medium sandstone with lag deposit upward into fine silty sandstone followed by organic rich silty clays.

Sedimentary structures: the channel-fill can be subdivided in three sections corresponding roughly to the subdivision of Walker and Cant (1984):

• Lower section: similar characteristics to the lower part of a point-bar sequence and consisting of massive trough cross-bedded deposits overlain by trough cross-laminated finer sandstone. This represents the active channel fill.

• Middle section: trough cross-laminated fine sands, sandy silts and silts representing the gradual abandonment and deposition during partial flow.

• Upper section: consists of predominantly clays and silty clays with abundant organic debris, plant material, root remnants and desiccation cracks. This represents the abandoned stage and vertical accretion occurring after cutoff.

Other examples: New-Waterford section, interval 72-75 m (Appendix A, Fig. 2); Glace Bay West section, interval 45-47 m (Appendix B, Fig. 3).

Interpretation: gradual abandonment (chute cutoff) of the main channel. After channel closure was completed, further filling was limited to deposition of fine and muddy material introduced by overbank flows.

4.2.2G Example 7. Channel abandonment filling: abrupt abandonment (neck cutoff deposit

Location: Morien North section, interval 4-7 m.

Illustration: Appendix A, Fig. 8B, interval 4-7 m; Fig. 12B.

Setting: Abruptly abandoned channel (2 m thick, 7 m wide) enclosed in a purple well-drained floodplain package with variable water table.

Lithology: basal sand unit: 60 cm thick silty, hematitic, micaceous medium to fine sandstone with basal 10-20 cm thick lag deposit composed of lithic clasts (3-10 mm diameter, various sandstones and mudstones). The basal sand unit, representing the active channel fill, is abruptly overlain by a thicker section (1.5 m thick) of interstratified organic rich and rooted clays and purple/hematitic, silty shale and locally shaly siltstone. This unit is very similar to the sediments of the well-drained floodplain with variable water table.

Sedimentary structures: fining-upward sequence from abrupt-erosional basal contact into interstratified large-scale and small-scale trough cross-stratified beds into a thicker vertical accretion sequence with local small-scale cross-laminated beds in the lower part.

Accessories: Root remnants and imprints and desiccation cracks observed in the zone of water-table fluctuation.

Other example: New Waterford section, interval 214-215 m (Appendix A, Fig. 2).

Interpretation: Sudden abandonment by neck cutoff or avulsion. The former meander loop is suddenly abandoned and sealed off by vertical accretion deposition. The ripple cross-laminated fine sands at the top of the basal sand unit represent low flow during abandonment and the rest of the sequence consists of vertical accretion deposits washed into the abandoned loop at flood time.

4.2.3 Overbank deposits (proximal)

Rivers flow through alluvium deposits under two main conditions: within the confines of the channel at ordinary river stages, and over the floodplain top stratum, in addition to within the channel, at flood stages (Leopold and Wolman, 1957). The coarser stream load materials are carried within the channel, while the relatively fine materials (finer sand, and silt and clay) maintained in suspension by the turbulent motion of the water are deposited beyond the channel banks on the floodplain as vertical accretion backswamp deposits and as levee and crevasse-splay deposits generated by overbank tractive transport (Fisk, 1944, 1947; Leopold and Wolman, 1957; Bernard and Major, 1963; Allen, 1964, 1965a). Surficial exposure and groundwater fluctuation, desiccation features, pedogenic deposits, interstratified coarse and fine sediments and autochthonous and transported plant debris are common features in vertical accretion deposits.

Levee deposits close to the river bank are typically coarser than the more distant backswamp deposits (Allen, 1964) but finer than proximal crevasse-splay sediments. Crevasse-splay deposits accumulate where flood waters break out of the main channel through low places in the natural levees, and hence tap suspended sediment from lower flow levels than that which accumulates on levees. The crevasse deposits thin away from the channel and fan out into aggrading distributaries erosively spreading tongues and lenses of relatively coarser sediment into the floodplain environment (Allen, 1965a).

The thinner, finer grained sandstone bodies of the Sydney Mines Formation are attributed to the related overbank deposit processes of levee, crevasse-splay and lake-fill deposition (Walker and Cant, 1984; Gersib and McCabe, 1981; Rust and Masson, 1981). These units are characterised by abundant root bioturbation and ripple cross-lamination (Rust and Masson, 1981; Rust et al., 1983). Overflowing through low points in the channel bank taps lower, coarser channel sediment and generates crevasse-splays elongated approximately normal to the channel trend (see examples 8, 9 and 10). These deposits are the commonest type of overbank sandstone in the Sydney Mines Formation and are characterised by upward coarsening or coarsening, then fining, trends. Lower or middle strata (splay channels) are trough cross-stratified, whereas the upper parts of splay units are finer and dominated by horizontally stratified or ripple cross-laminated sandstone (see examples 8 and 10), a response to waning flow. The siltstone and shale associations that commonly underlie splay sandstone (examples 8-10) represent sediments deposited from suspension at the distal portions of splay lobes. The interlamination of siltstones and shales with coals and carbonaceous shales indicates deposition as suspended sediments of flood waters that invaded backswamp areas. The spatial relationship of the siltstones and shales as deposits overlying and marginal to channel sandstones reflects deposition as suspended sediments in overbank-levee areas.

In the lacustrine-dominated environment where a crevasse-splay progrades into standing water, small lake deltas are generated (Elliott, 1974; Gersib and McCabe, 1981). Lakes formed by an excess of subsidence over sedimentation in parts of the floodplain are common features in the Sydney Mines Formation, particularly in the central part of the basin between Victoria Mines and Glace Bay (Masson and Rust, 1983). This lake-fill sequence type is characterised by upward coarsening with abundant bivalves and abundant plant debris in its lower part (see Chap. 5 for detailed discussion).

4.2.3A Example 8. Levee (channel margin) deposits

Location: Morien North section, interval 64-68 m.

Illustration: Appendix A, Fig. 8B, interval 64-68 m; Fig. 13 and Plate 19.

Setting: alternating tabular sandy (medium to fine) and fine clastic beds, laterally continuous for > 125 m, overlain and underlain by channels.

Lithology: thin cyclic units of light coloured, horizontally (tabular) bedded medium-fine sandstone (locally coarse) interstratified with siltstones and shales (mostly carbonaceous with variable organic and comminuted plant debris) underlying floodplain package of interstratified red-purple sandy siltstones and light pink very fine to fine sandstone.

Bedding: interstratified tabular and relatively thin wedge of sandstone, siltstone and claystone, ranging in thickness from 1.5 m to 20 cm, deposited by overbank flood waters. Thickest section is adjacent to channel located at the base of cliff and partially submerged. Individual sandy beds are thinning away from channel. Overall sequence is finer near the base and grades upward into increasing sand and silt.

Sedimentary structures: most recorded structures are ripple cross-laminations, parallel laminations, and local climbing ripples. Characteristic sequence exhibits horizontally laminated beds overlain by cosets of waning-upward small-scale asymmetrical ripple cross laminations (up to 8 cm thick) with local climbing ripples grading upward into suspension deposited horizontal/parallel laminations. Rapid vertical change of interstratification between coarser and finer sediments, on the scale of several cm, is a very characteristic feature. Levees generally consist of fining-upward sequences with well-stratified (ripple cross-laminated), locally burrowed sandy to silty lower portions grading upward into silty clay with intense burrowing and root bioturbation; ripple cross-laminated beds (averaging 1 m thick) of fine-clastic materials (mostly very fine sandstones and siltstones) enclosing aligned upright tree trunks (Plate 19) are prominent; iron-carbonate and calcareous nodules are present locally. A coarsening-upward sequence (up to 40 cm thick) representing alternating sand-laden currents is also present.

Accessories: mottled and homogeneous deposits abounding in roots, rootlets and plant debris; extensive occurrence of upright tree trunks.

Paleocurrents: mostly ripple crest-axes at approximately 90° to the channel direction, which flow in a northeasterly direction.

Other examples: New Waterford section, interval 151-155 m; Glace Bay East section, interval 57-60 m.

Interpretation: this example represents deposits overlying and marginal to a channel sandstone reflecting deposition of sediments in an overbank-levee area; the scale and the importance of interbedding of coarser and finer sediments is controlled by the size of the levees, the grade of sediment made available by the stream and the duration of flood and waning events; the thicker cosets of ripple cross-lamination and the climbing ripples formed under higher aggradation rates probably formed at the levee tops where flow was abruptly checked in velocity.

4.2.3B Example 9. Pebbly sheet splay deposits

Location: Morien North section, interval 91-96 m.

Illustration: Appendix A, Fig. 8B, interval 91-96 m; Fig. 14 and Plate 20.

Setting: Five tabular-sheetlike bodies 1.5 m to 60 cm thick, laterally continuous for 30 m and overlain by a channel with basal conglomeratic lag and are underlain by a floodplain package (Plate 20A).

Lithology: Pebbly-conglomeratic coarse to very coarse sandstone with a green to dark-grey poorly sorted muddy sand matrix interbedded with thinly bedded fine-medium sandstone and grey-green mudstone; conglomeratic intraclasts have variable characteristics (subrounded to subangular lithic clasts including: quartzose sandstone, siderite nodules, quartzitic lithic sandstones, variable mudstone), range from 5 mm to 5 cm and are framework supported with no apparent imbrication (Plate 20B).

Sedimentary structures: Series of five fining-upward tabular-horizontal bodies forming a fining-upward sequence and exhibiting upward thinning of the bodies (lowermost bed 1.5 m thick, topmost 60 cm thick). The main bodies are separated by thin beds (20-30 cm thick) of fine-clastic muddy material and internally the conglomeratic intraclastic beds are composed of sets 20-40 cm thick separated by thin sets 1-3 cm thick (increasing in number in the upper beds) of muddy material. All sets (with the exception of the lowermost bed. which is trough cross-stratified in its lower part) are horizontally laminated with slight wavy rippling appearing in the upper third. The conglomeratic beds are massive to horizontally laminated and exhibit lower erosional contacts and abrupt to gradational upper contacts. The most frequent internal structures present are: planar stratification, bedding-plane parting lineations, basal erosional surfaces, internal mud interlaminations and small-scale ripple cross-laminations.

Paleocurrent: measurements are from primary current lineations and clast elongation at base of beds and indicate that flow direction is roughly normal to the general northeast trend measured in the surrounding channels.

Other examples: Donkin West section, interval 94-97 m.

Interpretation: The setting of this sequence of alternating thin to thick bodies of pebbly-conglomeratic, coarse to fine sand and subordinate interbedded silt and sandy mud indicates that they formed marginally to channel fill facies and are interbedded with floodplain sediments.

The abundant planar stratification, tabular-sheet geometry and small-scale vertical "cyclicity" indicate pulsatory transitional and upper-flow regime conditions in an unconfined setting and high flood levels required to carry pebbles onto splays. Associated floodplain deposits suggest deposition of sheet splay units during periods of intense overbank flooding from a mixed load (bedload dominated) stream, and poor sorting, coarseness, and crude bedding indicate a provenance from stream-flooding as pebbly sheet splay deposit probably from a high-sinuosity stream with coarse bedload and episodic discharge.

4.2.3C Example 10. Crevasse-splays with distributary channels

Location: Glace Bay East section, interval 117-139 m.

Illustration: Appendix A, Fig. 4, interval 117-139 m; Fig. 15 and Plate 21.

Setting: Floodplain sequence with numerous crevasse-splay deposits and numerous distributary channels; sequence is laterally continuous for > 100 m and consists of laterally continuous thin to thick tabular fine - very fine sandstones interstratified and interfingering with floodplain or lacustrine mudstone and siltstone; individual beds or lenses within the sequence are usually 40 cm to 1 m thick and rarely exceed 2 m (Plate 21A).

Lithology: interstratified fine to very fine sandstone, siltstone, variable mudstone and shale (including carbonaceous shale) and minor discontinuous coal seams.

Sedimentary structures: typical splays exhibit fining-upward and/or coarsening-upward followed by fining-upward sequences, locally scoured by distributary channels (Plate 21A,B). The base is sharp and load structures are common; many of the primary structures are locally destroyed by roots. The stratification of the bed changes upward from horizontal thin bed laminations to small-scale ripple cross-laminations (including locally climbing and asymmetrical types) to wavy or slightly wavy into poorly defined to disrupted planar laminations, with a broad range of planar, ripple and cross-laminated types. Distributary channels observed range from 1 to 2.5 m thick and 5-15 m wide; the one described in the example (Plate 21A) is 1.3 m thick and approximately 5 m wide. Some channels may display lateral accretion bedding, are characterised by fining upward of sediments and are enclosed by floodplain sandstone and shale associations (Plate 21A,B). They can usually be divided into three parts having the following general characteristics:

• lower -- trough cross-stratified unit 35 cm thick overlain by 10 cm thick rippled unit with sets several cm thick;

• middle -- small-scale trough cross-laminated upward into rippled and horizontally laminated in the upper part; ripples are mostly sinuous and out of phase;

• upper -- finest sediments (silty claystone/mudshale unit) developing locally into seatearth, dominated by horizontal stratification but also ripple cross-laminated.

Paleocurrents: direction approximately normal to channel trend.

Other examples:

Morien North section, interval 61-69 m (Appendix A, Fig. 8B);

Glace Bay West section, interval 212-214 m (Appendix A, Fig. 3);

New Waterford section, interval 253-280 m (Appendix A, Fig. 2).

Interpretation: The tabular distribution of beds, the coarsening-upward sequence followed by a fining-upward sequence, the local climbing and asymmetric-ripple laminations and the local scouring by distributary channels indicate deposition by flood waters originating from crevasse channels cutting into levee crests of the main channels. The initial coarsening upward above the erosional base, followed by fining upward, reflects deposition during rising and waning flood stages (Elliott, 1974). The units fining upward from an erosive base represent erosion of the floodplain preceding deposition during waning flood velocities. Grain size and internal structural changes depend on local flow conditions and sediment availability.

4.2.4 Floodplain deposits -- well to poorly drained swamps and coal formation

The floodplain-dominated environment represents flood basin environments receiving fines from overbank flooding and sands as proximal and distal splays (overbank deposits). Floodplain deposits are blanket-shaped accumulations of clays, silty clays and muds deposited from a suspended load of flood waters into the topographically lower floodplain (Elliott, 1974). The main characteristics of the floodplain-dominated environment in the study area are given in Table 11.

The sedimentary facies of floodplain deposits in the study area can be grouped into distinctive associations in vertical sections, with each association containing different facies types. These associations represent two main environmental settings within the more general floodplain environment: the well-drained swamp with fluctuating water table subenvironment, and the poorly drained swamp subenvironment.

4.2.4A Well-drained swamps with a fluctuating water table are important in zone C of the Sydney Mines Formation, particularly in the New Waterford and the Morien North sections. The best examples (and their lateral extent) are located at:

- New Waterford section, interval 130-160 m (Appendix B, Fig. 4, and Appendix A, Fig. 2);
- New Waterford section, interval 220-234 m (Appendix B, Fig. 6, and Appendix A, Fig. 2);

• New Waterford section, interval 260-280 m (Appendix B, Fig. 6, and Appendix A, Fig. 2);

• Morien North section, interval 20.5-40 m (Appendix A, Fig. 8B). All of these examples can be characterised as floodplains exhibiting highly variable interstratification of light olive grey/greyish green to purple hematitic fine clastics locally exhibiting mottling. These claystones/mudstones exhibit variable silt content and are associated with sandy splay deposits. Association with lacustrine/pond deposits is also observed at a few locations in the New Waterford section.

The hematitic and iron oxide petrographic and diagenetic aspects of those sediments will be discussed in section 4.6. The best example illustrating the characteristics discussed in this section is the interval 260-280 m of the New Waterford section, illustrated in Appendix A, Fig. 2, and Plate 22.

This facies consists mainly of interstratified light olive grey/greenish grey to red claystones and mudstones that contain variable percentages of silt (5-50%) and low amounts of organic debris. This facies contains lenses and discontinuous layers of ripple cross-laminated very fine to fine sandstone and is associated with tabular, laterally continuous ripple cross-laminated to horizontally laminated very fine to fine sandstone bodies representing crevasse-splay deposits. In the Morien North example the sandstones are characterised by a light pink to purplish pigmentation (hematitic and iron-oxide staining).

Root-bioturbation is ubiquitous and iron-oxide mottling and desiccation cracks are common. Ferruginous deposits are often found as coatings on tubes that probably encased former roots, and pyrite is present in trace amounts. Calcium carbonate and iron-carbonate (siderite) concretions are locally present. Eight facies have been recognised based on grain size and sedimentary structures present (strata can be greenish-grey to purple and locally mottled): horizontally stratified sandstone, cross-stratified sandstone, ripple cross-laminated sandstone and siltstone, horizontally laminated mudstone, sandy and/or silty mudstone, bioturbated (mostly by roots and rootlets) to finely horizontally laminated claystone and distributary channel sandstone (similar to those described previously). Those facies may form individual beds ranging from 5 cm to 1 m thick.

Although generally the vertical arrangement of facies is variable and forms fining-upward sequences, locally coarsening-upward sequences and complete sequences have been observed (i.e., in the Morien North section). When complete, a typical sequence of facies comprises (from top to bottom):

- homogenised (root-turbated) varicoloured claystone/mudstone;
- sandy and/or silty mudstone;
- interlaminated sandstone and mudstone;
- ripple cross-laminated siltstone and sandstone;
- horizontally laminated sandstone;
- cross-stratified sandstone (locally this contains a lag deposit of rip-up clasts from the overlying lithofacies);
- erosional or abrupt surface;
- homogenised (root-turbated) varicoloured claystone/mudstone.

Such a sequence commonly shows an upward increase in mud cracking, thickness and amount of mud layers, traces of rootlets, mottling and bioturbation.

This sequence of deposition depends on: flow depth and velocity, the size distribution of the grains, concentration of suspended load, nature of the flow deceleration and distance from the channel (Collinson, 1978a).

The lithologies, sedimentary structures and aerial distribution indicate a flood basin origin for this subenvironment. The ripple cross-lamination in the siltstone and sandstone and the characteristics of the interbedding (i.e., vertical assemblage) reflect the low flow strengths of currents, relatively distant from the high energy channel system. Most of the sediment was deposited from suspension. However, the presence of polygonal desiccation cracks emphasizes the ephemerally submergent nature of this alluvial subenvironment. The numerous types of graded beds reflect complex interactions among the controlling variables during deceleration of the sheet flows. These graded beds are deposits of a lower flow regime stable over a wide range of flow depths (Elliott, 1974).

The purple-red mottling and staining suggest that soils were subjected to variable drainage with fluctuating water tables. Periods of subaerial exposure are evidenced by the occurrence of numerous desiccation features and calcareous paleosol units. Local discontinuous coal occurrences and lenticular pond deposits suggest periods of temporary swamp cover and ephemeral surface pools.

4.2.4B Poorly drained swamps (organically dominated) are the most important floodplain deposits in the study area. They occur in every lithostratigraphic zone but are particularly important in zone C. The best example illustrating the characteristics discussed in this section are the intervals 120-135 m and 180-200 m of the Glace Bay East section, illustrated in Appendix A, Fig. 4, and Plate 23. Other important locations are listed in Table 14.

This subenvironment consists of dark olive grey to olive black, highly organic claystones/mudstones with thin to thick coal seams, abundant coalified roots, twigs and leaves and comminuted plant debris and clasts of coal. It contains less silt and sand than the swamps with fluctuating water table, except when associated with crevasse-splay deposits. Siderite is common as nodules and discontinuous thin beds. Pyrite is common mostly as disseminated grains but is also locally concentrated as staining ferruginous patches.

This facies exhibits little to no internal stratification or laminations because of the extensive root bioturbation. When associated with crevasse-splay and distributary channels, it forms tabular ripple cross-laminated to homogeneous beds (10 cm-1.5 m thick) exhibiting fining-upward and/or coarsening-upward grading. Horizontally laminated homogeneous silty units with organic detritus are present locally. Because of extensive root bioturbation rare sedimentary structures are present. Coals and high organic content are its main characteristics.

Stratigraphically it is associated with: 1)well-drained floodplain deposits with fluctuating water table; 2)tabular laterally continuous crevasse-splay deposits (up to 1 m thick) containing drifted organic material; 3)coal seams of varying thickness (and importance) and carbonaceous shale interbeds.

Paleocurrents measured were rare and essentially from primary current lineations and ripple crest axes from the associated sandstone beds. They indicated a range of flow directions from 90° to 120° (i.e., NW-SE trend) to the predominantly northeasterly flowing channels.

This subenvironment indicates vertical accretion deposition on poorly drained floodplains characterised by fluctuating energy with suspension periods and periods of inundation long enough to permit vegetation growth.

The associated beds are interpreted as:

- crevasse-splays exhibiting plant colonisation: tabular VF sandy beds with silt and mud with plant and rootlet remnants;
- crevasse-splay deposits: tabular VF sandy beds with variable silt and mud and flutes and grooves or primary current lineation at base and with desiccated polygons on top surface;
- flood basin deposits with occasional sand influx and/or suspension: mudstone to claystone with variable comminuted plant and carbonaceous debris and with small-scale rippled to homogeneous VF sandy and silty interbeds.

The environment of deposition of the coal and related mining problems are discussed in section 4.7.

4.3 Environmental interpretation

4.3.1 Review of the literature on river systems

Rust (1978a) outlined the parameters for defining modern fluvial systems. Previously in the literature, the two most common types of streams, meandering and braided, were defined by different criteria -- i.e., sinuosity and the number of channels (Leopold and Wolman, 1957; Moody-Stuart, 1966; Leeder, 1973a,b). To avoid this ambiguity, Rust (1978a,b) defined a braiding parameter on the basis of the number of channel divisions per mean meander wavelength of the fluvial channel. In this classification fluvial systems with a braiding parameter of less than 1.0 are termed single-channel systems and those greater than 1.0 are termed multi-channel systems. In addition, channel systems were divided into low and high sinuosity types at the boundary 1.5, yielding four categories (Table 15A), the two most abundant being the meandering and braided systems, that is high-sinuosity single-channel and low-sinuosity multiple-channel systems.

Sedimentation in modern and ancient meandering streams has been studied by numerous workers (Allen, 1963, 1964, 1965a; Harms et al., 1963; Jackson, 1975, 1976, 1978), as have been braided stream deposits (Walker and Cant, 1976, 1984; Miall, 1977a; Rust, 1978b). The characteristics of the fluvial system in the Sydney Mines Formation do not show any of the main characteristics features of straight or anastomosing streams, and these will not be considered further in this study. However, a discussion of the characteristics of the meandering fluvial system and a comparison with the braided system are important in the definition of the fluvial system in the Sydney Mines Formation. Morphology, bedforms and sedimentary structures of generalised braided and meandering rivers are illustrated in Fig. 16 (taken from Walker and Cant, 1984), and the variables differentiating the two are listed in Table 15B (from Miall, 1977b).

Based on the following discussion, the Sydney Mines facies assemblage can be assigned to a meandering alluvial system.

Channel morphology is greatly influenced by the nature of the sediment load (Miall, 1977b). Stability of alluvial channels is directly related to the preservation potential of fine sediment and to the suspended load/bedload ratio (Rust, 1978a). Meandering streams have a high proportion of suspended load and cohesive banks of fine-grained sediment. These characteristics retard lateral erosion by the channel, confining the channel system to a meander belt bounded by resistant silt and clay material (Walker and Cant, 1976, 1984, and Fig. 16A). Collinson (1978b) showed a direct relationship between meander belt width and the thickness of the channel deposit (see section 4.5.2). Channel flow is marginally confined by marginal levees deposited at the channel margin during periods of flooding. Crevassing of levees during flood generates crevasse-splays and laterally extensive continuous sheets of sand transitional into fine-grained sediment in the flood basin. The net result is an elongated fining-upward sand tongue, which is interbedded with mudrocks. This contrasts with bedload-dominated rivers (including most braided streams) which generate vertically accreted sand sheets. Overbank muds have relatively low preservation potential. River banks composed of coarser, less cohesive material and rapid uninhibited lateral migration of channels result in discontinuous stacking of coarse-intraclastic blanket deposits and gravelly-pebbly fills of abandoned channels.

Large-scale trough cross-bedded units, resulting from the migration of sinuous-crested dunes, are the most important sedimentary structure on meander point bars and in many sandy braided channels (Walker and Cant, 1976, 1984; Miall, 1977b). Transverse bars generating large-scale planar cross-stratification (Miall, 1977a) and planar sets produced by sand waves (Cant and Walker, 1976; Walker and Cant, 1984) are common features of sandy braided systems and are less common in meandering river deposits, where they are formed by the migration of transverse bars, scroll bars, and sand waves superimposed on point-bar surfaces or in channels (Jackson, 1976). An important feature of some meandering streams is the presence of large-scale low-angle cross-strata (epsilon type of Allen, 1963), which represent the original depositional surface of the bar preserved by lateral accretion. They are diagnostic of point-bar deposition (Moody-Stuart, 1966; Leeder, 1973a,b; Walker and Cant, 1976). These lateral-accretion surfaces are not present in every point-bar sequence and can be difficult to recognise, because they are commonly obscured by down-channel migration of smaller scale structures, mainly dunes and ripples (Miall, 1977b). Facies Gm, St, Sh, Sr, Fl and Fm are common in meandering river systems, while facies Gt, Gp, Sp and Ss are rare to absent (Table 15B). One of the essential components of a meandering system is the presence of abandoned meanders which are ultimately filled with silt and clay (Fig. 16A).

The decrease in stream power from the base to the margins of stream channels is particularly regular in meandering stream channels. This results in upward fining and in upward decrease in scale of bedforms (i.e., large- to medium-scale trough cross beds to fine-scale rippled sets) in the resulting channel deposit (Allen, 1970; Walker and Cant, 1976, 1984). These bedforms are preserved as a vertical (cyclic) succession of sedimentary structures by lateral accretion of the point bar (Fig. 16A). The type of succession preserved is controlled by the nature of the flow in different parts of the meander belt (Jackson, 1976, 1978). Ancient alluvial environments exhibiting fining-upward point-bar sequences have been described in great detail by Allen (1964, 1965a,b, 1970) and numerous other workers.

Point bars are uncommon in braided systems, which mostly exhibit coalescing of smaller scale bedforms and complexes of in-channel bars. Longitudinal bars (elongated in flow direction) predominate in proximal regions, while transverse bars (predominantly transverse to flow) are more common in sandy, more distal regions (Rust, 1972, 1978b; Miall, 1977a). Sequences formed in sandy braided rivers rarely show the regularity of vertical sequences common in cyclic meandering successions. Walker and Cant (1976), Cant and Walker (1976) and Miall (1977a,b) have outlined a possible stratification sequence from modern and ancient braided river systems notable for their variability in scale and stratification sequence.

4.3.2 The Sydney Mines Formation as a meandering alluvial system

The meandering alluvial system in the Sydney Mines Formation reflects a low slope, distal (predominantly suspension load mode of deposition but with episodes of greater bedload influence), high-meandering streams within a lower sinuosity meander belt. This alluvial floodplain environment exhibits cyclicity and the presence of lacustrine calcareous deposits, carbonaceous mudstones and coals (Fig. 17).

The most critical diagnostic features observed can be briefly summarised as follows:

1) Fining-upward sandstone sequences averaging about 5 m thick with an erosional base, commonly overlain by an intraclastic lag. The lag fines upward to trough cross-bedded sandstone facies, then passes to trough cross-laminated sandstone and rippled fine-grained facies. These sequences are interpreted as point-bar deposits on the basis of the sequence of facies, structures and grain-size gradation.

2) In cliff exposures many of the point-bar sequences show lateral-accretion bedding in the form of gently sloping surfaces that pass right through fining-upward sequences and are made visible by drapes of finer grained sediments. In cases where the dip direction of the lateral-accretion surface can be determined, it is approximately perpendicular to the paleocurrent direction indicated by troughs in the point-bar sequence. The presence of lateral-accretion features strongly corroborates the meandering river point-bar interpretation.

3) A few mudstone-filled paleochannels are present. They represent clay plugs formed by accumulation of mud from suspension as flood waters inundated an abandoned meander. These paleochannels show a high width/depth ratio (average 1:5) characteristic of channel belt sand bodies (Schumm, 1968).

4) Coarsening-upward sandstone units with individual beds mostly less than 1.5 m thick lack basal erosional surfaces and are attributed to the progradation across the floodplain of rippled facies in crevasse-splays and natural levees. Levees are characterised by stands of mature vegetation, represented by erect trunks. Crevasse-splays appear to have built out into both vegetated swampy floodplains and lakes.

5) Floodplain deposits are represented by mud-rich sequences, rooted horizons and coals. In the latter case, compaction of the floodplain mud proceeded at a rate suitable for the accumulation of peat. The presence of thick sequences of hematitic mud and desiccation fractures indicates that the floodplain was subjected to periodic exposure and lowering of the water table. This is particularly evident in the Morien North section (see floodplain discussion, 4.2.4).

6) Sideritic nodules also developed from time to time, which indicates reducing conditions in ponds and lakes. Ponds were formed by channel abandonment and lacustrine bodies by subsidence of the floodplain below the water table (high rate of subsidence causing lacustrine transgression). Crevasse-splays or lacustrine deltas are an important characteristic of the thicker lacustrine deposits.

7) The presence of coals, paleosols (including in situ rooted horizons) and upright trunks indicate that the Morien Group was deposited in a terrestrial environment. There is no evidence for marine incursion; marine fossils are lacking, as are thick coarsening-upward deltaic sequences. Fossils are locally abundant in calcareous bands or limestones closely associated with coal seams in the upper part of the Morien Group. The fossils include stromatolites, ostracods, clams, gastropods, and fish fragments, all of freshwater origin (Masson and Rust, 1984).

Depositional studies of the main coal seams by Hacquebard and Donaldson (1969) have yielded the following conclusions concerning the stratigraphy and the lateral variations of those seams:

- peat formation beginning in the center of the basin and then migrating eastwardly in the Harbour and the Backpit seams;
- greater influence of fluvial sedimentation as shown by splitting, rejoining and digitation in the Emery, Phalen, Bouthillier, Harbour (in the western part) and Hub seams;
- the only extensive seam without splits is the Backpit. This reflects very broad and stable swamp conditions for the Backpit;
- the vertical arrangement of the seam sections show a general westward migration of peat swamps in successive seams. This could be due to the fact that higher seams are only exposed in the western part of the basin.

The progressive development of the alluvial plain is indicated by the succession of facies assemblages observed in the coastal sections. The underlying coarse sandstone assemblage of the South Bar Formation represents the most proximal alluvial conditions -- a braidplain on which a significant amount of gravel was transported. Mud accumulated in places but was rarely preserved except in the form of intraclasts within channel lag deposits. Marginal terraces of the braidplain supported moderately large plants and small peat swamps, but the peat was not preserved in place and is only present as transported peat rafts (now coals) (Gibling and Rust, 1984).

Sandstone/mudstone ratios are important for interpreting Sydney Mines Formation depositional environments. The following categories of sandstone/mudstone ratios were arbitrarily defined by the author as follows: very high (greater than 90%), high (75-90%), moderate (50-75%), low (25-50%), and very low (less than 25%).

The three "informal lithostratigraphic zones" (zones A to E, section 2-3, Fig. 4) are defined as:

zone A and C -- fluvial-channel-dominated with floodplain;

zone B and D -- fluvial-channel and floodplain with local lacustrine limestone beds;

zone E -- floodplain-dominated with minor distributary channels and lacustrine limestone beds.

They represent a fining-upward megatrend, reflecting a vertical change from channel to floodplain dominance. The channel sandstones have essentially the same characteristics in all the zones (Fig. 4 and Appendix B). The main characteristics of these lithostratigraphic zones are listed in Table 11.

The distinction between proven (walked out and observed) and likely (logical correlation) versus presumed (inferred) correlations are indicated for all the correlations in Figs. 1-6 of Appendix B.

The fluvial-channel-dominated zone accumulated abundant channel sandstones enclosed in floodplain sequences and related coal seams. This environment forms 45% of the total thickness of the sections measured (Appendix B, Figs. 1-6). The thickest section measured is 300 m, at New Waterford. These sandstones consist of abundant quartz with variable amounts and types of lithic fragments (see Chap. 3) and form elongated tabular sheets and lobate sandstone bodies. Compositionally, the zone forming this environment (zones A and C, Fig. 4 and Appendix B, Figs. 1, 3 and 4) contains 30-60% sandstone and related lag conglomerate, but locally the sand/mud ratio may range from 10% to more than 70%. Channel fills and lateral (epsilon cross-beds) accretion, fining-upward sequences, point-bar development, trough cross-stratification and ripple marks are the most common and characteristic features observed (Table 11).

The channel sandstone bodies dominating this environment constitute 40-50% of zones A and C (Appendix B, Figs. 1 and 3) and 20-30% of zones B and D (Appendix B, Figs. 2-6). The larger channels average 7 m in thickness (ranging from 4 to 11 m), which corresponds to a 750 m wide meander-belt sand body (Collinson, 1978b) and fits the dimensions of channel sand bodies determined from mining operations (Duff et al., 1982).

The majority of the channels are of a simple type, while channels correlated across several sections are multistory (i.e., stacked). The simple channel units mostly occur isolated and are completely surrounded by overbank deposits.

Multistory channel bodies contain one or more major erosional surfaces (ES). Erosional surfaces overlain by conglomerate lag deposits are commonly associated with scouring and may exhibit thin mudstone at the base of the erosional surface. The multistory channels are mostly double-stacked with few multi-stacked (3 episode) sequences observed. Multiple stacking indicates conditions within straighter reaches of meandering channels when the proportion of overbank mud was relatively low.

Correlatable channels form lateral composite belts (averaging 6-10 km), which are separated by mud-rich facies containing discontinuous sand units of variable thickness. Many meander-belt sandstones are much wider (< 7 km) (Appendix B, Figs. 1,2). These channel bodies presumably represent laterally overlapping (stacked) meander-belt bodies.

The single, isolated channels occur as isolated, well-defined bodies widely separated from each other and enclosed by floodplain sediments. In general, single-story bodies show variable evidence of scouring at the base and may exhibit local diastems related to bedform migration. Single-story bodies predominate in zones A and C. They represent the majority (roughly 65%) of sandstone bodies that formed.

The fluvial channel sandstone bodies from all zones grade laterally into equivalent crevasse-splays, which can be differentiated locally into proximal and distal parts on the basis of sedimentary features and thickness. Crevasse-splays are very well developed along the margins of channels. Splays tens of meters thick, indicating persistence of individual splays through many flood events from laterally equivalent channels, are observed (Appendix B, Figs. 1-6). Related facies include well-drained floodplain mud and silt; interchannel lake clay, mud and sand; isolated floodplain ponds, small-scale lacustrine beds and major and minor coal beds.

Limestone beds form 5-7% of zones A and C. Several beds can be correlated laterally over 7 km (Appendix B, Figs. 4 and 5). Most are isolated lens-shaped bodies, 1-3 m thick. They extend laterally from the margins of channels as part of the floodplain package and represent ponds or small-size lacustrine deposits exhibiting variable lateral continuity.

Zones B and D represent the <u>fluvial-channel and floodplain with local lacustrine limestone beds</u> (Appendix B, Figs. 2 and 4) and it has a cumulative thickness of 75 m, representing 25% of the total thickness of the stratigraphic column measured. This environment has many of the characteristics of the fluvial-channel-dominated environment (Table 11), but it has significant differences in the percentage of the main lithological components, which reflect important environmental changes.

The sand/mud ratio ranges from low to moderate, and a decrease in coarser sandstone is observed as well as an increase in limestone (20% of this zone). The sedimentary units exhibit a great variety of sizes and shapes, as well as vertical and lateral variations in components and structures. They range from isolated lenticular beds observed only in one section to units laterally continuous for 20 km. They will be discussed in

Chap. 5 as part of the discussion of the sedimentology of the lacustrine environment.

Most of the sedimentary structures listed for zone A (Table 11) are present, but increases in the percentage of small-scale current structures (i.e., variable ripples and small-scale trough cross-stratified beds) and in the tabular horizontally laminated units are observed. Small-scale coarsening-upward sequences, reflecting infilling of shallow lakes, are numerous.

Channels form 25% of zones B and D. They have the same characteristics as those in zones A and C but there is an increase in the abundance of suspended load deposits. This is reflected in the greater number of simple, isolated channels compared with the multistory type. The smaller channels are mostly simple channels averaging 2 m in thickness. The largest multistory channel observed is 10 m thick, and lateral equivalents can be correlated for 7 km between the New Waterford and the Glace Bay East sections (Appendix B, Fig. 4). Where the channel sandstones are common, the limestone beds are relatively uncommon. Zones B and D are a series of fluvial-floodplain units alternating with thinner lacustrine (limestone) units. The deposits formed during each of these range from 6 to 13 m in thickness. Within each channel sandstone cycle the channel sandstone bodies grade laterally into equivalent crevasse-splays and/or fine-grained floodplain sediments.

The pattern of coal accumulation in zones B and D are less continuous than in zones A and C and coals are more difficult to correlate laterally. Because of lack of good coastal exposures, only the Backpit and the Bouthillier seams can be correlated from Victoria Mines to Glace Bay East. The pattern of minor coals shows a complex spatial distribution and relationship with limestone-bearing intervals and the associated channel sandstones, crevasse-splay sandstones, siltstones, shales and the fine overbank material. Generally, coals are found in three main subenvironments: the interlacustrine-splay subenviron- ment, the interfluvial-crevasse-splay subenvironment and the interfluvial- channel-proximity subenvironment.

The floodplain-dominated zone forms zone E (Appendix B, Figs. 5 and 6). Zone E is 100 m thick at New Waterford. It is mainly composed of 70-80% variegated fine clastic material exhibiting local purple-red (hematitic) staining and mottling, 10-20% sandstone, mostly as crevasse-splay and isolated splay channel deposits, and 5-10% discontinuous, minor coals and calcareous pond and paleosol units. The rivers feeding such splays are only observed locally. Rocks of this environment form the greatest percentage of the Morien North section, which was not correlatable with the other sections.

The main characteristics of the floodplain-dominated environment are given in Table 11. It represents flood basin environments receiving fines from overbank flooding and sandstone as proximal and distal splays. The purple-red mottling and staining suggest that soils were subjected to variable drainage with fluctuating water tables. Periods of subaerial exposure are evidenced by the occurrence of numerous desiccation features and calcareous paleosol units. Local discontinuous coal occurrence and lenticular calcareous pond deposits suggest periods of temporary swamp cover and ephemeral surface pools.

4.4 Markov chain analysis and paleocurrents

4.4.1 Introduction

Markov chain analysis is used in sedimentology and stratigraphy to determine if facies transitions are random or part of a Markov chain. Till

(1974) defines a Markov chain as "...a process in which the probability of transition from one state in the chain to the next depends on the previous states." A Markov chain of the first order is one in which only the immediately preceding state influences the following state. In cases where earlier states influence the following state the chain is said to be of a higher order.

If facies transitions are part of a Markov chain, the sequence of transitions can be compared to a sequence predicted by "Walther's law," and an interpretation of the sequence in terms of cyclicity or "repetition of facies" can be made. The Markov analysis can be used to outline and detail specific depositional processes and refine facies models (Walker, 1979). Methods, analytical procedures and examples of stratigraphic applications of the Markov chain analysis are outlined in Gingerich (1969), Krumbein and Dacey (1969), Dacey and Krumbein (1970), Miall (1973) and Casshyap (1970, 1975). Mathematical and statistical aspects are discussed extensively by Anderson and Goodman (1957), Billingsley (1961), Gingerich (1969), Harbough and Bonham-Carter (1970), Agterberg (1974, chap. 12) and Schwarzacher (1975, chap. 5).

4.4.2 Application to measured sections

Markov chain analysis was carried out on all of the measured sections. The following sections were run individually: Victoria Mines, New Waterford, Glace Bay West, Glace Bay East, Donkin West, Donkin East and Schooner Head. The Morien South and North sections were run as one unit. In addition, a composite section was analysed by linking separate sections with transitions.

The data for this study were analysed with the aid of a computer program of the "embedded Markov chain analysis" type modified from one outlined by Miall (1973). The results obtained are presented in Appendix C.

The data were obtained by recording vertical transitions between facies from all measured coastal sections. Ten facies were used, mostly corresponding to the depositional facies defined in the previous section of this chapter. These are: Se, St, St lam, Sr, Sh, Fl/m, Coal (C), Fm sid, Ls-f and Ls-m. Facies Sr, Sh, Fl/m, C and Ls-m correspond to their depositional facies counterparts. Facies Ls-f corresponds to depositional facies Ls:algal. Depositional facies St has been split arbitrarily into facies St for trough cross-stratified beds thicker than 15 cm and facies St lam for beds less than 15 cm. Facies Fm sid was established in order to outline any significance of siderite material in terms of cyclicity. It corresponds to those units of depositional facies Fm exhibiting noticeable sideritic content.

All values for Transition Count Matrix, Transition Probability, Difference Probability Matrix, Independent Trials Probability Matrix and for two Chi square tests carried out are included in Appendix C. A Facies Transition Diagram was constructed (Fig. 18) from the values of the most probable transitions in the difference matrices (listed in Fig. 19 and Table 16). This diagram provides an indication of the processes active at the time of deposition (Walker, 1979). The results obtained were compared with published data to facilitate interpretation of the depositional environment of the various sequences. The sections were also compared to each other in order to determine any significant vertical or lateral changes present.

4.4.3 Analytical results and cyclicity.

The Markov chain analysis is an important tool for facies analysis in sections showing cyclicity. Facies sequences from all sections of this study were combined to give 3,266 transitions between the ten facies recognised from all sections; transition count and difference matrices are presented in

Appendix C and Fig. 19. The Chi square tests showed significance at the 99.9% confidence level, and the statistically derived Facies Transition Diagram is illustrated in Fig. 18. Cyclicity is an important characteristic of the Sydney Mines Formation. In some cases the cycles are thick successions of markedly different types of rock, or in other cases they are marked by more subtle, but very significant, variations in lithologic character.

Previous studies of cyclicity in coal-bearing successions have been extensive and varied, especially in Europe (Allen, 1964, 1970) and North America (Duff et al., 1967). A review of the different definitions of such cycles will not be attempted here. In the present study, the presence of a marked and well-defined scoured erosional base (Se) in the lower very coarse to coarse-grained sandstone member has been adopted as the main criterion for separating cycles.

Cycles observed in the Sydney Mines Formation can be divided into fining-upward and coarsening-upward types. The total number of occurrences, range and average thickness and type of cycles ≥ 1.5 m for each section are given in Table 17.

The main characteristics of the cycles can be summarised as follows:

1) cycles of fining-upward type are more numerous, generally thicker and have a better defined succession of facies than the coarsening-upward types;

2) 100 fining-upward cycles averaging 3.4 m and ranging from 1.5 to 11.0 m in thickness have been recorded and are reasonably constant in number and thickness in the different sections;

3) the numerous cycles observed thinner than 1.5 m were excluded from this compilation;

4) coarsening-upward cycles are thinner (range 1.5-5.0 m), with the thicker cycles representing small-scale lacustrine delta-type bodies. Most coarsening-upward cycles are related to the finer-size facies transitions of Fig. 18.

Transitions such as those illustrated in Fig. 18 are abundant in every section (figures from Appendices A and B). The cycles observed have been divided into two subenvironments by analogy with modern fluvial systems. These are channel deposits and overbank-lacustrine deposits (Fig. 18).

4.4.3A Fining-upward channel sequences

The dominant type of cycle is a fining-upward channel sequence comprising roughly three main parts. The lowest is a conglomerate-coarse sand assemblage lying on an erosional surface (Se). This unit is overlain by fining-upward sand members (St, St lam, Sr) capped by a siltstone-mudstone-shale complex (Fl/m). The cycle is terminated by an underclay member with variable content of sideritic nodules (Fm sid) and finally coal (C).

Cycles conforming to this general sequence are abundant in every section measured (Table 17), but the degree of "completeness" of this cycle shows great variability. The subdivision of the sedimentary package into two distinctive subenvironments is of extreme importance in the interpretation of the sequence in terms of hydraulic events related to the alluvial system under consideration, because each distinctive unit represents variation in the hydraulic energy of the system.

The more subtle and thinner fining-upward sequences (overbank-lacustrine subenvironment) are not considered here to form independent cycles. The main reason is that they are related laterally or vertically to the sandstone units.

The most probable transitions in all of the sections of the Sydney Mines Formation are shown in the facies transition diagram (Fig. 18). The corresponding composite section is similar to the meandering river facies model of Allen (1970) and Walker (1979). The sequence is divided into channel floor, point bar, bar top and overbank deposits.

The Sydney Mines Formation is characterised by an alternation of sandstone and mudstone sequences. The mudstones and associated fine-grained rocks commonly make up at least 50% of any section, but their true abundance is probably greater, on account of their recessive weathering. The typical fining-upward channel deposit sandstone sequence is about 5 m thick and fines upward from a distinct erosional base (Se) overlain by a lag deposit containing plant fragments and intraclasts of mudstone or siderite nodules.

This base commonly cuts into facies Fl/m or C. Locally lag components may form discrete beds. Imbrication is not developed except in a few rare exceptions. Stacking of several such bodies separated by erosion surfaces and thin, discontinuous mudstone layers also occurs in the deepest axial part of some channels.

The enclosing sandstone member decreases in grain size upward from very coarse to coarse-medium. The lowermost part of this sand body is usually massive, unlaminated or can be poorly to irregularly bedded. An assemblage of shale, coal, organic and nodular debris as well as oriented logs and tree trunks commonly forms the bulk of this deposit. This lithological assemblage usually forms the main filling material of the deepest part of the channel.

Se grades upward into well-developed trough cross-stratified facies (St and St lam). Trough size and thickness decrease upward from roughly 60 cm at the base to 5-15 cm in the trough cross-laminated beds (St lam). The cross-stratified units may be laterally continuous, forming well-developed cosets, or they may be separated by thinner beds of horizontally laminated sandstone (Sh) or by siltstone-mudstone laminations (Fl/m). Erosional trough bases are commonly observed in this troughed package. When fully developed, a general upward decrease in grain size from medium to fine sand grade is observed. Similar decreases in grain size can be observed within the thicker troughs. When fine sand is abundant enough, the cross-laminated sandstone beds are overlain by horizontally laminated to homogeneous beds (Sh). These beds rarely exceed 1 m in thickness. The bedding surfaces commonly show great abundance of mica flakes and carbonaceous debris, forming well-defined and thicker laminations. Current lineations are commonly well developed in these beds, especially when the carbonaceous debris content is low.

When Sp is present it is closely associated with St toward the top of the fining-upward sequence. Ripple cross-laminated (Sr) fine sandstone may follow St or Sh. The sequence S lag - St(Sp) - St lam - Sh - Sr is interpreted as the product of in-channel deposition. Facies Sr is also included in the overbank deposit subenvironment and is usually followed by Fl/m, Fm sid and/or Coal (C).

Fine- to very fine-grained sandstone separated by thin siltstone laminations terminates the sandstone sequence. This last phase shows current-ripple cross-laminations (Sr), which decrease upward in amplitude. Climbing ripple-drift cross-laminations are more common in the siltier units and usually mark the last unit before the advent of the overbank-lacustrine package. When climbing ripple-drift lamination is not developed, crumbly mudstone beds with few discontinuous silty thin beds and isolated asymmetric ripples close this sequence. Mottling, bioturbation, local boring and concentrations of small-sized random and layered siderite nodules are also present.

Although the Morien North section is composed mostly of red-purple sandstones and fine clastics, the facies types and characteristic cyclic sequence of the upper Morien Group are present throughout the section. Main cycles are therefore interpreted as meandering-fluvial channel sequences, the red colouration being due to secondary influences such as water table level.

4.4.3B Fining-upward overbank sequences

In all of the sections coal shows a strong tendency to follow facies Fl/Fm. This is expected since coal tends to accumulate in association with fine-grained material in areas suitable for peat accumulation. The transition from Sr to Fl/Fm is interpreted as the result of waning flow conditions. Other Sr transitions are to Sh and St, during increasing flow conditions. One other highly probable transition common to all of the sections is from St to Sh.

The channel sequence is overlain by a highly varied complex of interstratified and/or homogeneous beds of very fine sandstone, siltstone, mudstone, shale, limestone and minor coal occurrences.

Variation in composition of these components as well as the great diversity of lamination types characterise this subenvironment. Fine and very fine, well-defined to faint laminations are also conspicuous, especially in the more homogeneous shale, mudstone and siltstone beds. This sequence is also characterised by a number of variable types of small-scale fining-upward sequences discussed below.

Underclays commonly have a sharp lower contact with the underlying mudstone (i.e., silty mudstone to muddy siltstone). The lower half of the unit generally contains sideritic nodules, both as random and thinly bedded units. Abundant rootlets are commonly present below the coal or a highly carbonaceous shale unit, which completes the full sequence.

Non-deposition and erosion can greatly alter this sequence. There are many internal rearrangements of the units in response to changes taking place in the environment of deposition, which can further modify and alter the basic cycle.

The overbank assemblage is interpreted as the product of vertical accretion, with calm overbank and higher energy crevasse-splay sedimentation in flood basins. The thinner (0.5-2.0 m), fining-upward cycles are observed in all sections and show repetitive facies sequences. The most common ones are: Se→Sr+Sh→Fl/m, Sr→Sh→Fl/m; Fl/m→Ls:algal (Ls-f). These units are formed in the flood basin environment but are intermediate in character between fluvial channel sandstones and the flood basin distal crevasse-splay deposits. The first two are interpreted as more proximal crevasse-splay deposits with facies sequences resulting from decreasing flow strength (Leeder, 1973b) and the third as fill sequences of flood basin ponds or lakes.

In summary, facies St and St lam are the most abundant in channel sequences while Sp is the rarest. The most common transitions are (Table 16, Fig. 18): S lag (Se)-St, St-St lam, St lam-Sr, Sr/Sh-Fl/m. In the overbank-lacustrine sequences facies Sr and Fl/m are the most abundant, and the most common transitions are: Sr-Fl/m-C-Ls:algal. Transitions in this subenvironment exhibit greater variability, and reversal of transitions between facies is frequent. The tendency for Sh and Sr to alternate in the measured sections is attributed to deposition near the point-bar tops and possibly in near-channel proximal levees.

4.4.3C Coarsening-upward sequences

In contrast, coarsening-upward sequences are much less common and are in addition thinner and finer grained. Typically they are about 1 m thick and grade upward from mudstone to siltstone or from siltstone to very fine or fine sandstone. The dominant internal structures are ripples; plant roots are also present in most cases. Most examples are related to sequences enclosing coal or as small-scale deltaic-type lobes infilling lacustrine bodies (see section 5.3.3).

For example, in the sequence above the Phalen seam in the Victoria Mines section (App. A, Fig. 1) the cycle begins with a black, muddy shale carrying extensive fragments of ostracods. However, more generally the sequence begins with a silty mudstone, locally showing bioturbation, with numerous silty interlaminations and streaks with plant fragments. The silty fraction increases upward to thicker stratified muddy siltstone and finally purer siltstone beds. When the cycle is complete, the capping unit is a silty, fine to very fine sandstone with isolated current ripple lenses of low amplitude. This grades upward into ripple drifted or current ripple laminated siltstone or fine-grained sandstone. Sideritic nodules can be concentrated at the base of the sand members. This sequence, after repetition, may pass upward into a fining-upward cycle, or it can be overlain by an underclay with an overlying highly carbonaceous bed.

The coarsening-upward sequence records the submergence of the coal forest and swamp beneath a body of fresh water and the progradation of a depositional lobe into this water. The ostracods are characteristic of freshwater environments. A gradual silting up of the basin with a decrease of biogenic activity follows as a result of increased current competency derived from an approaching active channel. The complete filling of such lacustrine-type depressions eventually leads to emergence, regrowth of the flora (and eventually coal), and diversion of the drainage to regions of lower elevation.

Smaller scale coarsening-upward sequences also representing infilling of the interdistributary floodplain areas are present in the sections as well. These are the result of overbank flooding, crevassing and avulsion processes by which sediment-laden flood waters are transferred to the interdistributary area. The resulting bodies are the crevasse-splay deposits observed in the floodplain part of the sections.

Coarsening-upward sequences observed in the limestone package and representing lake delta fills with lacustrine limestone at the base will be discussed in section 5.3.3.

4.4.4 Cyclicity: mechanisms of formation

Cyclic sequences from the Appalachians with generally similar characteristics to those of the Sydney Mines Formation have been described by Duff et al. (1967) and Belt (1968a,b). Several mechanisms have been proposed by numerous workers (Wells, 1960; Beerbower, 1964; Pearn, 1964; Duff et al., 1967; Miall, 1980) to account for the formation of cyclothems. These can be divided into three main groups (Murchison and Westoll, 1968):

1) mechanisms involving periodic relative movement of land and sea levels, such as

a) repeated subsidence of the area of sedimentation followed by sedimentary accumulation to or above sea level, either simply or with oscillations,

b) eustatic movements controlled from outside the basin (allocyclic mechanisms of Beerbower, 1964) by glacial control or as a result of changes in the ocean floors or tectonic movements,

c) repeated uplift and erosion of the continental hinterland;

2) mechanisms involving repeated climatic changes (glaciation-deglaciation, etc.);

3) mechanisms whereby cyclic effects result from steady change, such as

a) isostatic adjustments,

b) adjustment to tectonic stress,

c) trapping and releasing of sediments from heavily vegetated swamps,

d) effects of compaction of sediments,

e) effects related to the continuous action of sedimentary processes in rivers and deltas (autocyclic mechanisms of Beerbower, 1964).

None of the theories listed above can account alone for the formation of cyclothems, but there is greater agreement in general that sedimentary cycles are related to more-or-less regular eustatic changes of sea level affecting a slowly subsiding basin of deposition, without having to invoke glaciation to account for all sea level fluctuations. Eustatic sea level changes can be caused by alteration of the total volume of water on the earth's surface, by growth and decay of glaciers, and by alteration in the shape of sea basins by sedimentation and tectonic or isostatic movements. The last factor is probably the one most capable of sufficiently affecting worldwide sea levels.

For Allen (1964) cyclicity in the Lower Old Red Sandstone, Anglo-Welsh Basin has three explanations:

1) Autocyclic mechanism: each river wandered across a portion of the floodplain under conditions of steady subsidence and sediment supply.

2) Autocyclic mechanism: influenced by allocyclic sea-level changes, the rivers in unison alternately eroded and aggraded the floodplain under steady subsidence and sediment supply conditions.

3) Allocyclic and autocyclic mechanisms: bursts of tectonic activity in the source area, which led to increased sediment supply through rejuvenated streams, caused the rivers alternately to erode and aggrade the floodplain. Base level and rate of subsidence of the basin need not have varied.

In view of the previous discussion, a predominantly sedimentary origin (autocyclic) of the cycles is the most probable mechanism operating in the study area. Autocyclicity is best expressed in 1)fluvial-migration and avulsion, and 2)floodplain flooding and build-ups. Both of these processes have "built-in" autocyclicity (Allen, 1982) taking place without the need of "external agencies" such as changes in sea level or tectonism (Allen, 1964; Beerbower, 1964). The Sydney Basin is a typical example of autocyclicity because 1)the entire Morien Group is a fining-upward sequence (≃1800 m thick), indicating gradually decreasing tectonic influence, 2)absence of marine bands, even though the upper Morien Group was deposited near base level.

The characteristics of the main coal seams as well as the lateral continuity of the lithostratigraphic zones indicate that the basin was undergoing a relatively constant rate of subsidence (allocyclic control) with steady supply of sediment. In particular, the extensive thin coal seams indicate a rate of subsidence permitting maintenance of plant growth for long periods of time and over a wide area. Compaction was also an important factor. An initial tectonic influence (see Chap. 6) followed by constant subsidence is also reflected in the change from the underlying braided system of the South Bar Formation upward into the meandering system of the Sydney Mines Formation (Rust et al., 1983). No marine incursion related to sea level change and no important influx of a thick coarse package of sediments related to abrupt rejuvenation are observed in the Sydney Mines Formation.

Paleo-topographic control probably had some local influence on the locations where the coal swamps developed. This topography was the main control of the thickness and of the lateral continuity of the coal seam. The internal processes within the swamps, such as plant growth and plant decay, and the environments coexisting laterally with the peat swamp directly affected the lateral continuity and the variations in thickness of the seams. Post-depositional processes, such as channelling, caused local thinning.

4.4.5 Paleocurrents: data and significance

Methods used in this study for the processing, plotting and interpretation of paleocurrent data are those outlined by Curray (1956), Collinson (1971), Pettijohn (1962), Allen (1966), Cant and Walker (1976) and Miall (1974, 1976). Paleocurrents were measured from a variety of unidirectional and bidirectional sedimentary structures with axes of trough cross-strata and flute casts from the base of sandstone beds being considered the most reliable unidirectional paleocurrent indicators. Other directional features measured include planar cross-strata, channel trends, ripple mark crests and cross-laminae, groove casts, parting lineations and aligned large-size logs, plant remains and rip-up clasts. For all sections, 535 crossbeds, 223 ripple-foreset (crest axis and direction) laminations and 83 parting lineations were measured. In many cases channel trends were construed as direction on the basis of directional internal structures.

The breakdown for each section is given in Table 18. Directional properties in beds exhibiting soft-sediment deformation were ignored. Orientation data from the various structures measured are expressed in Figs. 20 and 21 as mean azimuths for each section, with adjacent numbers indicating the number of observations included for each mean. The most striking result is the general uniformity of paleocurrents toward the northeast for all stratigraphic levels in the Sydney Mines Formation.

Looking at the paleocurrent variations by depositional facies and in fining-upward sequences, we can observe several significant characteristics. The general trend of current directions is toward the northeast, with a 40-70° variation on either side of the mean. This range of variation (70-130°) is believed to be an expression of the lateral and downstream migration of point bars in meander loops, which results in a vertical sandstone sequence with divergent cross-stratal attitudes. The more sinuous channels of meandering streams generally result in more variable paleocurrent distribution with vector magnitudes lower than comparable structures in braided systems. However, many other factors can influence vector magnitude, notably the rank of the structure studied (Miall, 1974).

The trough cross-bedded units in the lower part of the cycle show variations in mean paleocurrent directions coinciding generally with the northeasterly measured orientation of the channel axes. This confirms the origin of the trough cross-strata by downstream migration of sand dunes along the general axis of the channel. The variable and progressive divergence of some of the cross-bedded units from the general channel direction indicates divergence due to helical circulation of current within the channel (Allen, 1966).

The greatest deviations from the general direction are observed in the finer cross-stratified and rippled capping units of the sequence. This indicates that the principal components were deposited by overbank flooding or progressive filling of abandoned channel by more gentle currents, accompanied by suspension deposition. Measurements noted in ripple-foreset laminations and parting lineations obtained from sand bodies interpreted as levee and crevasse-splay deposits indicate subsidiary sediment transport trends to the northwest and southeast, approximately perpendicular to the main northeasterly transport direction.

The pronounced northeasterly dispersal pattern of paleocurrent measurement documented in this study corroborates the regional trend shown by Duff et al. (1982) and Giles (1983) and shows a close correlation with the strike of channel sandstone bodies mapped in underground workings (Forgeron, 1980), interpreted here as high-sinuosity channels within a lower sinuosity meander belt. This indicates a source area to the southwest of the Sydney coalfield, and not in the Cape Breton Highlands as had been suggested previously (Giles, 1983).

However, the results for the Sydney Mines Formation show more diverse dispersal pattern directions. Giles (1983) suggested that fanning of trough axes around the northeasterly extremities of the Boisdale Hills indicates basement control on regional paleocurrent patterns during deposition of the lower Morien. The more diverse dispersal pattern within the upper Morien Group subdivision reflects the upward change from a braided to a meandering fluviatile system and is consistent with the appearance in the upper subdivision of significant proportions of shales and silty shales, representing overbank deposits within a broad floodplain (Rust and Masson, 1981, and Rust et al., 1983).

4.5 Factors controlling the fluvial system in the Sydney Mines Formation

4.5.1 Introduction

The characteristics of the deposits produced by streams exhibiting greater sinuosity are particularly well known and have been the object of extensive discussion in the literature (Fisk, 1944, 1947; Brice, 1974; Allen, 1965a,b; Collinson, 1978a; Walker and Cant, 1984). Diagnostic characteristics include geometry of the channel deposits, presence of epsilon cross-stratification, presence and extent of fine-channel fill, position and extent of levee deposits and paleocurrent pattern. From previous sections, it is clear that the fluvial system in the Sydney Mines Formation has all the characteristics of mixed-load, high-sinuosity, low-gradient streams within a meander belt with lower sinuosity in which cyclicity is due to migration and avulsion of meandering channels in a constantly subsiding basin.

Factors controlling channel patterns considered important in the literature (Leopold and Wolman, 1957; Schumm, 1968, 1972; Coleman, 1969; and Stewart, 1981; Bridge, 1985) include gradient, discharge, sediment load, bank stability, width-depth ratio of channels, and paleoclimatic setting. An evaluation of these variables for the Sydney Mines Formation must be attempted before a complete evaluation of the depositional environment can be achieved.

Schumm (1960a,b) and McGowen and Garner (1970) have demonstrated that mixed-load streams have a more sinuous pattern than do bed-load streams characterised by high bed-load/discharge ratio. Mixed and suspended load streams are also characterised by low width-depth ratios and meandering channels. Discharge and sediment load are critical factors controlling channel pattern as well. The high mud content in the Sydney Mines Formation indicates that the banks were muddy and therefore stable. Bank stability is a cause of sinuosity in mixed-load channels, which carry much suspended material necessary for building thick and laterally continuous floodplain sequences.

Schumm (1968) estimated that the expected width-depth ratio for mixed-load channels is approximately equal to ten. Thickness and lateral extent, measured and estimated on the coastal sections, of channels and sandstone bodies of the Sydney Mines Formation are listed in Tables 12 and 13. The mean width:depth ratio observed on the coastal sections is 1:15.

4.5.2 Quantitative estimate of flow parameters

Methods for determining the morphology and flow parameters of ancient streams have been outlined by Moody-Stuart (1966), Schumm (1972), Leeder (1973a), Cant and Walker (1976), Ethridge and Schumm (1978) and Collinson (1978b). Problems related to the interpretation of the results of such methods have been discussed by Collinson (1978b), Jackson (1978) and Bridge (1985).

Ethridge and Schumm (1978) estimated paleoflow parameters on the basis of width and depth of channels only. Assuming that the full depth of a channel at a meander bend is represented by the thickness of a single-channel deposit (i.e., the top of the last cross-stratified unit or epsilon cross-strata in a fining-upward unit), the thickness of such a typical individual Sydney Mines Formation channel deposit is taken to average 6-8 m (Table 12). Ethridge and Schumm (1978) proposed the use of a correction factor to compensate for the depth in straight reaches being less than that in meander loops. No adjustment factor for compaction was recommended by these authors for sands subjected to shallow burial similar to sands of the Sydney Mines Formation.

Width of paleochannels is more difficult to estimate than depth. The width of the channel sandstone body measured on an outcrop is taken to represent the thickness of the meander belt (Walker and Cant, 1984). Leeder (1973b) and Collinson (1978b, p.582, Fig. 2) have suggested a method for prediction of meander belt width in relation to channel depth, taking into account field relationships. Utilising this method, taking the average thickness of the channel sandstone bodies (listed in Table 12) as 8 m and an average dip of 8-10° for the epsilon cross-stratified beds measured, results in a channel w:d of 1:90 and a meander belt width averaging 700 m. This value fits reasonably well with Forgeron's data on channel sandstone bodies from mining (in Duff et al. 1982).

This value for meander belt width must be used with caution since a change in angle of dip at the base of the channel can cause considerable variation in width. Some channel sandstone bodies might be narrower because of early avulsion followed by abandonment channel fills while others would be wider due to lateral amalgamation of meander belt sandstone. The high values for the lateral extent of channels obtained from the correlations of Appendix B (listed in Table 13) can be explained by the fact that the cliff exposure of these channels is only partial and that many of these extensive channel sandstone bodies observed are largely amalgamated sandstone bodies (Appendix B, Figs. 1-6).

4.5.3 Modern analogs

Although some of the sedimentary sequences of the Sydney Mines Formation were apparently deposited in standing water (i.e., lacustrine environment), no major coarsening-upward sequences or marine strata were observed and there is no evidence that a large body of water was being infilled by sediments; there is no evidence therefore for marine deltaic deposition.

Many aspects of the sequence, however, show similarities to upper delta plain sequences (Bates, 1953; Moore, 1966; Leblanc, 1975). The upper delta plain of the Mississippi, for example, has a large meandering river, levees with crevasse-splays, densely vegetated swamps and extensive shallow lakes (Coleman and Gagliano, 1964). One important difference from the Sydney Mines

Formation environment is that some of the delta lakes are connected to the open sea.

The salinity tolerance of Carboniferous ostracods and bivalves is still debated, and it could be argued that in the Sydney Mines Formation their occurrence indicates invasion of brackish water. A delta top model could then become a possibility (Ferm and Cavaroc, 1968; Coleman and Wright, 1973; Donaldson, 1974). This argument is doubtful for the Sydney Mines Formation and cannot be applied in light of the fact that not one truly marine fossil or indicator has been found in any part of the exposed coastal sections or in 10 km offshore cores measured. There is therefore no evidence of any associated marine sediments of lower delta or delta top sequences. What then would be an ideal modern analog to the fluvial system of the Sydney Mines Formation?

Modern analogs with similar parameters and characteristics are the Brazos River of the Texas coastal plain (Bernard and Major, 1963) and the Atchafalaya River flood basin in the lower alluvial plain of the Mississippi River (Coleman, 1966; Frazier and Osamik, 1969). Although neither river basin exhibits significant peat accumulation, similarities in the fluvial processes and products make them acceptable (although imperfect) analogs to the fluvial system of the Sydney Mines Formation.

The most striking comparable features are the presence of freshwater lakes and the laterally extensive swamps. Swamp deposits are 40-50 km across in the Sydney Mines Formation, if we exclude the Backpit as being exceptional. In the Atchafalaya River basin these freshwater shallow lakes and ponds cover more than 500 km^2 and constitute one of the most important subenvironments (Coleman, 1966; Frazier and Osamik, 1969). These lakes exhibit great variety in shape, size and extent (diameter varying from 0.5 to

20 km). Coleman (1966) proposed local subsidence and compaction as the mechanisms for peat accumulation. A major difference is the poor productivity of peat formation. Lacustrine delta deposition and equivalent lake-splay deposits resulting from stream diversion and flooding are also important in the Atchafalaya. These are all important characteristics observed in the Sydney Mines Formation. However, carbonate deposition appears to be more diversified and volumetrically important in the Sydney Mines Formation (see Chap. 5).

The backswamps of the Atchafalaya River flood basin were divided by Coleman (1966) into poorly drained (reducing conditions) and well-drained swamps (fluctuating oxidizing and reducing conditions). The coals deposited in the lacustrine-dominated environment of the Sydney Mines Formation were probably deposited under similar depositional conditions (i.e., backswamps and marginal flood basin to lakes, ponds and levees) (see Chap. 5).

4.5.4 Paleoclimatic controls

The detailed study of the sediments of the Upper Carboniferous of Nova Scotia by numerous authors (see Chap. 2) indicates a progressive change of climatic conditions from the lower Namurian (arid conditions with evaporites) to humid conditions in the Westphalian (of major river systems and abundant coal deposition).

The previous discussion of the characteristics of the lithostratigraphic zones (Chap. 2) as well as the preceding discussion in this chapter reveal that the sediments of the Sydney Mines Formation were deposited on an alluvial plain subject to frequent periods of flooding and local periods in which water tables were somewhat lower. These periods are best observed in lithostratigraphic zones B and C (Figs. 4, 5 and 6 of Appendix B), in the Morien North section (Appendix A, Fig. 8) and as alternating beds of hematitic sandstones and finer clastics at numerous localities, especially above the Harbour Seam (Appendix B). The major sandstone bodies with the presence of numerous channels, point bars, etc., reflect a relatively humid-pluvial paleoclimate, whereas the redbed sections would record intervals of lower fluctuating water table, perhaps recording drier intervals within a generally pluvial paleoclimate.

The presence of thick coal seams indicates conditions sufficiently humid to insure widespread swamps and shallow lakes and permit abundant plant growth. This suggests a warm, humid-subhumid, tropical (?) paleoclimate. The variation in thickness of the seams observed reflects any or combinations of the following:

- slow or rapid accumulation of vegetation;
- slow or rapid burial rates;
- fluctuating groundwater levels;
- repeated subaerial exposure of decaying vegetation.
- interrupted growth with switching of fluvial channels.

Evidence of vegetation (roots, plant debris, upright and transported logs, large plants and trees -- i.e., Calamites, Sigillaria) are also indicative of humid conditions.

The presence of sideritic nodules (see discussion, Chap. 3) in modern environments requires a mildly reducing environment (see discussion, Chap. 3). It is a common phenomenon in subhumid to per-humid areas where periods of considerable rainfall alternate with periods of lesser rainfall (Murchison and Westoll, 1968; Spackman et al., 1969). The presence of sideritic nodules below the seatearths in the Sydney Mines Formation is taken to indicate paleoclimate in which fluctuating rainfall was conducive to coal formation.

The presence of pedogenic calcrete units at several locations in overbank sediments (see Chap. 3) in the Sydney Mines Formation is generally taken as a local indicator of relatively dry conditions and/or subaerial exposure. Formation of pedogenic calcrete units in modern environments reflects interaction between precipitation, temperature, runoff, soil texture and relief (Blatt et al., 1980) and is indicative of a humid paleoclimate with a periodically lower water table and drier intervals within a generally pluvial paleoclimate (James, 1972; Reeves, 1976; Blatt et al., 1980). This interpretation is supported in the Sydney Mines Formation by the presence of desiccation cracks, interlaminated red-purple hematitic beds and the low percentage of preserved organic matter locally.

A gradual but significant climatic change is observed in the upper part of the Sydney Mines Formation above the Harbour Seam (Appendix B, Figs. 4, 5 and 6). This change manifests itself in the sedimentary package by:

- the increased number of small-sized and confined splay channels and their associated splays and levees;
- the presence of laterally and vertically extensive red-purple (hematitic) fine clastic sequences with locally rooted beds and minor carbonaceous shale layers;
- lack of marine influence with the environment dominated by shallow lakes and ponds and their associated floodplains;
- the predominance of fine clastics and mudrocks over the coarser sandstone lithofacies;
- increase in the presence of desiccation cracks and local abundance of calcrete in association with secondary coals and/or carbonaceous shale.

These features seem to indicate a decrease in rainfall and humidity expressed in a decrease in the importance of lateral channel migration. The paleoclimatic indicators point to a lower energy of the alluvial regime during extensive periods in which rainfall was less and the water table fluctuated. The association of calcrete and secondary coals reflects a rise of the water table between the time of calcrete formation and peat deposition (Reeves, 1976). Similarly, fine-clastic to non-clastic deposition was controlled at times by fluctuations of the water table.

4.6 Diagenesis of the sandstones from the Sydney Mines Formation

4.6.1 Introduction

Diagenetic reactions are defined as "those that occur in a rock from the time the crystals or grains are deposited until the time the texture or mineralogy of the ensuing sedimentary rock is markedly changed" (Blatt, 1979). Sandstone diagenesis is controlled by a wide variety of interdependent processes, including: range of temperature and pressure, burial rate, sediment composition and texture, sedimentary and tectonic environment, chemical reaction rates, degree of lithologic variation, and hydrodynamic and geothermal gradients (Blatt et al., 1980; Friedman and Sanders, 1978).

Common processes of diagenesis involve: 1)compaction, 2)cementation and addition of new material, and 3)dissolution and removal of material and transformation of material by change of mineral phase or replacement of one mineral phase by another (Friedman and Sanders, 1978). Physical changes, such as compaction, fluid migration and pressure solution, are accompanied by chemical changes caused by mineral reactions, mineral replacement, cementation and dissolution. Fluids have a great influence on diagenesis, and diagenesis in turn controls fluid movement and the location of redeposited cements.

Petrographic study of 146 thin sections of sandstones and fine clastics obtained from cores and coastal sections of the Sydney Mines Formation has yielded information showing a fairly regular recurrence and distribution of primary and secondary cements and after results of diagenetic processes. The purpose of this section is to outline the main diagenetic features observed in these samples and to give a tentative sequence of events (paragenesis). The main diagenetic features discussed will be: burial diagenesis and compaction, primary and secondary clay content, silica cementation and overgrowth, calcite cementation and ferruginous cementation and staining.

4.6.2 Burial diagenesis and compaction

Scholle and Halley (1983) define burial diagenesis as "...the changes in rock composition, mineralogy and texture which occur below the zone of near-surface water circulation, generally becomes the dominant control on rock porosity at depths below a few hundred meters." Porosity loss through burial diagenesis results from both chemical precipitation and physical compaction. Compaction, the reduction in pore space within a body of sediments in response to pressure from the weight of overlying material or from structural deformation, can greatly reduce porosity even in near-surface sections through dewatering, grain reorientation, grain breakage and other mechanical processes (Friedman and Sanders, 1978; Scholle and Halley, 1983).

Compaction affects all sediments but the effects are more important in fine-grained sediments such as silts and clays. This is mainly due to the ease whereby overburden pressure reduces the natural open packing observed in clays. With increasing depth, loss of porosity in shales appears to be largely a chemical process involving precipitation of cements, rather than further mechanical compression (Potter et al., 1980).

The factors influencing compaction in sands are mostly the sorting and shape of particles, types of particles and depth of burial (Blatt et al., 1980). Compaction of quartz sands in laboratory experiments results in a decrease of 10-15% of the thickness of the aggregate as a result of rearrangement and chipping of grains. The increased compaction of sand is inversely proportional to the porosity of the sand (Blatt, 1979). Of great importance is the fact that compaction is greatly enhanced by an increase in the proportion of ductile rock fragments (such as mud clasts, schist fragments, micas and micaceous lithic clasts). These deform easily under a relatively light load. The increased plastic deformation with depth of ductile rock is reflected in the types of grain-to-grain contacts observed (Taylor, 1950). The most common types include: tangential long (strato), concavo-convex and sutured.

Although no quantitative measurements of the percentage compaction of sandstones were obtained, nor were porosity/depth plots constructed for the sandstones of the Sydney Mines Formation, excellent examples of compaction cementation were observed in every sand size fraction of these sandstones. The main evidence of compaction includes:

- pressure-solution sutured quartz grains and silica overgrowth contacts (discussed in 4.6.4);
- compaction and squeezing of ductile lithic clasts (mud clasts, schistose lithic clasts, mica flakes, micaceous lithic clasts) exhibiting well-developed concavo-convex, strato and locally sutured grain-to-grain contacts;
- chipping and fracturing of quartz grains;

- wrapping and bending of ductile clasts around the edges of stronger quartz grains;
- fracturing and reorientation of individual mica flakes and micaceous lithic clasts (Plate 24A);
- penetration of soft clasts by quartz grains with sharp edges;
- squeezing of primary clay;
- stylolitisation of grain-to-grain contacts in samples with predominant calcareous mud clasts (Plate 24B).

Several trends related to sandstone grain size have also been observed:

- a decrease in evidence of destruction of the grain-supported framework with decrease in sandstone grain size;
- a decrease in number of sutured contacts with a decrease in grain size;
- a decrease in evidence of compaction in many fine-very fine sandstones, which is related to 1)finer size of the quartz grains, 2)higher organic content, 3)higher clay matrix percentage, which absorbs most of the compaction effects.

4.6.3 Primary and authigenic clay content

Clay minerals in sandstone are both detrital and diagenetic in origin and exhibit a complex relationship. Because their relative proportion is difficult to determine, they can easily be misinterpreted. Allogenic (or syndepositional) clays are formed prior to deposition and are mixed with the sand fraction during or immediately following deposition. They occur as clay-sized particles and clay aggregates, mainly as part of a dispersed matrix. They also occur in intercalated laminae, mudstone and shale lithic fragments, floccules, biogenic pellets, burrow linings and filling and infiltration residues (Wilson and Pittman, 1977). Authigenic clays develop after burial and include both new and regenerated forms either as a direct precipitate from formation waters (neoformation) or through reactions between primary materials and the contained waters (regeneration -- Wilson and Pittman, 1977). Clays are generally degraded during weathering, erosion, and transport and are subjected to neomorphism (recrystallisation) and regeneration during burial diagenesis.

Clays in the sandstones and fine-clastic rocks of the Sydney Mines Formation are predominantly primary, but authigenic clay is also present locally. The mineral composition of 25 clay and mudrock samples from the study area was determined by X-ray diffraction (Table 3). The clay minerals, in order of decreasing abundance, are kaolinite, illite, chlorite, and minor amounts of mixed illite-chlorite. Kaolinite is by far the most abundant (Table 3).

Carrigy and Mellon (1964) and Millot (1979) have noted that in nonmarine strata the assemblage kaolinite-quartz predominates in quartzose sandstone and kaolinite-chlorite and illite-chlorite in sandstones with lithic content and moderate amounts of volcanic detritus. These observations apply to the nonmarine assemblage of the Sydney Mines Formation.

In the study area, mica content is important and is present in all sandstone sizes observed as mica flakes or micaceous lithic fragments (sizes range from coarse to very fine crystals) exhibiting various degrees of deformation and disintegration. Composition is mostly biotite, but muscovite and chlorite are also present. Feldspar grains are almost all entirely weathered or corroded and are predominantly potassium feldspar with minor plagioclase present locally. The weathering of mica and feldspar is the key to the understanding of the origin of the clay.

The predominant primary clay in all of the sandstones of the study area exhibits the following characteristics:

- presence of impurities (such as silt, Fe oxides and staining) -- this is directly related to the origin of the clay during or immediately following deposition;
- highly variable type and size of occurrence -- it occurs mostly as dispersed clay-sized particles and clay aggregates forming the matrix and local laminations; mudstone and shale lithic clasts and fragments; burrow linings and fillings and infiltration residues;
- pluri-mineralic clay assemblage exhibiting poorly defined outlines of crystals and a low to moderate degree of crystallinity (Plate 25A);
- no pattern or zoning of colour observed in the clay assemblage;
- the clay assemblage exhibits two textures -- 1)VF cloth clay texture, and 2)VF-M mica flakes with a wide variation in orientation (Plate 25A);
- extensive compaction and deformation effects observed in clasts and in the matrix (i.e., squeezing of mud clasts within the matrix);
- little to no recrystallisation of the matrix;
- scattered interparticle filling;
- mixing of primary clay locally with other cements present, such as silica and calcite;
- encompasses all laminations with no change in recrystallisation of the clay.

Kaolin genesis indicates a humid environment and removal of Ca^{2+}, Mg^{2+}, Na^+, K^+, Fe^+, and possibly SiO_2 and the addition of H^+. The $[K^+]/[H^+]$ ratio in relation to H_4SiO_4, and probably Al^{3+}, in solution is significant (Keller, 1970). In quartzose sandstone the volume of pore space that is filled by authigenic clay is very small and kaolinite (or dickite) predominates. The required alumina is brought in by circulating waters (Keller, 1970). At greater depth and in the presence of interstitial water, potassium feldspars and micas in contact with these waters would be unstable and tend to break down chemically into the more stable authigenic kaolinite. Abundant petrographic evidence exists to support the idea that unstable detrital mineral grains in the Sydney Mines Formation sandstone have been converted to kaolinite.

Scanning Electron Microprobe research has proven to be a powerful tool in the identification of authigenic clay minerals but is beyond the scope of this study. Under the microscope the authigenic clay from the study area occurs essentially in the fine-very fine and medium-fine sandstone assemblages. Two main types were observed, with the first forming 90% of the occurrences. These are:

1) fine crystalline aggregates and coatings on the rims of detrital grains, in which the individual clay crystals exhibit some degree of orientation (Plate 25B) either parallel or perpendicular to the grain boundaries; early deposition of such a coating inhibits later precipitation of silica cement;

2) complete filling of pore spaces by a coarser crystalline clay assemblage with a more random orientation of the clay crystals; the clay is uniform in colour and texture and lacks impurities such as silt or iron-pigmented material.

The most reliable criteria for establishing the authigenic origin of the clay of the study area are:

- alteration of original biotite mica to expanded, vermicular crystals of low birefringent kaolinite;
- varying degrees of alterations of potassium feldspar grains to kaolinite;
- composition of clay exhibiting a monomineralic clay assemblage with the absence of impurities and differing significantly from the associated primary clay in both colour and texture, due to replacement and recrystallisation;
- idiomorphic outline of crystals, mostly undeformed and exhibiting alignment of individual flakes;
- greater authigenic content observed in med-F and F-VF sand fraction.

4.6.4 Cementation

A) Silica is the predominant cement in the Sydney Mines Formation; it occurs in every sand fraction. It mostly forms at pressure solution contacts and as authigenic quartz overgrowth of quartz grains, almost entirely eliminating the initial pore space. Chert grains present are not as susceptible to silica overgrowth as are quartz grains because of the variable orientation of the individual silica crystals composing them. Pressure solution and quartz overgrowth cements are commonly the earliest types of cementation to occur. A late-event silica cementation occurring as microcrystalline silica filling microfractures is also present locally.

Pressure solution is characterised by: dissolution of grains at grain-to-grain contacts and by stylolites (Hutcheon, 1983). In the study area, dissolution at grain-to-grain contacts is commonly observed in sandstones (Plate 26A,B) and is particularly important in the coarser grained types. Stylolites are more common in the carbonate rocks (Plate 24B).

Recent experimental work by Sprunt and Nur (1977), DeBoer et al. (1977) and Robin (1978) give excellent descriptions of the theories of pressure solution. Basically, pressure solution develops as a response to the weight of overlying sediments gradually causing readjustment of detrital grains to positions of greater stability in detrital sediments lacking early cementation. With increased pressure, high stresses at small contacts result in welding of these contacts by solution, followed by movement and redeposition of silica at points of less stress. This redeposition continues until the contact area is sufficiently strong to withstand the stress (Blatt et al., 1980). In the study area, pressure solution appears to be the main mechanism of silica release. Robin (1978) concluded that the force across a grain contact is a function of burial depth (weight of overburden), grain size and shape, original grain packing and the degree of pressure solution (i.e., stress applied at contacts). This is directly reflected in the number of contacts per particle and the type of contacts (whether tangential long or straight, concavo-convex or sutured) in the sediments. Solution also plays an important role and is related to 1)strain, 2)rate of flow, 3)chemistry of water, and 4)temperature (Friedman and Sanders, 1978).

In the sandstones of the Sydney Mines Formation tangential long or straight and concavo-convex welded contact types predominate (Plate 26A). Sutured contacts are of lesser importance and are present only locally. The very coarse sand fraction exhibits quartz-welded contacts with a lesser percentage of accompanying authigenic quartz overgrowth than observed in the finer sand fractions. The highest degree of pressure solution-welded contacts is observed in the medium-fine sandstones and in sandstones with high clay content. The predominance of straight and concavo-convex contacts indicates that pressure solution took place at a moderate depth and that quartz overgrowth cement was precipitated following quartz grain adjustment to pressure. An inverse relationship exists between the amount of quartz cement and the abundance of detrital clay matrix. Because of the low porosity and permeability of sandstones rich in clay matrix, the presence of clay minerals retards the formation of quartz cement.

Quartz cement growing outwardly from and in crystallographic continuity with other quartz crystals is called "authigenic quartz overgrowth" (Friedman and Sanders, 1978; Blatt et al., 1980). It characteristically develops around single crystals. This crystallographic continuity between quartz particles and quartz overgrowth makes the identification of the boundary between them difficult.

In the thin sections viewed under the petrographic microscope, the boundary between particle and overgrowth was recognised by the presence of clay minerals, iron oxides and/or inclusions rimming the particle as a dusty border (Plate 26B). In the richer quartz sandstones the separation between quartz particles and cement was inferred by the unusual shape or oversize of the quartz particles and by cathodo-luminescence examination. The abundance of quartz overgrowths was highest in the coarse to fine sand fraction and in those sandstones with lower lithic clast and clay matrix content. Irregular surfaces resulting from quartz overgrowths from neighbouring grains of differing orientation interferring with one another were not observed. Quartz overgrowth characteristically develops around single quartz particles (Plate 26B).

An additional source for silica (in addition to the principal pressure solution source) in the study area could be provided by the diagenesis of clay minerals that on compaction provide silica-supersaturated waters. Siever (1962) and Towe (1962) have shown that the diagenetic conversion of clay minerals (for example, smectite or interlayered smectite-illite to pure illite) might be an important source of silica. The presence of microcrystalline silica cement within a clay matrix as filling of poorly defined pores at a few localities indicates the possibility that small amounts of silica might have been exported locally from mudrocks during their diagenesis. However, there is no evidence of large-scale migration of silica by this process in the study area.

B) Calcite cementation - Carbonate cementation in the study area is more irregularly distributed than is silica cement. It occurs as irregular, discontinuous lenses and/or patches in stratigraphic intervals a few cm to several m thick, exhibiting sharp and abrupt contacts. This irregular pattern corresponds in the subsurface to the often sinuous channels of solution migrating through the sediments. It occurs early in the diagenetic sequence and follows silica cementation.

Calcite cementation in the Sydney Mines Formation is observed in all the sandstone types but is more widespread in medium-fine sandstone. No pattern of deposition was observed other than this greater occurrence in medium-fine sandstone. The calcite cementation occurs either as a crystalline pore-filling cement (poikilotopic calcite cement type, Plate 27A) or as a mud-clay replacement or grain-coating cement (very fine to fine granular calcite cement type).

The main characteristics of poikilotopic calcite cementation (Bathurst, 1975) in the study area are:

- deposition in free pore spaces as sparitic cement enclosing all grains and particle types (Plate 27A); usually confined to thin beds or as local patches of variable extent and/or entirely filling interparticle pore space;

• expansion and pushing aside of framework matrix and individual grains and particles (Plate 27A);

• pushing aside of honeycombed, fractured quartz grains as well as quartz grains coalesced by pressure-solution contacts (Plate 27A) and syntaxial overgrowth cement (this characteristic supports a later origin than silica cement);

• no expansion of framework where primary clay matrix is extensive; in this case granular calcite cementation develops;

• composed of coarse to fine sparitic crystalline rhombs with well-defined rhombohedral cleavage and locally exhibiting typical calcite twinning; readily stained by Alizarin Red-S.

The very fine to fine granular calcite cement type is characterised by:

• occurring mostly as replacement of interstitial clay matrix as disseminated crystals, clusters or patches of granular crystals within the clay matrix;

• also occurring as fine to very fine granular coating of lithic particles;

• crystals showing a variable percentage of impurity inclusions: when this type of cement fills a more open matrix network a slight increase of crystal size and a decrease of impurity content can be observed away from the non-replaced clay matrix;

• composition of fine to very fine crystals lacking well-developed rhombohedral cleavage and exhibiting a variable percentage of inclusions.

Several factors may affect the release (including source) and calcite precipitation in the study area. Carbonate solubility is directly influenced by pH, temperature changes and saturation rates. At a high pH, in excess of 9.5, calcite may be rapidly precipitated (Bathurst, 1975; Friedman and

Sanders, 1978). Similarly high pH and temperature values may promote calcite cementation. The source of calcite is not a problem in the Sydney Mines Formation since calcareous beds are numerous and widespread (see Chap. 5). In addition to proximity to extensive carbonate environments and calcareous beds, other factors leading to calcite precipitation may include:

1) dissolution of calcite from fossiliferous material occurring in the numerous calcareous beds (see Chap. 5);

2) dissolution of limestone by pressure-solution and the subsequent migration and redistribution of carbonate-saturated waters to strata where calcite is precipitated;

3) precipitation of calcite by bacteria (such as methane and sulphate reducers);

4) direct inorganic precipitation yielding near-surface calcite cements.

Boundaries between pressure-solution quartz grain contacts and quartz syntaxial overgrowths indicate that calcite cementation occurred later than silica overgrowth. The sequence of diagenetic events is: 1)compaction of sediments; 2)deposition of silica cement (pressure-solution contacts and quartz overgrowths); and 3)calcite cement precipitation. A late episode of calcite cementation is also observed locally. This late episode is essentially a fine-granular to fine-drusy cementation of leached voids and microfractures grading to fine-drusy calcite cement toward the center of the void or fracture. This episode of calcite cementation appears to occur later in the diagenetic history of the sandstone since it is cementing microfractures that traverse all the other diagenetic features.

C) Hematitic and iron-oxide cementation - Although of lesser importance than the previous cements, hematite and ferruginous staining are locally extensive. They appear at several localities (e.g., in the Morien North section [Appendix A, Fig. 8B], 0-65 m, and in the New Waterford and Glace Bay West and East sections [Appendix B, Figs. 4, 5 and 6]) in the sandstones and fine-clastic rocks as a reddish-purple to rusty pigmented staining and replacement material, as a blackish granular rim surrounding detrital grains, or as an alteration product of pyrite and siderite.

Under the microscope the pigment is generally red but sometimes black. In the sandstones it occurs as a grain coating, in colloform interparticle patches complexly mixed or replacing the clay matrix (Plate 27B), in a red marly matrix (believed to be weathered intraclasts), and as red grains and concentrations. In the mudstones, marlstones and siltstones it generally appears as a uniform pigmentation or as patches of red-purple colour. The pigment is principally hematite, as determined by X-ray diffraction of the clay-sized fraction (Tables 3 and 4). Ferruginous staining is present mostly as an alteration product of pyrite.

Walker (1974) and Walker et al. (1978) have studied the origin of red pigment in sands of late Tertiary and Quaternary age and have discussed the method by which it accumulates to form red sandstones. Hematite apparently can form through intrastratal solution as well as in relation to changes in the elevation of the ground water table during weathering. The essential requirements for the authigenesis of hematite in pore spaces are a source of iron atoms and sufficient circulation of meteoric water to maintain oxidizing conditions in the pores. Time periods of 10^6 years are sufficient to form the bulk of the red pigment.

In the study area, this type of cementation appears to be a later event in the paragenetic sequence. Hematite and ferruginous staining patches usually replace and/or coat primary and secondary clay, silica cement and detrital quartz and locally corrode the edges and boundaries of calcite cement, therefore supporting dating of their occurrence after those cements.

4.6.5 Summary: paragenetic sequence

From the previous discussion, we can summarize the paragenetic sequence in the clastic rocks of the Sydney Mines Formation as follows (from earliest to latest):

1) compaction of sediment, including deformation and squeezing of soft lithic clasts;

2) with shallow burial and compaction, pressure-solution contact silica cement begins to form, to be followed by syntaxial quartz overgrowth cementation;

3) early calcite cementation (poikilotopic and very fine to fine granular) forms at a later stage following or during the last stages of (2); corrosion of silica cements and detrital grains takes place with the increase in carbonate growth;

4) secondary clay cements (mainly kaolinite) appear as a pore-filling medium at any time during this sequence; it has been observed to precede, occur with or follow calcite cementation;

5) hematite and iron-oxide (and/or pyrite) cements appear as a late event following the previous sequence;

6) late-event calcite cement filling of microfractures/fine fractures and open voids (leaching effect) may appear locally as a final cementation event; this type of cementation appears to be restricted to sandstones occurring proximally to a local carbonate source.

4.7 Coals

4.7.1 Coal formation characteristics -- The material of present-day bogs contains very high percentages of water, almost never less than 90% and averaging 95% (Miller, 1949). The weight of solid matter contained in a unit volume of growing bogs varies within fairly broad limits, depending on both water and ash content (Hanrahan, 1954; MacFarlane, 1959). For example, the solid matter content for fairly pure peats is of the order of 50 kg/m³.

Ashley (1907) estimated that a peat layer changing into coal shrinks to one-twentieth of its original thickness. Falini (1965) estimated the transformation from peat carrying 95% water to brown coal with 50% water involves a reduction to about one-tenth of the original thickness (i.e., this figure is not taking into account the loss of weight of the vegetal matter due to chemical reactions in the coalification process. A survey of estimates of peat:coal ratios in the literature conducted by Ryer and Langer (1980, Table 1) reveals that they range from 1.4:1 to 30:1, with the median ratio being 10:1. The great range of values is explained by the authors in terms of a number of factors, including the following:

1) problems inherent in the various methods employed (i.e., petrographic, density, stratigraphic, inclusions);

2) variations in the values used for the density of peat;

3) variations in the rank and, therefore, density of different coals; and

4) variations in the ash content of coals.

The mineralogical and petrographical characteristics of the coal seams from coastal exposures of the Sydney Mines Formation as well as the related seatearth and roof rocks (including their significance) have been discussed in section 3.5. The characteristics establishing the autochthonous origin of these seams were discussed in section 3.6. Here the environmental significance of the coal as well as its influence on mining operations will be discussed.

The coal seams of the Sydney Basin, and particularly those within the upper Morien Group, have been studied extensively by P.A. Hacquebard and co-workers. Hacquebard et al. (1965) and Hacquebard and Donaldson (1969) have established basinwide petrographic variations within the major seams microscopically determined and expressed as percentages of microlithotypes. These data were interpreted in terms of peat-forming environments (Hacquebard and Donaldson, 1969), listed in order of increasing wetness as follows:

1) forest-terrestrial moor: relatively low water table, capable of supporting arboreal vegetation;

2) forest-moor: higher but generally non-emergent water table; herbaceous vegetation;

3) reed-moor (perhaps better termed reed-marsh): emergent water table, supporting water-tolerant rooted vegetation (reeds);

4) open moor (marsh): non-rooted vegetation accumulated sub-aquatically.

The coals of the upper Morien Group (the Emery, Phalen, Backpit, Bouthillier, Harbour and Hub seams) are more extensive and thicker than those of the lower Morien Group (Rust et al., 1983). This is attributed to deposition of those upper Morien seams on a meandering-fluvial floodplain. The floodplain of a meadering river is generally located below the water level in the main channel (Walker and Cant, 1984) and maintains the high water tables suitable for growth and preservation of peat. Lateral channel migration or avulsion of the fluvial system can terminate peat growth over a wide area, but the fibrous peat commonly resists erosion, because its base is low enough to avoid undermining. Lastly, the development of upright tree trunks of large dimensions (a common feature observed in the Sydney Mines Formation; Plate 13) is possible only when the rise of the water level ceases completely or almost completely for periods of thousands of years (Falini, 1965). The presence of the trunks indicates a slow growth of the peat deposit. Hence peats formed on floodplains of meandering rivers (upper Morien Group situation) are thicker and more widespread than those developed on braidplains (lower Morien Group situation; Gibling and Rust, 1984).

The most widespread seam of the Sydney Mines Formation, the Backpit, extends some 40 km normal to the northeastward paleocurrent trend and does not contain splits (Hacquebard and Donaldson, 1969, Plate 1). The width of the Backpit swamp is comparable with those of the lower Mississippi Valley, but the latter are confined within a post-glacial valley, and thus are less extensive than they would be in an unconfined situation. This implies that the Sydney Mines Formation swamps were of considerable size, although not as large as those of the modern Mississippi. Other extensive seams in the Sydney Mines Formation show lateral splitting, due to the proximity of channel systems and the consequent progradation of splays into swamp margins. This suggests that the Backpit swamp was unusually extensive, and a 40-50 km spacing between channels is a reasonable estimate.

In general, the petrography of the upper Morien coals (Sydney Mines Formation coals of section 3.5) is consistent with deposition in swamps situated below the elevation of the major meandering channels and exhibits affinities with somewhat wetter peat-forming environments. Exceptionally, the Backpit seam -- the most extensive and thinnest of the upper Morien seams -- contains a considerable percentage of microlithotypes associated with accumulation in a forest-moor environment (Hacquebard and Donaldson, 1969, Fig. 6) and indicating relatively slow subsidence during its deposition. Hence local elevations within the swamp (remote from channel-derived floods) developed, and drier peat-forming environments evolved.

The occurrence of thin, dull bands (Plate 10A,B) that persist across the basin (in the Harbour, Backpit, Phalen and Emery seams) is a notable characteristic and represents microlithotypes indicative of wetter environments (Hacquebard and Donaldson, 1969, Figs. 5 and 8). These bands represent basinwide increases in water level, probably due to increased precipitation within the catchment area. The widespread thin, dull bands of coal indicate a high degree of basin stability, with very little relief across the floodplain.

The sulphur content of the Sydney Mines Formation coals (see section 3.5) belies a marine sulphur source, because if this were so sulphur content would decrease rapidly landward. The sulphur must have been derived, then, from terrestrial sources. Haites (1951) suggested that the most likely source is gypsum in marine evaporites of the Windsor Group, which immediately underlies the Morien Group in parts of the Sydney Basin. Sulphur concentrations would have been low in the river waters but were increased by evaporation from swamps and shallow lakes.

The pattern of lateral coal distribution is best illustrated in the cross sections in Figs. 1-4 of Appendix B. These figures show the detailed spatial associations of channel sandstones, the crevasse-splay sandstones and the enclosing floodplain fine-grained sediment units, limestones and coals for the sedimentary package enclosed by the Harbour and Emery seams. In Fig. 1, thicker channel sandstones predominate in the eastern sections (Donkin East to Port Morien) in the lowermost part of the cross section. These are succeeded in the middle part by both large and small channels occurring in a slightly offset fashion to each other. The upper part of the cross section shows a predominance of deeper channels occurring as a westerly offset from the lower and middle part of the cross section. This distribution of the channel sandstones suggests that the position of each succeeding body was controlled by the location and topography of the preceding channel and intervening floodplain. Differential compaction of the flood basin sediments was probably the main cause for the relocation of the channel. The coal beds distributed throughout these cross sections show a close relationship to the channels in vertical sequence, but not laterally. Individual coal beds, some laterally continuous for several km, commonly abruptly terminate or ride underneath or over channel sandstones. Most coals overlain by channel sandstones are partly scoured by them, and coal clasts are found as part of their lag deposits. Numerous coal beds extend laterally away from the channels into inter-channel floodplain areas, while others occur in the margins or as capping to pond/lacustrine limestone beds. In the floodplain areas, the coal beds are separated by crevasse-splay sandstone, siltstone and shale. The significance of the association of minor coal seams with the limestone units will be discussed in Chap. 5.

The coal and carbonaceous shale deposits are organic accumulations of reducing subenvironments of the fluvial backswamp environment. Freshwater fossiliferous limestone sediments interbedded with the coals (see Chap. 5) suggest inland swamps that supported freshwater plants. This vegetation flourished in backswamps formed in narrow to extensive interchannel flood basins.

Carbonaceous shales were products of two main modes of origin:

1) full or partial erosion of exposed organic accumulations and redistribution in muddy backswamp areas or reworking and mixing with flocculated clays;

2) in situ formation by widespread incursions of suspended sediments.

Associated ironstone deposits (as nodules and discontinuous thin beds) occur (in addition to the fine-grained detritus of splay lobes and above the crevasse-splay sandstones of the floodplain environment) as concretions in the sandstone, siltstone and shale partings of coals and carbonaceous shales. These associations suggest deposition in backswamp and overbank-levee subenvironments. Ironstone concretions are also associated with lacustrine limestone deposits (see Chap. 5). The occurrence of ironstone as enclosing deposits around concentrations of rootlets and plant fragments suggests precipitation under reducing conditions. However, the in situ association of ironstone with well-oxygenated deposits (such as in overbank-levee sediments) suggests that ironstone also formed under oxidizing conditions.

In general it appears that, in terms of sulphur content, the Sydney Basin differs from other Appalachian coal basins. In the basins of West Virginia, for example, higher sulphur content in the coal can be directly linked to an overlying ~~sedimentary~~ package comprising marine limestone units (Renton and Hidalgo, 1975; King and Renton, 1979). In the Sydney coalfield higher sulphur content is linked to overlying sandstone channels, not marine units (Forgeron, 1980).

Bell (1944) and Haites (1951) suggested that this sulphur originated from pyrite formed in the coal after deposition. Forgeron (1980) proposed that sulphate ions derived from the large gypsum/anhydrite deposits of Mississippian age were brought into contact with the coal by the river channelling at that time. This source, in addition to iron reduction by anaerobic bacteria in the presence of the organic material making up the peat, iron supplied from highly organic swamps and/or brought by streams, and the proper chemical setting (i.e., generation of H_2S and its subsequent reaction with iron to form iron sulphide), explains the higher sulphur content in the coals overlain by channels. These coals also show a higher ash content than the classical types overlain by a fine-clastic sedimentary package. This sulphur is mainly concentrated in the upper part of the seam and decreases downward into the seam. It covers cleatings and stains the related clays and the surface of the seam. Erosion of the Mississippian rocks provides a good enough source for the formation of iron-carbonate nodules and ironstone root and plant replacement. The iron source for the ironstone is believed to be the same as previously mentioned for the sulphur.

The cross sections (Appendix B, Figs. 1-6) indicate five general characteristics of the coal seams in the Sydney Mines Formation:

1) the coal swamps were widespread;

2) the amount of plant debris preserved varied from place to place;

3) the patterns of thickness of coal beds, including both the coal and the associated beds, suggest that the pathways for water entering the coal swamps were similar to those during deposition of the sediments;

4) plant growth, or swamp development in a broad sense, responded to physical conditions in the depositional basin, such as topography of the basin floor, position of drainage pathways, and depth of water;

5) characteristics of the thin, discontinuous coals occurring in the study area between the major seams suggest that they developed as small interchannel peat swamps in low-lying, poorly drained areas where lakes also formed. Frequent sedimentation on these swamps by overbank floods or crevasse-splay deposits was probably responsible for the shale interbeds commonly observed in these thin coal seams within the study area.

4.7.2 Mining problems -- Geological structures in mine roof rock that contribute to many roof falls have been described in the geologic literature. Such structures contributing to many roof falls in Appalachian coal mines

(Moebs and Ellenberger, 1982) and in the Sydney coalfield (Forgeron, 1980) were formed through syngenetic or diagenetic processes. Most of the structures are small scale, less than a few m in thickness, and may include paleochannels, scours, pinchouts, slickensides, clay veins, crevasse-splays and joints.

The geological department of the Cape Breton Development Corporation (Devco) has been studying geological conditions disrupting the uniformity of roof and floor strata revealed when the normal shale and mudstone roof rock, and even the coal seam itself, is locally cut out abruptly or "intruded" by sandstone. To date the information has been derived from the collection and assessment of data from the working mines on the Harbour and Hub seams, mainly from the mapping of mine workings, the monitoring of methane drainage and the cross measure of drill holes (Forgeron, 1980 and personal communication).

Sandstone-related structures observed in mine roof rock and posing a serious mining problem in the Sydney coalfield (Forgeron, 1980) can be summarised as follows:

1) sandstone pinching out into the country shale or mudstone roof rocks (weakened by tensional stresses during differential compaction of the sediments), subject to collapsing upon removal of the supporting underlying coal during mining;

2) weak roof rocks exhibiting extensive slickensides and polished planes (i.e., cutter roof) formed partially as a result of differential compaction and partly as shearing of the softer sediments by movement of the more rigid sandstone member within the weaker argillaceous rocks during basin warping; falls range from several cm to a couple of m above the seam;

3) reduction or cutting out of mineable coal seams due to the erosive action of stream channels;

4) spark generation during mining due to the siliceous nature of overlying channel sandstone (Plate 28) and taking place in an atmosphere containing methane gas -- this aspect of channeling constitutes the most serious safety hazard;

5) concentration of pyrite or marcasite (i.e., sulphur) along the sandstone-coal contact;

6) methane gas inflow along the contact between the sandstone and coal.

In the study area, structures in units overlying coal seams that serve as surface examples of the underground structures listed by Forgeron (1980) posing safety problems during the mining process are numerous and widespread (see section 3.5 and Table 8). The structures observed can be regrouped under three main headings:

A) problems related to overlying fine clastic bodies, including any factors enhancing brittleness, such as the presence of

a) fissile shales;

b) shales and mudstones with a high content of plant debris (Plate 12A);

c) shales exhibiting a high content of micaceous and plant debris coating on parting planes (Plate 12A);

d) slickensides and polished planes;

e) fracturing creating pathways for water or gas seepage (Plate 12A);

f) any combinations of a-e (Plate 12A).

B) problems related to overlying sandstone bodies (Plate 28)

a) sparks during mining due to the siliceous nature of the sandstone;

b) collapse related to heavy overlying weight of the sandstone body (Plate 11B);

c) rock fall from upright tree trunks in tabular sandstone bodies (Plate 12);

d) water and gas seepage along porous zones at eroded channel bases or at contacts between a channel and coal (Plate 12B).

C) diagenetically related problems

a) sparking from highly siliceous or calcareous cemented overlying sandstones (section 4.6);

b) seepage of gas in overlying porous sandstones (section 4.6);

c) type of clay present in roof rocks, i.e., non-reactive (kaolinite-dickite) as opposed to reactive clays (montmorillonite) -- this is of importance in weakening of roof rocks or swelling of root systems.

Sandstones thinly interbedded (rippled and horizontally laminated) with shale/mudstone or thin bedded, laminated, micaceous, medium-fine micaceous sandstone occur directly above coal occurrences in 23% of the situations listed in Table 8 in the upper Morien Group. This type of unit has all the characteristics of crevasse-splay deposits or sandy/silty deposits of a floodplain environment closely related to a stream channel environment. Sandstones of this type were deposited outside the channel as the trunk stream breached a natural levee during the flood stage and carried sand out over the adjacent floodplain. Another mode of deposition is as the tabular finer basal part of coarsening-upward sand sequence. These units range in thickness from 10s of cm to a few m in thickness and persist laterally as sheetlike or lenticular bodies.

Such sandstone bodies occurring within 2.0 m of the top of the coal bed and contributing part of the roof rock could directly affect roof conditions. The inherent weakness of such splay deposits is due to the poor bonding between the mica- or shale-rich laminations. The deposit is further weakened by the inclusion of thin coal laminae on bedding planes and a predominance of clay in the material that cements the grains of the sandstone.

Trough cross-bedded paleochannels eroding the shale and mudstone roof rock and sitting on the coal seams are observed in 16% of the situations of Table 8. The sandstones are coarse to fine and most exhibit lag deposits. They are best recognised by their lenticular to sheet-like shape, slickensided margins, and their hard, cross-bedded, poorly sorted sandstone filling.

A mine working is said to be affected by the sandstone when the latter is actually observed within or in close proximity to (generally less than 1.5 m) the roof of the coal seam. All those observed in the study area are within this range but none is actually eroding into the coal. The slickensides on the undersurfaces of the U-shaped channel constitute planes of weakness and a lack of bonding. Thus the weak shales and coal adjacent to and directly beneath the sandstone-filled channel separate readily from it as soon as the underlying coal bed is mined. Great varieties of cut-and-fill structures and pinchout located near the flanks of channels are also potential hazards and are observed locally in the study area.

The occurrence of slickensides in the study area is varied and widespread. In addition to underlying paleochannels, slickensides are common in highly argillaceous rocks such as shales and claystones. They are particularly abundant around the margins of some minor cut-and-fill structures where differential compaction has occurred. Minor occurrences of clay veins (claystone dykes) are observed locally in wedge-shaped masses of slickensided claystone or mudstone filling a crevice in a coal bed. These never exceed 60-70 cm in length and are usually much smaller. The pattern and character of clay veins suggest they formed as tension fissures in peat, which became filled with clay-rich material and then were compacted after burial. There is some evidence that clay veins occur chiefly in areas that were slightly above the level of the surrounding swamp, such as a peat island, and were therefore more subject to desiccation and fissuring. Fractures in the overlying beds of coal seams are observed at a few locations but those are believed to result from loading from the overlying rock package and are not a prominent feature.

Diagenetically related problems are mostly due to cementation, discussed in section 4.6.

CHAPTER 5. SEDIMENTOLOGY: THE LACUSTRINE ENVIRONMENT

5.1 Introduction

Limestones are widespread and highly variable in the sections studied, forming an average of 16% of the sedimentary package (Fig. 5). Lakes formed by an excess of subsidence over sedimentation in parts of the floodplain were an important feature in the Sydney Mines Formation, particularly in the central part of the basin between Victoria Mines and Glace Bay (Masson and Rust, 1983).

The five main sublithofacies forming the limestones have been described in section 3.4. They form a great variety of bodies that can be classified (and will be discussed) as:

- lacustrine deposits (section 5.3.1);
- marginal lacustrine deposits (section 5.3.2);
- lacustrine delta and splay deposits (section 5.3.3);
- lacustrine floodplains and related coal deposits (section 5.3.4);
- ponds and very shallow lake deposits (section 5.3.5).

These various bodies can be categorised from the definitions of Hutchinson (1957), Reeves (1968), Elliott (1974) and Gersib and McCabe (1981) as follows:

- lacustrine - a body of water too deep to permit vegetation to take root completely across the water expanse and of a much greater extent than a pond; in the Sydney Mines Formation the typical lake-fill sequence is characterised by upward coarsening with abundant bivalves and plant debris in its lower part (Masson and Rust, 1983).

- pond - a small (usually shallow) freshwater accumulation across which vegetation may or may not be continuous.

• lake deltas - a lenticular coarsening-upward accumulation generated where a crevasse-splay progrades into standing water in a lacustrine-dominated environment.

Lacustrine floodplain deposits are associated with well to poorly drained swamps and coal formation (section 4.2.4B) and because of their association with coal they originate in nonmarine swamps (area of poor drainage with saturated ground supporting trees) and require a humid climate supporting a rich growth of vegetation and a high water table to permit prolonged accumulation of plant material in a reducing environment.

Limestone bodies are most prominent in lithostratigraphic zone E (Fig. 4 -- floodplain-dominated with minor distributary channels and lacustrine limestone beds), where they form 30-40% of the sedimentary package. They form roughly 15% of zones B and D and ⩽ 7% of zones A and C. The locations of the principal limestone bodies found in the Sydney Mines Formation as well as their interpretation, thickness and lateral extent (when applicable) are given in Table 19 (locations on Figs. 1-6 of Appendix A) and in Table 20 (locations on Figs. 4 and 5 of Appendix B). Selected examples from each of the five principal body types are discussed in section 5.3.

5.2 Environmental interpretation

The various limestone subfacies of the upper Morien Group occur within a coal-bearing fluvial succession that lacks any indication of marine incursion. Evidence for terrestrial deposition is the presence in the algal laminites and the mudstone-packstone subfacies of nonmarine shark and fish remains. Closely associated shell beds contain nonmarine bivalves, abundant thin-shelled ostracods, and less numerous thin-shelled gastropods and *Spirorbis* worm tubes. It is concluded that these limestones were formed in and in relation to temporary lakes and/or ponds on the floodplain of a river system that deposited the coal-bearing cyclothems (Fig. 17).

Fairbridge (1968) has demonstrated that sediments of freshwater lakes vary considerably and are influenced by numerous factors. These include: the nature and origin of the lake basin, the type of rock and soil surrounding the basin and present in the drainage area, the size and depth of the lake, the extent of the nearshore shallow portion of the lake, the amount and type of vegetation surrounding the lake and present in the drainage area, the climatic conditions and the organisms living in and around the lake.

5.2.1 Limestone subfacies of the Sydney Mines Formation

Link and Osborne (1978) found that in the lacustrine Pliocene Ridge Basin Group, California, the carbonate and terrigenous deposits of nearshore environments display the greatest lithologic and biotic diversity. The facies include blue-grey mudstone, fine- to medium-grained sandstone and limestones containing ooliths, pisoliths, stromatolites, and intraclasts. Stromatolites are common and include both oncolites and filamentous algal laminations (Link et al., 1978). They are commonly associated with bivalves, gastropods, ostracods, and plant debris, all interpreted as freshwater genera (Crowell, 1950). Associated sediments range from poorly sorted to well sorted and include horizontally laminated, cross-stratified, and massive units, which are commonly burrowed.

The algal laminite and stromatolite (Plate 5) and the mudstone-packstone subfacies (Plate 6) and associated deposits of the Sydney Mines Formation show many features similar to those described by Link and Osborne (1978). They therefore are attributed to deposition in shallow lakes, subject to the agitation characteristic of a shoreline subenvironment.

In the Sydney Basin, however, sedimentation was strongly controlled by fluvial processes, so that lakes only developed on parts of the floodplain remote from clastic deposition in channels, levees, or crevasse-splays. These remote areas accumulated mud and, if isolated long enough from coarse fluvial sediments, compacted to form depressions that either developed into peat swamps or were inundated to form lakes. Carbonate precipitation and entrapment were triggered by algal colonization of the lakes, and in many cases ostracods became abundant at maximal stages of lake development. Lowering of lake level or depletion of algae by overgrazing may have reduced ostracod abundance, allowing the algae to resume dominance and form another layer of sediment in the stromatolite colonies.

The mudstone-packstone subfacies is believed to be a direct result of fluctuation in lake level causing cyclic deposition. This is reflected in variations in the high mud and skeletal content of this subfacies.

The oncolites beneath the domal stromatolites (Plate 5C) near New Waterford probably formed in more agitated waters adjacent to the lake shore. Agitation is indicated by the presence of ooliths and by analogy with modern oncolites in Onondaga Lake, New York, which Eggleston and Dean (1976, p. 487) observed on a platform less than 2 m deep along a shoreline, where agitation is sufficient to overturn them. Oncolites in Lake Constance, Germany, also acquire their form by wave agitation in shallow waters (Schäfer and Stapf, 1978). The oncoids from Lake Constance (Schottle and Muller, 1968) are smaller but otherwise similar in form to those of the Sydney Basin. In contrast, Jones and Wilkinson (1978) attributed flattened oncoids in some Michigan lakes to the infrequency of wave agitation. Relatively frequent wave action is envisaged for the oncolites of the Sydney Basin, allowing algal growth and sediment entrapment to form successive layers of smooth concentric laminae all around the nucleus. When conditions became less agitated the oncoids were stabilized, so that continued algal growth encrusted them, eventually covering the entire surface with domal stromatolites. Compared with the algal laminites, the domal forms and oncolites were evidently less favourable for colonization by shelly faunas. This and the nature of the fauna, the algae, and the presence of ooliths suggest that the lakes may have developed elevated salinity from time to time. They were broad and shallow and probably received an unusually high input of dissolved salts derived from weathering of Windsor Group evaporites exposed within the paleodrainage basin of the Morien Group.

Stratigraphically, the algal units of the Sydney Mines Formation occur within the fine members of fining-upward calcareous sequences, while the mudstone-packstone units are more prominent in the coarser and lower members of these sequences. This indicates that algal development took place during periods when fluvial clastic input was low and of fine grain size. The algal units and associated shelly faunas probably represent the maximum inundation of floodplain areas and essentially indicate a transition from fluvial plain to lacustrine conditions. This lacustrine transgression was terminated by renewed fine clastic deposition, probably due to the approach of an adjacent channel. In some cases peat swamps were then established, eventually leading to the formation of a coal seam. Subsequently, the channel traversed the depositional area, and a new fining-upward sequence commenced.

In effect, the lacustrine stromatolites of the Sydney coalfield occupy a position analogous to that of marine bands in paralic coal-bearing successions, such as those described by Wanless et al. (1970), Ferm (1970) and Elliott (1975). In paralic successions, marine bands represent conditions of maximum marine transgression within cyclic deltaic deposits, whereas the stromatolites of the Sydney Basin represent maximum lacustrine inundation within fluvial cyclothems. In both cases the controlling mechanism is the localised compaction of fine-grained sediments superimposed on the effect of subsidence on a regional scale.

The carbonate units forming calcretes (Plate 7) are thought to be of pedogenic origin, representing paleosols developed on subaerially exposed parts of the floodplain in a warm to hot climate with moderately low seasonal rainfall.

Calcretes broadly similar to the upper Morien Group have been described by Allen (1965) in the Upper Old Red Sandstone of South Wales. Similar rocks are also well developed in the Lower and Upper Old Red Sandstone and in the Carboniferous strata of Scotland (Muir et al., 1956; Friend et al., 1963; Leeder, 1973a; Allen, 1974). The pedogenic origin of these rocks is well established.

In Sydney they are interpreted as subaerially exposed floodplain (overbank) deposits. The hematitic-bearing variety is interpreted as a product of local/regional high water table within a moderately wet climate. The more organic-bearing variety was probably deposited in a subaerially exposed back swamp or might reflect a shorter exposure time (Wright, 1980). Mottling and reddening of the clays of fluvial sequences is typical of calcrete paleosols (Walker, 1974; Van Houten, 1972). The red coloration is due to the presence of hematite in the matrix and as coatings and is of diagenetic origin. Associated burrows are another possibility.

The conglomeratic/breccia subfacies (Plate 8) is believed to originate from subaerial exposure of lacustrine mud flats (Berryhill et al., 1971). These units probably formed in two main stages -- a drying up of the surface exposed, followed by a renewed influx of water. Following the formation of desiccation cracks and hardening of lime mud, a rubble of limestone fragments and powdery material was formed by mechanical weathering. Subsequent influx of water reworked and redeposited the limestone debris as lag type conglomeratic/brecciated limestone units. The poor sorting, the chaotic fabric, the nature of the contacts, and the nature and provenance of the clasts give strong support to such an interpretation.

Because of its lack of structure and high degree of recrystallization, the massive, microgranular limestone subfacies is more puzzling. However, it is believed that most of the structureless, microgranular calcareous mudstones are of chemical origin, the calcium carbonate being deposited from the warm water of the shallow, isolated ponds or small water bodies. The localised, well-preserved, restricted fauna is taken to indicate a slightly hypersaline character for these shallow warm water bodies. The presence of faint horizontal lamination, minor organic material and small, rounded calcareous mud clasts suggest that these shallow bodies were subjected to periodic current influence.

5.2.2 Environmental significance of fossiliferous content

A) Fossil assemblages from Maritime Canada and the Sydney coalfield considered to originate in nonmarine waters have been described by Bell (1944), Copeland (1957), Rogers (1965), Belt (1968a), Masson and Rust (1983, 1984) and Vasey and Zodrow (1983). These assemblages comprise associated shell beds containing nonmarine bivalves, abundant thin-shelled ostracods (Carbonita, Naiadites) and less numerous thin-shelled gastropods. The various pelecypods identified include Carbonicola, Naiadites, Anthraconauta and Anthraconia.

Masson and Rust (1983, 1984) described algal limestones from the upper part of the Morien Group in the Sydney Basin and concluded that the depositional environment was nonmarine, based on several aspects of the sedimentology and fossil content of the succession. The presence in the limestones of teeth and skeletal fragments of freshwater sharks (xenacanthids) and of various associated fish remains (Plate 9) is an important indicator of nonmarine origin.

B) Significance of fish remains present: Xenacanthid remains are well known from Carboniferous and Permian deposits of Europe, the mid-western and Appalachian regions of the United States and eastern Canada (Hotton, 1952; Lund, 1970; Dick, 1981; Baird, 1962, 1978). The xenacanthids are regarded as an "exotic" group of elasmobranch sharks that diverged very early at the cladodont level from the main lines of elasmobranch radiation (Schaeffer, 1967; Zangerl, 1973). The members of this group are among the very few elasmobranch fishes thought to have lived almost exclusively in nonmarine environments (Zangerl, 1981, p. 65). For this reason, they have greater environmental significance than other faunal elements in the Morien Group of the Sydney Basin.

Spines and cranial fragments are generally regarded as the most diagnostic elements for xenacanthid taxonomy, although Johnson (1980, 1981) used teeth for shark identification. The xenacanthid specimens recovered in this study are isolated teeth and dermal denticles, but neither cranial nor spine fragments were found.

The fossil fish in limestones of the Sydney Mines Formation are associated with an invertebrate fauna, commonly including bivalves in carbonaceous shale, ostracods and Spirorbis worm tubes. A similar faunal association has been reported from Carboniferous rocks in Nova Scotia by Robb (1876), Copeland (1957) and Carroll et al. (1972). This invertebrate fauna does not provide conclusive evidence for nonmarine deposition, although the lack of any marine elements is highly suggestive of a freshwater or brackish environment. Associated stromatolites do not of themselves permit distinction between marine and lacustrine deposition (Masson and Rust, 1983), and geochemical evidence is equally inconclusive (Vasey and Zodrow, 1983).

Most of the osteichthyan fragments recovered are also not diagnostic environmental indicators because they could be freshwater or marine forms (Denison, 1979). However, several well-preserved lungfish fragments (Family Ctenodontidae) occur in each unit studied. They closely resemble specimens described from the freshwater Duquesne Limestone (Pennsylvanian) of Pennsylvania by Lund (1970). The lungfish fragments in the Sydney Mines Formation are closely associated with xenacanthid remains, strongly supporting a freshwater or low brackish depositional environment (Zangerl, 1981).

The most conclusive environmental evidence comes from the xenacanthid remains, which have been reported frequently from freshwater deposits. For example, the most distinctive feature of an early Carboniferous xenacanthid shark from nonmarine deposits in Scotland is its small bicuspid teeth of "Diplodus" type (Dick, 1981). Lund (1970) described the Pennsylvanian Duquesne Limestone, in which the "...distinctly fresh water nature of the deposits is indicated by the presence of Orthacanthus and Xenacanthus sp. teeth and spine fragments, Hybodus (Agassiz) spine fragments, Sagenodus periprion and Monongahela stenodonta vomerine teeth, as well as by several tetrapod remains." Zidek (1972, 1976) reported the occurrence of xenacanthid, acanthodian and palaeoniscid remains, of freshwater origin, in Pennsylvanian coal balls and coal-bearing sequences in Oklahoma. In addition, numerous other freshwater Pennsylvanian successions have yielded isolated remnants of xenacanthid, orthacanthid and ctenacanthid teeth and spines (Zangerl, 1981); Olson, 1946; Mamay and Yochelson, 1962). Duffin and Ward (1983) reported xenacanthid teeth in marine strata but regarded them as transported from freshwater environments.

Similar fossil fish occurrences in eastern Canada were documented by Carroll et al. (1972) and Baird (1962, 1978). Nova Scotian examples include palaeoniscids (Family Haplopidae) in the Westphalian A, the lungfish Ctenodus in the Namurian A, the specialized C. murchisoni in the late Westphalian D and Pennsylvanian records of the acanthodian genus Gyracanthus. In addition, numerous xenacanthid teeth and spines are present in W.A. Bell's collection (made in the 1930s from Pennsylvanian rocks in the Mabou coalfield, Nova Scotia) now in the Natural History Museum in Ottawa. Robb (1876) reported fragments of rhipidistian fish (Holoptychius and Megalichthys) and palaeoniscoids (Palaeoniscum, Amblypterus and Gyrolepis) from what is now termed the Morien Group.

Masson and Rust (1983) discussed the depositional environment of the upper part of the Morien Group (the Sydney Mines Formation) in the eastern Sydney Basin. From the lithofacies, sedimentary succession, fauna and flora they concluded that the environment was an alluvial plain with large meandering channels. Areas of low elevation between channels were subject to variable compaction and subsidence and were either inundated by relatively deep water, forming lakes, or were colonized by abundant aquatic vegetation, forming swamps. Algal limestones formed in the lakes, whereas the swamps ultimately accumulated peat deposits.

The two different calcareous lithologies in which the fish fragments occur can be understood in terms of variation within the lacustrine environment. The carbonaceous, calcareous shale dominated by osteichthyan fragments also contains coprolites, ostracods, bivalves and Spirorbis worm tubes. Stratigraphically it is closely associated with coal and probably represents a transition from lake to swamp environments. The carbonaceous content indicates abundant aquatic vegetation, with relatively low oxygen concentrations in shallow water. Evidently the bony fish were able to tolerate a lake-margin swamp environment.

The massive limestone lithology containing most of the shark remains is interbedded with algal laminites. This indicates a deeper, well-oxygenated lacustrine environment, with stromatolites and oncolites occasionally developed in shallower water (Masson and Rust, 1983). This suggests that the sharks required more open, oxygenated water, probably of greater depth. In contrast, bony fish could tolerate lake-margin swamps, as well as open lake environments. The greater variety of environments exploited by the bony fish may indicate a more varied diet, including aquatic plants, whereas the sharks were predators on the other animals present.

5.3 Selected examples of limestone deposits in the Sydney Mines Formation

Five main types of limestone deposits representing vertical and lateral facies changes are recognised within the Sydney Mines Formation. These vertical sequences of facies reflect areal distribution of large and small lakes within floodplains in which major channels pass laterally into overbank and crevasse-splay areas. In this section the characteristics of these main deposits (defined in section 5.1) are outlined and selected examples discussed (Fig. 22 and Plates 29-33). The characteristics of the individual lithofacies present within each deposit are not outlined, since they are fully discussed in section 3.5. The most important diagenetic features observed in the deposits are discussed briefly in section 5.4.

5.3.1 Lacustrine deposits

The lacustrine deposits are the best developed and the most widespread limestone deposits observed in the Sydney Mines Formation. They range in thickness from 1 to 4 m, mostly as composite tabular and lenticular stacking of several thinner bodies. Most of the limestone bodies correlated across several sections belong to this group (Table 20). They generally grade laterally into and are stratified with the marginal lacustrine deposits and in a few cases with the pedogenic calcrete subfacies.

The dominating lithofacies forming these deposits are the algally laminated and horizontal stromatolites exhibiting extensive interstratification with the mudstone to packstone subfacies, marlstone and carbonaceous shale.

5.3.1A Example 1. Interstratified algally laminated, stromatolite and mudstone to packstone limestones

Location: Victoria Mines section, interval 1-6 m.

Illustration: Fig. 22A, Plates 5A and 29.

Setting: laterally extensive upcliff for approximately 20 m; coarsening-upward sequence (1.5 m thick) of 4 tabular limestone bodies averaging 30 cm thick enclosed in a marly claystone/mudstone package; grading upward into a coal seam (Plate 29A).

Lithology: interstratification of numerous limestone subfacies exhibiting the following upward sequence within each of the four bodies: marly claystone - stromatolite - mudstone-packstone - algal laminites - carbonaceous shale; individual subfacies occurrences range in thickness from 3 mm to 3 cm (Plate 29B,C); fossil content includes: ostracods, bivalves, *Spirorbis* worm tubes, coprolites and fish debris (dominated by osteichthyan fragments).

Sedimentary structures: well- to moderately well-defined horizontal to slightly wavy laminations and thin beds (3 mm to 3 cm thick) to poorly defined thicker marly claystone thin beds (up to 15 cm thick).

Interpretation: lacustrine sequence composed of several small episodes of limestone deposition on an interflow floodplain; formed probably as a result of subsidence due to differential compaction; close stratigraphic association with coal probably represents a transition from lake to swamp environment; the carbonaceous content indicates abundant aquatic vegetation, with (fluctuating) relatively low oxygen concentrations in shallow water; bony fish fragments indicate that these fishes were able to tolerate a lake-margin swamp environment.

Marlstones, although a relatively minor component of the Sydney Mines Formation, are distinctive, recur at different levels and are locally important. Marlstone is defined as a calcareous-argillaceous rock containing 25-75% lime (Dunbar and Rodgers, 1957). Otherwise, there is no lithological distinction between these marlstones and the silty mudstones and the argillaceous siltstones already described. They occur most commonly as laterally extensive units within the fine members and range in thickness up to 6 m. Internal stratification ranges from several cm to 20 cm.

Most marlstones contain variable amounts (trace to 5%) of silt-size quartz and are frequently rich in ostracods. The carbonate content (under thin section) is mostly very fine grains less than 0.01 mm in diameter.

The marlstones of the Sydney Mines Formation are environmentally of the marginal/proximal open lacustrine type (as defined by Bradley, 1931) and exhibit the following main characteristics: association with algal carbonate, stromatolite and fluvial sandstone; generally grey to greyish green with variable pyrite content; carbonate content is almost entirely calcite; local horizontal and discontinuous laminations; contain algal fragments, ostracods, plant debris and variable fish debris.

5.3.1B Example 2. Well-developed coarsening-upward lacustrine sequence within a marly-floodplain sequence

Location: New Waterford section, interval 108-110 m (unit NW-17, Plate 9).

Illustration: Fig. 22B, Plate 30A.

Setting: laterally exposed for 30 m; coarsening-upward (1.1 m thick) sequence composed of four composite beds; enclosed and interstratified with marlstone and marly claystone and progressively overlain by a fluvial floodplain with splay deposits.

Lithology: interstratified mudstone-packstone (Plate 6), algally laminated horizontal stromatolite (Plate 5A) subfacies and marly claystone; variably fossiliferous and extensive localised organic content; unit exhibits highest percentage and variety of fish debris.

Sedimentary structures: general coarsening-upward sequence of four main bodies (20-30 cm thick); each is composed of several thinner horizontal to lenticular beds (3-10 cm thick); each exhibits an upward change from mudstone-packstone subfacies to algally laminated and horizontal stromatolite; thinner beds (5 mm to 5 cm thick) of marly claystone and/or organic shale separate the four main bodies; desiccation cracks, calcareous nodules and comminuted plant debris are present in the overlying unit.

Interpretation: well-developed lacustrine sequence composed of several bodies representing deeper, well-oxygenated lacustrine episodes; this lithology contains most of the shark remains; its interbedding with algal laminites indicates a deeper, well-oxygenated lacustrine environment with stromatolite development in shallow water.

5.3.2 Marginal lacustrine deposits

Marginal lacustrine deposits form elongated, narrow belts laterally grading into lacustrine deposits or pedogenic calcrete units. They form coarsening-upward units capping, interstratified with or laterally grading into lacustrine deposits, as in Example 2, section 5.3.1. They are characterised by the predominance of domal stromatolite and oncolite beds underlain by mudstone-packstone subfacies interstratified with massive or laminated marly claystones with common rootlets.

Example 3. Domal stromatolite and oncolite deposit

Location: New Waterford section, interval 177-181 m.

Illustration: Fig. 22C, Plates 5B,C and 30B.

Setting: elongate narrow belt of thin, massive limestone bodies (≤ 30 cm thick) within a mudstone/claystone sequence exhibiting variable marl and fine-clastic content; enclosed by a fluvial floodplain succession exhibiting splay deposits and overlying a sequence similar to Example 2, section 5.3.1.

Lithology: greatest lithologic diversity of any limestone sequence; it includes: stromatolites, oncolites, oolites, intraclasts, grey mudstone and claystone, locally marly and fine-medium sandstone in overlying bed. Stromatolites are the most common and diversified (horizontal to domal) in this setting and are associated with oncolites (Plates 5B,C), ooids, mollusks, ostracods and plant debris. Oncolites, ooids and ostracod-bearing strata are interbedded with the stromatolites and are transitory into the adjacent lacustrine facies observed in Example 2.

Sedimentary structures: general coarsening-upward and thinning of beds (50-30 cm) upward from predominantly horizontal stromatolitic to beds with domal stromatolites and oncolites (Plate 30B); thinner beds (average 5-10 cm thick) of claystone and mudstone separate the main bodies; stratification ranges from massively bedded to horizontally and slightly wavy laminated; burrowing and desiccation cracks are prominent in the overlying units.

Interpretation: lacustrine origin but marginal shoreline to Example 2; in this more marginal environment an increase in percentage and of diversity of stromatolites (i.e., domal are prominent) takes place and oncolites develop in the shallower, more agitated waters (Plate 5C); wave agitation in these nearshore lacustrine sediments is indicated by the formation of oncólites, ooids, the presence of intraclasts, small-scale cross-lamination and local rippling of the finer sediments.

5.3.3 Lacustrine delta and splay deposits

Bates (1953) described rivers entering freshwater lakes and forming small deltas in which topset, foreset and bottomset beds develop with characteristic features and a general coarsening-upward sequence. These deltas result when equally dense inflow from a river enters freshwater lakes - homopycnal flow - with mixing occurring readily in all dimensions and the flow pattern being that of an axial jet.

Progradation of similar small-scale lacustrine deltas and splays producing stratigraphic sequences that coarsen occurred during deposition of the Sydney Mines Formation (Tables 19 and 20). These sequences form sheet-like to lobate bodies, lacking the well-defined bottomset to topset zonation of Bates but exhibiting a well-developed upward coarsening and changes from horizontal and slight wavy stratification to cross-stratification. In the splay sequences soft-sediment deformation is one of the main characteristics. Lithologically these deposits are characterised by complexly interstratified calcareous beds, including: silty to sandy limestone, massive to algally laminated composite limestone, highly calcareous very fine to medium sandstone, variable calcareous siltstones and mudstones and marly claystones.

5.3.3A Example 4. Lacustrine delta deposit

Location: New Waterford section, interval 185-191 m.

Illustration: Fig. 22D, Plate 31.

Setting: coarsening-upward sequence (totalling 5 m thick) exhibiting transition from a true lacustrine deposit upward into deltafill; boundary to transition is an algally laminated limestone bed (60 cm thick) located roughly in the middle of the section (in Plate 31A this bed is the uppermost tabular one at the level of A and in Plate 31B it underlies the bottom 1/3 of the ruler); this sequence is underlain by fluvial floodplain sediment and overlain by a sequence of fluvial crevasse-splays.

Lithology: general coarsening-upward sequence (complex interstratification of beds ranging in thickness from a few cm to 60 cm) exhibiting the following upward changes of lithofacies (the first four parts of the sequence are illustrated in Plate 31A and the last three parts in Plate 31B):

- interstratified medium-grey organic shale, marly claystone, and silty calcareous mudstone;
- silty microgranular limestone;
- thin-bedded massive to algally laminated limestone (10-30 cm thick);
- composite limestone bed (60 cm thick) composed of interstratified algally laminated horizontal stromatolite and mudstone to packstone subfacies; fossil content includes: nonmarine bivalves, fish scales and plant debris;

- interstratified siltstones and silty, very fine sandstones with variable calcareous content;
- interstratified very fine to medium calcareous sandstones.

Sedimentary structures: upward change in stratification from predominantly horizontal laminations and thin beds in lower half of the sequence (Plate 31A) to predominantly lensoid and small-scale cross-laminated in the upper half (Plate 31B).

Interpretation: outermost portion of a distributary channel prograding into a lacustrine body as a small-scale delta; transition from lacustrine sediment (Plate 31A) to deltafill (Plate 31B).

5.3.3B Example 5. Lacustrine splay deposit

Location: Glace Bay West section, interval 176-183 m.

Illustration: Fig. 22E, Plate 32.

Setting: interstratified tabular sandy finely crystalline limestone and calcareous sandstone within a floodplain environment.

Lithology: interbedded grey to light brown, very fine to medium sandstone with variable calcareous content, sandy and silty microgranular limestone and light-medium grey to green-grey mudstone.

Sedimentary structures: characterised by very well-developed tabular continuous bedding (up to 40 cm thick) and planar laminations with laterally continuous laminae (several mm to 2 cm thick) of constant thickness produced by change in the abundance of organic matter and slight grain size differences; local development of loading, soft-sediment deformation, contorted bedding (Plate 32A) and desiccation cracks (Plate 32B).

Interpretation: deposition from suspension in a low-energy environment as evidenced by absence of current structures, nature of laminations and grain size of material; lacustrine origin is suggested by high calcareous content, association with floodplain deposits and lack of marine fauna.

5.3.4 Lacustrine floodplain and swamp deposits

Lacustrine deposits are located in organic-dominated swamps in proximity to coal seams and represent fluctuating episodes of lacustrine flooding of swamps. Those bodies form generally thin ($\leqslant$ 1.5 m thick) well-developed coarsening-upward sequences composed of complex interlaminations (several mm to 2 cm thick) overlying coal (Plate 33A). The best developed examples are located at the Glace Bay West section, interval 66-68 m, and the Donkin East section, interval 123-127 m.

The complex interlaminations are represented by abrupt changes of several lithofacies. These lithotypes include thin beds of nonmarine bivalves, ostracods, algal-laminites, calcareous mudstones, ironstone bands, carbonaceous shale and coal stringers. The fossils are abundant, but limited to a few species. This package usually caps a well-developed coal seam (Plate 33B). A typical facies sequence found through an interval (bottom to top) is:

- coal with underclay;
- black carbonaceous shale containing fish and plant debris plus in situ remains of nonmarine bivalves (Naiadites and Anthracosia) and/or ostracods;
- alternating laminations of mudstones, local thin algal-laminite beds, dark plant-debris-rich layers and bands (1-3 cm) of siderite in the upper part of the sequence.

This sequence is then usually overlain by a small-scale coarsening-upward succession of rippled sandstones indicating increasing currents and sedimentation rates..

These deposits are interpreted as lacustrine flood episodes controlled by subsidence taking place in a swamp environment. The mud and bivalve layers represent suspension deposition when the influx of mineral detritus exceeded organic material and when the lake bottom was well oxygenated. This oxygenation would also have increased the decay of organic matter.

The carbonaceous shales and coal stringers represent periods when the influx of organic matter predominated. Thus, plant fragments were preserved, and this anaerobic floor hindered animal life. Fossils were preserved when buried in the bottom sediment.

The rapid changes in interstratification represent quick changes between these two settings and probably indicate flood pulses.

5.3.5 Pond and very shallow deposits

Shallow, discontinuous, isolated lenticular and tabular calcareous bodies (< 1 m thick) of small lateral extent are widespread within the fluvial floodplain and in both the well-drained and poorly drained swamps of the Sydney Mines Formation. They are interpreted as isolated ponds that accumulated very shallow deposits. Locally, they are laterally related to calcrete, marly deposits and/or coal. They are invariably enclosed in floodplain sediments and at a few locations are eroded by channels.

These bodies are composed of three main types of lithofacies, which are, in order of decreasing importance:

1) interlaminated micritic mudstone to packstone - organic (carbonaceous) shale - fine clastic (silt and VF sand) and iron carbonate (example at Glace Bay East section within interval 104-110 m). Micritic mudstone to wackestone is the most extensive lithofacies present. Fossiliferous content is concentrated in thin beds of exclusively ostracod and/or fish (osteichthyan) debris. Laminations are horizontal to slightly

wavy continuous and range in thickness from 0.5 mm to 1 cm. Accessories include: coprolites, small iron carbonate spherules and mud intraclasts and local disseminated pyrite. Desiccation cracks are present locally.

2) microcrystalline limestone beds enclosed by marly mudstone/claystone (i.e., massive microgranular limestone subfacies discussed in sections 3.4.5 and 5.2.1).

3) conglomeratic/breccia limestone (i.e., conglomeratic/breccia limestone subfacies discussed in sections 3.4.4 and 5.2.1).

These deposits are interpreted as forming in shallow lacustrine bodies and ponds in blocked backwater areas <u>or</u> in isolated pools along the stream courses on the alluvial plain or as channel flank depressions <u>or</u> in areas of discontinuous subsidence on the floodplain. Between periods of stability these shallow lakes and ponds did not overflow or were periodically and temporarily exposed as evidenced by the presence of desiccation features and local lateral association with calcrete deposits. Siltstone and VF sandstone laminations are probably wind-blown in origin.

5.4 Some diagenetic aspects of limestones from the Sydney Mines Formation

The carbonate rocks of the Sydney Mines Formation are combinations of calcite, minor dolomitic rhombs and a variety of detrital minerals and rock fragments. A study of 90 limestone thin sections representing each of the subfacies units listed shows that micrite and clay-sized calcareous content varies from 20 to 50% and dolomite from a trace to 5%. Dolomite content increases upward within limestone units in which middle and basal beds commonly show very little to no trace of dolomite.

The fabric of most limestones is a combination of a microcrystalline calcite matrix (micrite) and varying amounts of particles (skeletal, mud clasts, organic, etc.) that range from clay size to rock fragments up to several cm in diameter. Totally crystalline limestone, although present, is of lesser importance, while conglomeratic beds are locally prominent.

This section briefly outlines the main microstructures and diagenetic characteristics observed in the algal laminite and stromatolite subfacies (including horizontally algal laminated and domal stromatolites) and the interstratified mudstone-to-packstone subfacies.

Thin sections from these subfacies all exhibit a variable degree of compactional effects. The response of the carbonate sediments to burial is manifested in localised solution-precipitation features (stylolites) and more extensively by physical readjustment or crushing of particles. Most particles, including those totally enclosed in micritic mud, have been deformed. Deformation ranges locally from mild to severe. Locally, micritic mud has been bioturbated and pelletized by the action of organisms but there is no evidence of compaction of these pellets.

The two types of stromatolites distinguished on the basis of their gross morphological characteristics have similar microstructures, but the horizontal forms contain a more abundant shelly fauna than the domal stromatolites. A variant of the horizontally laminated type has isolated domes within an otherwise horizontally laminated unit (section 3.4.1).

<u>5.4.1 Horizontally algal-laminated and stromatolitic limestone</u>: In thin sections these algal units have a prominent subhorizontal layering that varies in thickness from 0.2 mm to a little over 1 cm (Plate 5A). The laminae vary in sharpness of definition and show no obvious cyclicity. Their algal origin is indicated by the presence of disrupted algal remnants and rolled-up algal mud lumps. Variable algal growth rates and differential diagenetic calcification are probably the main factors in the development and preservation of lamination. The laminae are mostly composed of micrite and

exhibit varying degrees of calcification and recrystallization, as indicated by sparite and microsparite contents. They are commonly horizontal but slightly wavy forms (Plate 34A,B) are also prominent, and contortion due to compaction and diagenesis is locally distinct. Quartz silt, very fine sand, local pyrite and hematite commonly are concentrated within specific layers, varying individually in abundance from 1 to 7%. Fossiliferous material varies greatly in abundance (sections 3.4.6 and 5.2.2).

The horizontally algal-laminated and stromatolitic limestones in the study area are believed to contain variable remnants of microfossils of presumed blue-green algal affinities. In this subfacies the filamentous microfossils are horizontal, non-branching, small filamentous forms ($<$ 0.5 mm in thickness and 1-6 μm across) oriented perpendicular to laminae. Their surfaces can be horizontal, bumpy or microfractured.

The laminae that constitute the microstructure can be grouped into two categories based on preservation and appearance in thin section: 1)distinctly banded (Plate 34A,B) and 2)poorly banded. Distinctly banded microstructures are characterised by well-defined continuous parallel dark and light layers having sharp boundaries. Light layers are thinner ($<$ 1 mm) and usually are composed of moderately to poorly preserved (neomorphosed or sparitized) radial fibrous calcite. Individual layers are separated by filaments a few micrometers thick (Plate 34A,B). Dark layers are micritic in composition and thicker ($\leqslant$ 5 mm). Poorly banded microstructures have indistinct internal banding and the boundary between dark and light layers is diffuse and grades through several micrometers.

The initial stromatolitic structure (reflected by this couplet) was modified during its evolution by the following diagenetic processes: dissolution, cementation, replacement, internal sedimentation and disruption of stromatolitic laminae and internal detrital structure by neomorphism and/or sparitization. No evidence of subaerial desiccation structures was observed within these stromatolites.

5.4.2 Domal stromatolites and oncolites: The domes are mostly symmetrical, vary in diameter from 1 to 10 cm, and are up to 5 cm high. They have a columnar internal structure (Plates 5B and 35A) with individual columns rarely exceeding a few mm in diameter and several cm in length. Most are vertical, but a few are slightly inclined. They contain crinkled laminae in which the principal convexities are in the growth direction (Plate 35A). The shapes of the laminae are reflected in the shape of the outer surface of the entire algal body. The shelly fossils in the domal stromatolites are the same as those in the algal laminites but are much less abundant; they are limited to a few fragments in the cores of some of the domes and serve as interdomal fillings (Plate 35C). Algal fragments are also present. Most are too "sparitized" to be identified, but forms resembling Girvanella, Garwoodia, and Ortonella were identified among those responsible for the algal buildup (Plate 34C,D) (B. Mamet, personal communication, 1983).

Microscopically, the stromatolites show extensive sparitization, especially of laminae within the domes (Plate 35A), in which all features except the laminae have been destroyed or altered by diagenesis. Dolomite rhombs are scattered randomly within the laminae. Carbonate intraclasts, penecontemporaneous dolomite rhombs, isolated ooliths, pelleted mud lumps, ostracod and gastropod shells, detrital quartz grains, acritarchs and fish fragments are contained within the sparry calcite cement filling the interdomal areas (Plate 35C). The ooliths range from 0.25 to 1.5 mm in diameter and show a nucleus of variable nature (shell fragments, quartz grains, peloids, etc.) surrounded by several concentric layers. Staining shows that they are formed almost entirely of calcite.

Most oncoids underlying the domal stromatolites are nearly spherical but some approximate flattened spheroids (Plate 5C). Individually, they range from several mm up to 5 cm in diameter, but they also occur as larger composite clusters. They have been subjected to disruption and compaction, as evidenced by flattening and tilting, so that the long axes of some are vertical. Internally, the oncoids display smooth concentric laminae (0.5-5 mm thick), which become more crinkled, less well defined, and thicker toward the outside. The laminae enclose a nucleus of rock and/or shell fragments, mud clasts, and hematitic grains, some with coarse-grained calcite cement. The concentric laminae have a wide range of composition, including variable micritic mud, hematite, marly claystone, microcrystalline silica and dolomitic mudstone.

The domal stromatolites are separated from the oncoids by a thin zone of irregular, wavy micritic laminae with a high hematite content. Hematite replacement does not occur in the stromatolites but is extensive in the oncoids, entirely replacing several of the concentric laminae and in some cases acting as a nucleus for other oncoids. Hematite replacement was probably caused by reaction with iron-rich waters in an oxidizing freshwater environment, whereas in the reducing coal-swamp environment similar waters precipitated siderite nodules.

The microstructural fabric is very distinct, exhibiting a domal/columnar arrangement with internal layering and linked, closely spaced internal structures (Plate 35B) morphologically related to the presence of a central nucleus. This columnar internal arrangement is composed of stacked, convex, alternating dark- and light-coloured laminae similar to those described for the horizontal stromatolites (Plate 35A,B). Laminae are slightly thicker at the dome crests. Although some of the lighter-coloured laminae display a faint radial fibrous habit, they consist almost entirely of sparry calcite crystals.

A complete vertical profile across a domal structure not encrusting on oncolites comprises the following succession of layers (Plate 5C):

- thin zone of irregular, wavy to horizontal micritic laminae exhibiting variable mud, organic and hematitic content; this sequence varies greatly in thickness (usually not exceeding a few cm thick) and represents the main material encrusted by the stromatolites;

- base of stromatolitic buildup exhibits a zone of large, subrounded to irregular open-space structures (0.5 mm to 1 cm high) locally filled by sparitic calcite cement; these probably represent multiple episodes of carbonate deposition and solution occurring within the basal part of the stromatolites and/or the upper part of the underlying encrusted layers (Osborne et al., 1982); they could also represent the compacted and leached remnants of spongy structure (possibly astrorhizes, pores and/or crypts) encrusted by the overlying Codiacean algal complex (B. Mamet, personal communication, 1983); this spongy but now structureless aggregate of pores and of calcite cement is comparable to the deposits of calcium carbonate localised by members of the Cyanophycea at the present time in freshwater lakes;

- zone of algal fragments encrusting the previous layers and in several examples the cores of the domal structure; most are too "sparitized" to be identified, but forms resembling Girvanella, Ortonella and Garwoodia (Plate 34C,D) were identified among those responsible for the algal buildup (B. Mamet, personal communication, 1983).

• zone of small, flattened-elongated, open-space structures (≲ 0.3 mm high) occurring in the basal part of the domal structure; these probably represent voids formed by stromatolitic encrustations over irregular surfaces of the previous encrusting zone or by the decomposition of calcite-encrusted organic matter (Osborne et al., 1982); locally the pores appear to be enlarged and interconnected by the dissolution of surrounding carbonates or are cemented by sparite (Plate 35A);

• domal buildup proper formed of alternating light layers and filamentous micritic layers previously described.

This sequence repeats itself or is partially covered by material from the interdomal fill.

Cementation in the interdomal cavity fill does not exhibit a regular pattern and is predominantly sparry calcite cement (Plate 35C), locally intermixed with patches of micritic mud with variable detrital content (dolomite and quartz grains) and with dolomitized pockets. The presence of small oolite bands in the lower part of several interdomal areas indicates that, at times, the water was saturated with respect to calcium carbonate and agitated. Late-event microfracturing cutting across the domal buildup and the interdomal cavities and cemented by fine drusy cement is present locally.

Thin section study indicates that the dolomite present in the interdomal cavities is of two main types: 1)disseminated detrital rhombs located predominantly in the lower part of some cavities and enclosed by sparry calcite cement (Plate 35A); 2)continuous crystalline dolomite cement pockets, mostly of probable penecontemporaneous origin related to high-magnesium waters or as later authigenic dolomite cement related to high-magnesium-bearing water filling pores created by earlier leaching episodes.

5.4.3 Horizontally laminated mudstone to packstone subfacies: is characterised by prominent layering, with thickness ranging from a few mm to a few cm (Plate 6). Interstratification of well- (to moderately well-) defined individual beds of alternating calcareous mudstone, wackestone and/or packstone (Plate 36A-D) with well-defined individual laminae of different composition (mainly carbonaceous shales or silty mudstones and shales) is the most characteristic feature of this subfacies.

The laminae are generally composed of micritic mud exhibiting various degrees of bioturbation (Plate 36B), calcification and variable percentages of recrystallization (i.e., microsparite to sparite content). Some layers are almost entirely composed of skeletal debris (Plate 36C,D), which is absent from others (Plate 36B). The percentage of mud and skeletal material varies from 10 to 80% and their relationship is roughly inversely proportional. Accessories are varied (see section 3.4.2).

The associated fauna is similar to that of the algal laminite. It is particularly rich in ostracods (Plate 36D) but bivalves, thin-shelled gastropods, serpulid worm tubes (Plate 36C) and fish debris (Plate 36C) are locally important. Packstone beds are predominantly composed of ostracods (in many cases forming "ostracodite" beds) (Plate 36D). Teeth, scales and bone fragments of freshwater sharks (pleuracanths), acanthodian and paleoniscid fishes (sections 3.4.6 and 5.2.2B) are in greater abundance in the mudstone-to-wackestone beds. All units have been subjected to variable compaction, deformation and cementation (Plate 36A-D).

Although a detailed diagenetic and paragenetic study of the carbonate sediments is beyond the scope of this study (its main object being their sedimentology and stratigraphy), the main diagenetic processes can be listed in their approximate paragenetic order, as follows:

1) local recrystallisation of micritic mud to microsparite;

2) compaction;

3) two main types of leaching

A) non-selective leaching of micrite - creation of microvugular, fine-vugular and intercrystalline porosities later cemented by sparite, VF granular calcite or microcrystalline silica;

B) selective leaching of skeletal debris - creation of vuggy, moldic, shelter and intraskeletal porosities later cemented by VF-M equant granular to F-M drusy calcite cement; the general cement gradation is controlled by the size of the molds and ranges from geopetal fabric to VF granular to F-M drusy in the center of the mold;

4) stylolitization;

5) early microfracturing exhibiting cementation by equant blocky calcite cementation, microcrystalline silica or iron hematitic material related to (6);

6) hematitic ferruginous staining of matrix material;

7) later episode of fracturing and microfracturing.

CHAPTER 6. TECTONIC SETTING AND STRUCTURAL CHARACTERISTICS OF THE SYDNEY BASIN

6.1 Introduction

Carboniferous rocks are distributed widely in eastern Canada and form part of the Appalachian mountain system covering large parts of the provinces of Quebec, Newfoundland, Nova Scotia, New Brunswick and Prince Edward Island and the U.S.A.

The Carboniferous comprises six major rock units: in ascending order, the Horton, Windsor, Canso, Riversdale, Cumberland and Pictou groups. The last three form the Upper Carboniferous sequence and were assigned the following ages by Bell (1944): the Riversdale Group (Westphalian A), Cumberland Group (Westphalian B) and Pictou Group (Westphalian C and D). Originally these groups were believed to be bounded by parallel time planes, but more recent stratigraphic work supported by palynological evidence (Belt, 1964, 1965; Barss and Hacquebard, 1967; Kelley, 1967) has shown an important time-transgressive character for the Canso, Riversdale and Cumberland groups, which may also be true for the Pictou Group. Sedimentation was predominantly continental, except for the Windsor Group, which is essentially marine. Continental sedimentation is characterised by a great variety of fan-conglomerate, fluvial, lacustrine and palludal facies (Belt, 1965, 1968a).

6.2 Tectonic setting and development of the Carboniferous of the Maritimes

Carboniferous sedimentation was controlled by the tectonic processes that were part of the final deformation phase of the Appalachian geosyncline. Most of the Carboniferous sediments of the Maritimes accumulated in rapidly subsiding basins (Belt, 1968b) bounded by strike-slip faults (Belt, 1968b; Webb, 1969). These basins are believed to be pull-aparts (Fralick and Schenk, 1980; McCabe et al., 1980; and Bradley, 1982) and extension basins formed during dextral strike-slip movement related to closure of the supposed Hercynian Ocean (Leeder, 1976; McCabe et al., 1980) and left lateral movement during the major joining of Africa with North America (Schenk, 1971; Arthaud and Matte, 1977). Dextral strike-slip also dominated the tectonics of Nova Scotia (Fig. 23) in the early Carboniferous (Bradley, 1982; Bradley and Bradley, 1983; Arthaud and Matte, 1977).

The development across the region of a zone of steep northeasterly and also east-west trending faults followed the mid-Devonian Acadian orogeny. Subsequent regional subsidence of this zone caused the formation of a series of connected troughs and intermontane basins separated by positive blocks collectively referred to (Bell, 1944; Belt, 1965) as the Fundy Basin (Fig. 24). It occupies parts of the provinces of Nova Scotia, New Brunswick, Prince Edward Island and Newfoundland and has been interpreted as a complex rift valley bounded on both sides by high-angle faults that were active during sedimentation (Belt, 1965, 1968b; Hacquebard, 1972; Fralick and Schenk, 1981).

Following the Acadian orogeny, Upper Devonian, Carboniferous and Lower Permian rocks were deposited in the Fundy Basin and adjoining platforms.

The complex of small basins (Fig. 24) and the related positive blocks of the Fundy Basin appear to have developed at compressional regions located at the intersection of major faults (Figs. 23, 25; Bradley, 1982; McCabe and Schenk, 1982). Blocks uplifted during the Upper Carboniferous are illustrated in Fig. 25.

Paleomagnetic data (Morris, 1976; Kent and Opdyke, 1979, 1985) and geological evidence supports 160-200 km dextral displacements on the northeast-trending faults. A dextral slip displacement of about 200 km on the east-west Cobequid-Chedabucto fault system was estimated by Webb (1969). This is very close to the 225 km estimated by McCabe et al. (1980).

The timing of fault movement has a significant influence on sedimentation. Rust (1984) stated that the maintenance in the Horton and Windsor groups of alluvial fan deposition through space and time was due to continued strike-slip deformation of the faults bounding the depositional basins. He attributed this deformation to translation along the North American continental margin subsequent to oblique microcontinental collision in the mid-Devonian Acadian Orogeny.

Ample evidence for fault activity during the Namurian and early Westphalian was provided by Belt (1965, 1968a,b), Fyson (1964, 1967), McCabe et al. (1980), Fralick and Schenk (1981), McCabe and Schenk (1982) and Bradley and Bradley (1983). Fault control of sedimentation appears, however, to have died out during the late Westphalian and Stephanian, and the Fundy Basin simultaneously expanded beyond its former limits onto pre-Carboniferous basement (Belt, 1965; Carroll et al., 1972; Bradley, 1982). This phase of tectonic quiescence and expanded sedimentation corresponds with deposition of the Pictou Group.

Due to changes over time in the configuration of these connected small basins and to the introduction of complexities not usually encountered in relatively simple rifts, the entire Fundy Basin region became a stable craton during late Westphalian time. Bradley (1982) discussed some of these complexities (i.e., mainly overlapping effects of local extension, local transpressional deformation and regional thermal subsidence) and the broaderscale aspects of the Upper Paleozoic of the northern Appalachians in terms of the diachronous two-stage subsidence of extensional basins within an intracontinental transform fault zone, which McKenzie's (1978) model explains. He also noted that the Chedabucto and Hollow faults were major faults to the Sydney Basin.

6.3 Structural setting of the Sydney Coal Basin

The Sydney Synclinorium (named by Keppie, 1977a,b, 1982) is bounded on the south by pre-Carboniferous rocks of the East Bay and Fourchu blocks and on the northwest by the Kellys Mountain block. Both margins are major fault boundaries. The Synclinorium comprises three major synclines with intervening arches formed by pre-Carboniferous rocks of the Coxheath and Boisdale Hills (Fig. 26; Giles, 1983, Fig. 2, p.58). A pronounced northeasterly trend is noted for most major structures.

Data generated during the Sydney Basin Project (Giles, 1983) indicate that the broad structural configuration of the Sydney Basin was achieved in Visean time or slightly earlier. Post-Carboniferous fault movements have accentuated the major boundaries.

The tectonic development of the Sydney coalfield has been relatively gentle, and serious structural disturbances are absent from the mine workings. In general, gentle folding and minor thrust faulting is present, affecting the seams mainly in the submarine part of the field. The folds fan out seaward and trend in a northeasterly to easterly direction, with gentle seaward plunges of their axes. There are four major synclines present: Boularderie, Sydney Harbour, Glace Bay and Morien (Fig. 27). The prevailing dips throughout the coalfield vary from 4° to 15°, with a maximum of 45° north of Port Morien.

The Boularderie and the Sydney Harbour synclines are separated by a broad arch (the Boisdale Anticline) reflecting the northeasterly extension of the Boisdale Hills (Fig. 26) and extending into the offshore area of the Sydney Basin (Giles, 1983; Hacquebard, 1983). Giles (1983) mapped a similar arch over the basinward continuation of the Coxheath Hills (Fig. 26). Future completion of mapping should reveal whether this arch is equivalent to the Bridgeport Anticline of Bell and Goranson (1938) or if it represents a larger structure (Giles, 1983).

All the major folds observed in the study area (Fig. 27) are best qualified by the attitudes and the outcrop patterns of the older Carboniferous strata. In the Sydney Mines Formation (i.e., the northeast part of the Sydney Basin) where the folds are of smaller scale and where the beds are gently dipping, the definition of the folds and their relation to the major fold axial traces is highly speculative given the present state of knowledge. Warping related to compaction during deposition to explain the origin of the present fold pattern by Haites (1951) is also doubtful. The main characteristics of the strata of the Sydney Mines Formation suggests that major folds and arches outlined by Giles (1983) no longer controlled the structural setting during late Carboniferous.

The major faults within and marginal to the Sydney Basin follow the regional northeasterly structural trend. They include the Mountain, the Georges River, the McKenzie-Coxheath and the Mira River-Bateston faults. Their location and main characteristics were discussed by Giles (1983) (Fig. 26).

A seismic survey by Fortin and Quinn (unpublished report, 1983) showed local folding and minor faulting in upper Morien sediments in the nearshore zone (i.e., water depth 20-75 m) of the Donkin block of the Sydney coalfield.

The authors characterised the regional structure as being "...relatively simple, except for local folding, and is essentially arcuate with the beds dipping towards the deeper and central parts of the basin." Interpretation of the seismic sections revealed the presence of a major structure named the Flint Flexure. This structure had been previously identified as an anticline-syncline pair (Nova Scotia Research Foundation Corporation, 1979). No direct investigation was made on the deeper part of the structure, but preliminary investigation based on a deeper seismic method suggests possible thrust faulting associated with the Flint Flexure.

The author, during the course of field work and mapping of the coastal sections, did not find any evidence for major faulting in the strata of the Sydney Mines Formation. Clearly, more work such as that of Fortin and Quinn and the completion of the inland mapping will be necessary before the structure of the Sydney Basin is fully understood.

6.4 Strike-slip faults, arcuate fold patterns and deformation in the Sydney Mines Formation

A general decrease in the abundance of alluvial fan deposits from the Canso to Cumberland groups indicates a gradual decrease of activity of the Alleghenian fault movement. The absence of alluvial fan deposits from the late Pennsylvanian to early Pictou Group indicates a greater maturity of the Pictou rocks. Their extent and maturity indicate deposition in large basins with low slopes, as the fault-bounded relief of earlier deformation episodes was gradually worn down.

In addition to separation in time from periods of fault deformation, the Sydney Basin is relatively remote geographically from the major fault systems nearest to it: the northeast-trending Hollow and Aspy faults of eastern Cape

Breton Island and the east-west-trending Cobequid-Chedabucto fault to the south (Figs. 23 and 24). The compressive zone is characterised by thrusting and folding and with pull-apart basins occurring in areas of extension (Fralick and Schenk, 1980).

Intersections of strike-slip faults have complex structural patterns with splitting, rejoining and offsetting of the major fault. Splays and sub-parallel synthetic strike-slip faults are common, and more-or-less perpendicular antithetic strike-slip faults occur with a direction of offset opposite to that of the main strike-slip fault. Zones of extension lead to the formation of normal faults (resulting in graben-type structures), while zones of compression generate folding, which may lead to reverse faulting and overthrusting (Wilcox et al., 1973).

Periods of transtension (divergent strike-slip) or transpression (convergent strike-slip) may have an important influence on a regional scale on strike-slip systems (Reading, 1980). The characteristics by which ancient strike-slip belts may be recognised and the main effect of strike-slip motion on sedimentation have been outlined by Wilcox et al. (1973), Reading (1980) and Christie-Blick and Biddle (1984). Strike-slip motion has its greatest impact on the sedimentation process when rapid sinking of sedimentary basins and uplift and erosion of source areas are a direct result of dip-slip motion (Reading, 1980). This results in a laterally and vertically varied (but laterally restricted) sedimentary package.

Arthaud and Matte (1977) have shown that the Mississippian and Pennsylvanian strata are folded only in the vicinity of the Chedabucto Fault and that these northeast to north-northeast upright folds may represent locally a coarse, vertical axial-plane cleavage and that they are consistent with right-lateral displacement of the Chedabucto Fault. The northern New

Brunswick and Cape Breton area is bounded farther south by this fault. The authors have also shown that it acts as a stable block very weakly deformed after the Acadian Orogeny. The greatest number of faults described by Webb (1969) in this area are pre-Pennsylvanian and have acted as normal faults during sedimentation of the Carboniferous.

The extent of the Hollow and Chedabucto faults and of their related shears and the time of occurrence of the related folds is unknown and other faults may be buried and still unknown. Fault terminations at that time remain largely unknown and the cause and the positions of the horsts and grabens are not obvious (Fyson, personal communication, 1983). The overlapping of fault ends is one possible solution for the location of the horst and graben structures, but a proper solution requires geophysical surveys and is beyond the scope of the present study.

The delineation and evaluation of these faults are presently difficult to prove. However, an attempt to model this process and to evaluate the nature of possible faults, the amount of fault movement and the extent and timing of the faults might be a worthwhile future contribution.

In summary, the Sydney basin records a period of increasing tectonic quiescence, as source relief inherited from earlier deformation was progressively worn down. Slopes decreased with time, and as a result the Morien Group comprises a fining-upward sequence some 1.8 km thick. The consistency of mean paleocurrent direction throughout accumulation of the Morien Group is further evidence for basin stability.

CHAPTER 7. CONCLUSION

In the Sydney Mines Formation, sandstones, siltstones and mudstones were deposited in channels and flood basins of a meandering alluvial floodplain. Coals accumulated in the floodplain mudstones of this high-sinuosity, low-gradient fluvial system. Levees and crevasse-splays supported large upright trees and plants, and interchannel swamps provided habitats for thick plant accumulation but were inundated periodically to form lakes in which algae-forming stromatolites, ostracods and other organisms flourished.

Paleocurrent data indicate that all of the fluvial sediments were deposited by rivers flowing in a northeast direction and that major faults along the western and southeastern margins of the Sydney Basin formed subsequent to deposition. This suggests that the basin originally extended farther to the southwest, where coarser, basin-margin facies assemblages may have developed (Forgeron, 1980; Rust et al., 1983).

The coarsest deposits in present outcrops (the coarse sandstone facies assemblage) are limited to western and southwestern parts of the basin, extending no farther to the northeast than South Bar (Rust et al., 1983). These were deposited on a braidplain of moderate energy and slope on which peat units were formed but not preserved in place. Paleocurrents on Boularderie Island indicate basement control by what was probably the Boisdale Anticline (Rust et al., 1983). At the present state of knowledge it is not possible to propose this sedimentary package as a formal lithostratigraphic unit. Integration of data from inland outcrops and borehole data is required before this can be done.

The coarse sandstone facies assemblage is transitional upward into the sandstone assemblage, the South Bar Formation (Boehner, 1984). This transition represents a gradual decrease in slope and energy on the braidplain. These deposits occur well up the stratigraphic succession in the western and central parts of the basin but in the presumed lowest strata (south of False Bay and at Bateston) on the east coast (Rust et al., 1983).

The lithostratigraphic change from the sandstone (South Bar Formation) to the alternating facies assemblage (Sydney Mines Formation) is close to the mapped boundary between the Ptychocarpus and Linopteris zones in the western and central parts of the basin. In sections at Sydney Mines, Victoria Mines and Lingan the logical horizon for this boundary is the base of a major fine-grained unit that contains the Emery Seam. This seam was chosen as the boundary by Hayes et al. (1938) and Bell and Goranson (1938a,b) and is about 10 m above the boundary recommended here.

In relation to the approximate time markers represented by the coal seams and the floral zones, the lithostratigraphic change from a sandstone to an alternating assemblage occurred much earlier on the east coast than to the west (Rust et al., 1983). Once again, the mapping of this contact across the basin must await data from inland exposures and boreholes.

The Sydney Mines Formation alternating assemblage represents deposition on a low-slope, low-energy alluvial plain, with relatively few large, high-sinuosity channels within a lower sinuosity meander belt. This gave rise to relatively large areas on the floodplain on which mud was deposited; compaction caused water tables to be continuously high, so that swamp vegetation flourished. In general terms this explains why the thicker, more abundant coal seams occur in the alternating facies assemblage. The initiation of this facies assemblage earlier in the eastern part of the basin indicates that gradients and energy levels decreased earlier there.

Lacking evidence for tectonic or other external causes, the cyclicity in the Sydney Mines Formation is attributed to autocyclic mechanisms due to channel migration, avulsion, etc. A pre-upper Morien strike-slip fault system may be responsible for the folding pattern observed in the Sydney Basin.

Extensive thin limestone units are associated with mudstone sequences in the Sydney Mines Formation between Victoria Mines and Glace Bay. They contain algal laminations, either planar, oncolitic or stromatolitic and an abundant freshwater fauna including bivalves, gastropods, ostracods and fish.

The faunal association of limestone strata in the Sydney Mines Formation is strongly indicative of nonmarine deposition. This is compatible with the sedimentary facies and succession, interpreted as deposited on an alluvial plain. Among the faunal elements, the most diagnostic group comprises teeth and other skeletal fragments of freshwater xenacanthid sharks and the lungfish Ctenodus. They are thought to have inhabited shallow lakes on the alluvial plain, which also from time to time developed algal blooms, forming algal laminites and stromatolites. More restricted depressions on the floodplain became peat swamps, also inhabited intermittently by bony fish and other fauna tolerant of partial oxygen depletion. The presence of lacustrine sediments immediately above coals indicates that many lakes were formed by submergence of a vegetated floodplain. The presence of a nonmarine fauna above a coal is common in the other coal-bearing strata of Nova Scotia (McCabe and Schenk, 1982).

In other cases limestone deposition ceased due to progradation of a lake-fill delta, as a channel system migrated toward the lake. A noteworthy point is that lacustrine limestones in the Morien Group occupy a stratigraphic position similar to that of marine bands within classic paralic coal-bearing successions, although they are less extensive.

Local subsidence (failure of depositional areas on the floodplain to keep up with subsidence), regional subsidence (compaction related to the thick sedimentary pile present in the basin) and uneven compaction related to the presence of buried peat were the main factors controlling the formation of lakes in the Sydney Mines Formation.

In summary, the tectonic setting, uniformity of paleodrainage and the nature of the Morien Group succession all indicate that the alluvial plain on which it accumulated was a stable environment. Stream power diminished with time, as source relief was worn down and alluvial slopes decreased. Hence the onshore succession records a change from medial braidplain, through distal braidplain to meandering-fluvial plain. The transition to meandering-fluvial deposition occurred earlier in the southeast part of the basin than elsewhere, indicating that this was the lowest and flattest part of the drainage system (Rust et al., in preparation).

The development of basin-wide economic coal seams did not occur until the meandering-fluvial plain spread across the basin, as the Sydney Mines Formation was deposited. Only then did high water tables persist, allowing the development of widespread swamps and locally of lakes. Offshore wells located within about 10 km of the north coast of the study area show that upper Morien strata pass upward into post-Morien redbeds (Boehner, 1984). The redbeds lack marine facies and represent deposition on a distal alluvial plain, on which water tables were once again low, and peats were insignificant. Such a widespread response could be due to paleoclimatic change, but more data are required before any conclusion can be reached. Previous workers have assumed that there is a transition to shoreline deposits in the offshore part of the Sydney Basin. However, the Atlantic was closed at the time of basin filling, and there may not have been a connection to the sea. The resolution of this question must await the results of offshore drilling in the basin center.

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TABLES, FIGURES AND PLATES

Table 1. Location, extent and average thickness of main productive seams from top to bottom of the Sydney Coalfield, Cape Breton Island (Source: NSDME, Inform Ser. 2, 1978)

Point Aconi Seam -- Average thickness: 1.0-2.2 m
    District: Sydney Mines
Interseam thickness: 70 m
Lloyd Cove (Upper and Lower Bonar Seam) -- Average thickness: 1.2-3.7 m
    District: Sydney Mines
Interseam thickness: 113 m
Hub Seam -- Average thickness: 1.5-3.7 m
    Districts-Seams: Glace Bay-Hub
        New Waterford-Barachois
        Sydney Mines-Stubbart
Interseam thickness: 91 m
Harbour Seam -- Average thickness: 1.2-4.6 m
    Districts-Seams: Port Morien-Blockhouse
        Glace Bay-Harbour
        New Waterford-Victoria
        Sydney Mines-Sydney Main
Interseam thickness: 76 m
Bouthillier Seam -- Average thickness: 1.0 m
    Districts-Seams: Glace Bay-Bouthillier
        New Waterford-Fairyhouse
        Sydney Mines-Edwards
Interseam thickness: 23 m
Backpit Seam -- Average thickness: 1.0 m
    Districts-Seams: Port Morien-Tunnelshed
        Glace Bay-Backpit
        New Waterford-North Head
        Sydney Mines-Indian Cove
Interseam thickness: 32 m
Phalen Seam -- Average thickness: 1.0-2.5 m
    Districts-Seams: Port Morien-Gowrie
        Glace Bay-Phalen
        New Waterford-Lingan
        Sydney Mines-Collins
        New Campbellton-Four Foot
Stony Seam -- Average thickness: 1.0 m
    Districts-Seams: Sydney Mines-Stony
        New Campbellton-Six Foot
Interseam thickness: 39 m
Emery Seam -- Average thickness: 1.2 m
    Districts-Seams: Port Morien-Spencer
        Glace Bay-Emery
        New Waterford-Emery
Interseam thickness: 130 m
Gardiner Seam -- Average thickness: 1.2 m
    Districts-Seams: Port Morien-Long Beach
        Glace Bay-Gardiner
Interseam thickness: 305 m
Mullins Seam -- Average thickness: 1.2-2.2 m
    Districts-Seams: New Waterford-Mullins
        Sydney Mines-Mullins
Interseam thickness: 175 m
Tracy Seam -- Average thickness: 1.2-2.0 m
    District-Seam: Port Morien-Tracy

Table 2. Relationships of lithostratigraphic and biostratigraphic units within the Morien Group of Cape Breton Island, Nova Scotia

	Age	Robb (1876)	This work (1985)	Hayes, Bell and Goranson (1938)	Barss and Hacquebard (1967)
Upper Carboniferous (Pennsylvanian)	Westphalian D	Productive Coal Measures	SM Fm* (Upper Fine Morien)	*Ptychocarpus unitus* zone	*Thymospora* zone C
			Emery Seam		
	Westphalian C	Millstone Grit	SB Fm** (Lower Coarse Morien)	*Linopteris obliqua* zone	*Torispora* zone B
			Tracy Seam		
				Lonchopteris zone	*Vestispora* zone A

* SM Fm = Sydney Mines Formation
**SB Fm = South Bar Formation

Table 3. X-Ray Diffraction Results: Mudrocks

Location	Depth (m)*	File sample number	Type of Sample	Composition (Decreasing importance)
Victoria Mines	0.5	VM 3	dark grey silty shale	Q-K-S-I
	5	9	med-grey shale (homog)	K-I-Q-M
	19	18A	mottled purple silty mudstone	H=S=Q-K-I
New Waterford	174	NW 28	sandstone with white clay cement	Q-K-I-M
Glace Bay West	102.5	GBW 20	whitish clay cement from ss	Q=K-S=A-I-M
Donkin West	16	DW 11	claystone silty (homog)	Q-K-I-M
	19	13	claystone (homog)	K-Q-I-M
	28	20B	sandstone with white clay matrix	Q-K-I-M
	35	27A	sandstone with white clay matrix	Q-K-I-S=A-M
Donkin East	124	DE 33	overclay (homog)	K=I-Q
Morien North	1.0	NM 1	sandy-reddish claystone	Q-K-H-I-A
	100	53-1	silty-reddish mudstone	Q=H-K
	106.5	59	reddish mudstone (inhomog)	C-Q-H=S=K-I
	110	60	reddish silty mudstone	Q-K-H=S=I
Devco H1A Well	856.1	H1A 2808'	silty mudstone	Q-K-I
	863.4	2832'	grey shale (homog)	K-Q-I-M-S
Devco H3 Well	298	H3 977'	grey shale (homog)	K-Q-I-S
	471.4	1546'	reddish silty mudstone	Q-K=I-H-S=A
	480.8	1577'	reddish silty mudstone	Q-K=I-H
Devco P1 Well	270	P1 885.5'	mudstone enclosing nodule	S-Q-C-K-I
	332.5	1090.5'	bituminous shale	K-Q=I=S
Devco P2 Well	246.5	P2 808.5'	grey shale (homog)	K-Q=I-Cl-M
Devco P4 Well	298.2	P4 978'	sandstone with white clay matrix	Q-K-I-S
	363.7	1193'	sandstone with white clay matrix	Q-K-I
	412.2	1352'	sandstone with white clay matrix	Q-K-I-S

Code

Q-Quartz
S-Siderite
C-Calcite
D-Dolomite (Ferroan)
A-Ankerite
H-Hematite
K-Kaolinite
I-Illite or illite mix
Cl-Chlorite
M-Mica (unspecified)
=-approx. equal
>-much greater content

Note: Organic content was not investigated.

*Depth refers to stratigraphic height as measured from coastal sections and to depth below sea level in wells.

Table 4. X-Ray Diffraction Results: Nodules (Note: Code as in Table 3)

Location	Depth (m)	File Sample Number	Type of Nodule	Composition (decreasing abundance left to right)
Victoria Mines	4	VM 8	ferruginous (homog)	S-Q » K-I
	6.5	13	ferruginous (homog)	S-Q » I-K
	13	16	ferruginous (homog)	A-S-Q-K
	14	17	ferruginous (homog)	S-Q-K
	21	20	calcareous, silty	C-D-Q-K-I
New Waterford	10.0	NW 1	ferruginous (homog)	S-Q » K-I
	13.0	3	ferruginous (homog)	S-Q » K-I
	71.0	7	ferruginous-calcareous, silty	S-Q-C » K-I
Glace Bay West	27	GBW 4B	ferruginous, silty	S-Q-C » K
	58	11	calcareous, silty	D-C-Q » K-I
	79	17	ferruginous, silty	Q-S-K-I
Glace Bay East	13	GBE 5	ferruginous-calcareous (inhomog)	S=C=Q » K=I
	29	7	calcareous (inhomog)	C-D-Q » K-I
Donkin West	34	DW 26	ferruginous (homog)	S-Q-K-I
	42.5	32A	calcareous, silty	C-Q » K-I
	92	68	ferruginous-calcareous (homog)	S=C=D-Q » K-I
	106.5	71	septarian-matrix, silty	S-Q-K
	125.5	84	septarian-fracture filling	C-S » Q-K-I
Morien South	0.5	SM 2	ferruginous, silty	S-Q » K
	99	LAST	septarian fracture filling	C-S » Q-K
Morien North	7.0	NM 2	ferruginous (inhomog)	S-H-Q » K-I-M
	42	26	calcareous, silty	C-Q-K-I
	100	53	septarian-matrix (homog)	S » Q » K
	105	56	ferruginous (homog)	S-Q-K
	109	62	calcareous-ferruginous	C-Q-D=S-K-I
	112	66	separian-fracture filling	C » S » K
Devco P4	257/277.7	P4 843/911	ferruginous-calcareous	S-C-Q-K-I
Devco B162	72.9	B 162.239	ferruginous (homog)	S » Q-K
Devco H1A	856.1	H1A 2808	ferruginous-calcareous	S=C-Q » K-I

Table 5. Limestone Subfacies: Location* and Distribution of Beds Thicker than 50 cm (thickness in m)

Victoria Mines	(th)
1.5- 2.7 m	1.2 m
21 - 23	2
47 - 48	1
63 - 64	1
66 - 68	2
71 - 73	2

Glace Bay West	(th)
22 - 23.5 m	1.5 m
28.5- 30	1.5
30.5- 31.5	1.0
40.5- 43	2.5
47.5- 48	0.5
50 - 50.5	0.5
56.5- 58	1.5
66 - 67	1.0
91.5- 92.5	1.0
118 -119.5	1.5
130 -131	1.0
170.5-171.5	1.0
194.5-196	1.5

New Waterford	(th)
38.5- 39.5 m	1 m
73.5- 75	1.5
82.5- 83.5	1
108 -109.5	1.5
128 -129.5	1.5
138.5-140.5	2
146 -147	1
177.5-180 with oncolites	2.5
196 -203	7.0
225 -228	3.0
242 -244	2.0
279 -280	1.0

Glace Bay East	(th)
10 - 11 m	1 m
29.5- 31	1.5
34.5- 35.5	1
39.5- 41	1.5
67 - 68	1.0
105 -106.5	1.5
162 -163.5	1.5

Donkin West	(th)
14.5- 15 m	1.5 m
31.5- 32.5	1
86 - 89	3
90.5- 92	1.5
107 -108	1
123.5-124.5	1

Donkin East	(th)
67 - 68.5 m	1.5 m
76.5- 78	1.5
105.5-107	1.5
125.5-126.5	1.0

Morien South	(th)
87 - 88 m	1 m

Morien North	(th)
86 - 88.5	2.5 m

*Stratigraphic interval of each 1st unit.

Table 6 . Distribution of fossil fish fragments from three units studied, from samples of approximately 1200 g each

Location section (m)	Unit	Total micro-fossils	Elasmobranchs (%) Dermal denticles and placoid scales	Elasmobranchs (%) Bicuspid teeth, membranes and scales	Elasmobranchs (%) Total	Acanthodians (%) Spine fragments, with a few scales	Osteichthyes (%) Teeth, bones, dermal plates, and scales
Victoria Mines (2-3)	VM-14	630	9.3	5.5	14.8	12.0	73.2
New Waterford (108-110)	NW-17	175	30.0	3.1	33.1	13.1	53.8
New Waterford (128-130)	NW-20	1168	18.9	7.2	26.1	13.0	60.9

Table 7 . Characteristics of Coal from the Sydney Coalfield

(From: Hacquebard and Donaldson, 1969)

Characteristics				Sydney coalfield
Microscopic data of the coal	Coal Petrography		Intervals	Petrographic intervals present, indicating vertical changes in composition of seam section
			Micro-lithotypes	Vitrite and clarite greatly predominate in nearly all seams; varying amounts of "intermediates", durite, and fusite occur
		Macerals	Amounts	Per seam total: vitrinite always more than 70 percent, exinite 10 percent and less, inertinite 20 percent or less
			Dominant types	Vitrinite occurs as telinite and post-telinite, inertinite as granular micrinite and fusinite splinters
			Preser-vation	Excellent, particularly noticeable on spore exines
		Mineral matter		Syngenetic pyrite, mostly in finely disseminated form, sometimes less than 2 μ in diameter
	Palynology	Miospores	Popula-tion	Total number of genera in both coalfields depends entirely on geologic age; Lycospora and Monolete spores predominate throughout
			Assem-blage	Variable within each seam section, different between seams
			Vegeta-tion	A correlation exists between coal facies and (spore) flora
			Age of productive measures	Upper Carboniferous: Westphalian C and D
Proximate analysis of productive coals	Per seam total		Sulphur	From 2.0–5.3 percent
			Ash	From 4.5–11.5 percent
			V.M. mm-free	From 36–40 percent
			Rank	High-volatile "A" bituminous

V.M. - Volatile matter

Table 8. Location and Distribution of Coals and Enclosing Beds (thicker than 40 cm)

Sections/ Seams	Th/ Location	Under-lying	Over-lying
Victoria Mines			
E	7.3- 8.0	2	6A
m	10.3- 13.5	2	3A
m	35.5- 36	1	3A
Ph	45 - 48	1	4→6A
Ba	79.5- 81	1	3A
Bo	109.5-110.5	8	3A
New Waterford			
E	0.3- 3.5	2	3A
m	11 - 13	1	4→5
Ph(?)	37 - 39.5	6→1	4→6A
m	55.5- 57.3	5→1	6B
Ba	65 - 67.5	7→1	3A
Bo	82 - 83	3	4
m	98 - 99	1	3A
m	113 -114	1	6B
Hbr	161 -163.5	8	3A→6B
m	184.5-185.5	1	3B
m	201.5-203	2	4→3A
m	212.5-213	1	3A
m	247.5-248.5	1	6A
H	283 -285	8	8
Glace Bay East			
Ba	0 - 1.5	8	3A
m	17.5- 19	8	3B
m	20.5- 22	7	3A→6A
m	27 - 29	1	4
Bo(?)	33 - 35.5	5	4
m	39 - 40.5	1	4

Sections/ Seams	Th/ Location	Under-lying	Over-lying
Donkin West			
m	8.5- 9.5	5→1	3B
m	10.5- 12	2	3A
m	60.5- 62	5→1	6B
m	64.5- 65.5	1	3A
Ba	68.5- 70	2	6B
m	73.5- 75	1	6B
m	105.5-106.5	2	3A
m	113.5-114.5	1	6B
m	120.5-121.5	8	3B
m	123 -124.5	1	4
Donkin East			
E	0.2- 2.0	1	6A
m	4.5- 5.5	2	6B
m	22.5- 23.5	2	6B
m	34 - 35	1	6A
Ba(?)	76.5- 78	8	4→6A
m	101.5-103	2	6A
m	105 -107.5	2	4→5
m	115.5-116.5	5→1	3B
m	117.5-119.5	2	3A→6B
m	122.5-124	2	3B
Schooner Head			
m	0 - 1	8	6A
m	2.5- 3.5	7	6A
m	4 - 5	6A→1	6B
E	32.5- 36	2	3A→6A
m	50 - 51.5	1	3A→5
m	57 - 58	5→1	5→6A

(continued)

Table 8 (concluded)

m	40.5- 41	1	6B
m	52.5- 53.5	1	3A
m	56 - 57	7→1	6A
Hbr	93.5- 96	2	3A→5
m	100.5-101.5	2	3B
m	120.5-121.5	6A→1	3A
m	133 -135	6A→1	3A→5
m	162 -163.5	5→1	4→6B
m	181 -182.5	1	3A
H	205 -210	5→1	8

Glace Bay West

m	19.5- 20.5	1	3A→5
Ph	37.5- 41	8	4
Ba	65 - 67	2	4
m	82 - 83.5	2	3A
Bo	96 - 98	1	4→3A
m	99 -100	5	3A
m	106 -107	6A→1	6B
m	121.5-122.5	1	3A
Hbr(?)	158 -161	8	8
m	163.5-165	2	3A
m	195 -196	4→1	5
m	199 -200	5	6A
H	275 -280	2	4

Note: Thickness includes part of enclosing beds.

Morien South

E	0 - 2.5	2	3A→6A
m	16 - 17.5	8	3A
m	28 - 29	1	6A
m	86.5- 87.5	1	5
m	99.5-100.5	2	6A
m	100.5-102	7→1	6A

Morien North

m	19.5- 20.5	2	6A
m	75.5- 77	1	6A
Hbr(?)	78 - 81	8	8
	106.5-108	1	5
	110.5-111.5	1	6A

Code: Identification of enclosing units

1 -Rooted zone
2 -Rooted zone with Fe nodules at base
3A-Carbonaceous shale
3B-Silty mudstone/shale with Fe nodules
4 -Calcareous (skeletal), carbonaceous, shale and/or limestone
5 -Tabular interstratified siltstone and sandstone
6A-Coarsening-upward rippled siltstone and sandstone
6B-Trough cross-bedded sandstone (channel)
7 -Ganister
8 -Covered

Seam identification and location

E-Emery, Ph-Phalen, Ba-Backpit, Bo-Bouthillier, Hbr-Harbour, H-Hub, m-minor unidentified
→ -grading to
? -probable location

Table 9. Lithofacies and Depositional Facies Relationship

Lithofacies (petrographic observations)	Depositional Facies (Miall, 1978) (relative order of decreasing importance)
1. Conglomerate to very coarse quartzolithic and quartzosublithic sandstone	Gm, St, Se
2. Coarse-medium quartzolithic to lithisubquartzose sandstone	St, Sh, Sp, Sr, Se
3. Medium-fine quartzosublithic to lithisubquartzose sandstone	St, Sr, Sh, Sp, Fl, Se
4. Fine-very fine lithisubquartzose to lithiquartzose sandstone	Sr, Sh, Fl, Fm
5. Sand-siltstone-shale/mudstone interstratification	Sr, Fl, Fm, Ls-m
6. Silty shale and/or mudstone-claystone	Fm, Fl, C, Ls-f, Ls-m
7. Nodules	Gm, St, Sr, Sp, Ls-m
8. Various limestone subfacies	Ls-f, Ls-m, Fm, Fl, Sr, Sh
9. Coal	C, Fm, Ls-f, Fl-Sh

Depositional Facies Code

Gm - massive or crudely horizontally bedded conglomerate
St - trough cross-stratified sandstone
Sp - planar cross-stratified sandstone
Sr - ripple cross-laminated sandstone
Sh - horizontally stratified sandstone
Se - erosional scours with intraclasts
Fm - massive mudstone or siltstone
Fl - laminated siltstone and shale
C - coal and related carbonaceous shale
Ls-f - algal laminite and stromatolitic limestone subfacies, mudstone-packstone (interstratified limestone) subfacies and massive micrогranular limestone subfacies
Ls-m - calcrete paleosols and pedogenic nodular subfacies, conglomeratic/breccia limestone subfacies

Table 10. Lithofacies and Principal Sedimentary Structures

Facies code	Lithofacies	Principal sedimentary structures	Interpretation
Gm	massive or crudely bedded gravel with vc-c ss matrix	massive non-bedded to crudely horizontally bedded	longitudinal bars, lag deposits, minor channel fills
St	sand, medium to very coarse, locally pebbly	solitary or grouped trough cross-stratified beds fining upward	sinuous crested dunes (lower flow regime)
Sp	sand, medium to very coarse, locally pebbly	solitary or grouped planar cross strata	linguoid, transverse bars, sand waves (lower flow regime)
Sr	sand, very fine to coarse	ripple marks of great variety	ripples (lower flow regime), levees, splays, upper point bars
Sh	sand, very fine to coarse	horizontal lamination, parting or streaming lineation	planar bed flow (lower and upper regime), crevasse splays, levees
Se	erosional scours with intraclasts	crude cross bedding	scour fills
Fl	sand with minor very fine silt, mud	fine horizontal laminations, very small ripples	overbank or waning flood deposits
Fm	mud, locally sandy	massive, locally with freshwater faunal debris, desiccation features	backswamp deposits, backswamp pond deposits, overbank deposits
C	coal, carbonaceous shale	coal, plants, under-lying roots, fine laminations	swamp deposits
Ls-f	carbonates, with algal and/or fossiliferous content	fine interstratification, fine scale wavy lamination, non-laminated	lake and pond deposits
Ls-m	all non-algal or fossiliferous carbonate subfacies	pedogenic features, conglomeratic/ brecciated bed	soil, rip-up deposits

Table 11. Summary of Depositional Assemblages (from Lithostratigraphic Zones, Appendix B)

Depositional Characteristics	Lithozones A,C Fluvial channel with floodplain	B,D Fluvial channel lacustrine with floodplain	E Floodplain/ lacustrine
Lithology	mostly VF-C SS; CGL; siltstone-mudstone; good coal and purple sequences locally	Ls locally; under-clay and coal; VF-C SS; siltstone and mudstone	predominantly vari-egated Ls and mud-stone-siltstone; minor sandstone content locally; local minor coal
Shape of main bodies	tongue and lobate SS bodies	variable, irregular lobate-sheetlike SS bodies	generally sheetlike to tabular bodies to tongue shape
Structures and sequences	fining-upward cycles; channels, trough cross-stra-tification; point-bar development; epsilon cross-beds; ripple cross-laminated	SS: thin to medium bedded; small-scale festoon and tabular cross-laminated and horizontally lamin-ated; Ls: even-bedded to nodular	Ls: even and closely spaced horizontal laterally continuous; brecciated-conglomer-atic fabric locally; soft-sediment fea-tures; mudstone/silt-stone rippled
Sand/mud ratio	low to high	low to moderate	very low
Nature of flood-plain deposits	sheet and crevasse splays	sheet and crevasse splays	sheet and well-deve-loped crevasse splays
Grain size/ texture	fine-grain in upper part; med-cse in lower part; moder-ately poor sorting	Ls: micro-granular to granular; SS: F-VF grading into silt	Ls: mostly granular to microgranular; local breccia; SS: VF-F, fair sorting
Fossils and accessories	plant debris and imprints, logs and woody fragments; mica abundant and clay minerals in-creasing upward	Ls: ostracods, gas-tropods, fish rem-nants; mudstone: carbonised plant debris; mica mostly in SS along parting plane with carbon-ised plant debris	Ls: similar to previous siltstone/ mudstone carbonised and macerated plant debris; purple-hematitic sequence; thin lenses of coal locally
Interpretation	high-sinuosity rivers	sinuous (meander-ing) rivers with backswamp lakes and ponds	variable lacustrine and pond deposits with related flood-plain; fluctuating water table and local surficial exposure

Table 12. Parameters of some significant sandstone bodies - New Waterford section

Location (m)	Type of body	Thickness measured (m)	Cliff exposure Lateral extent (m)*
7-9.5	lacustrine delta or splay	2.5	≤ 50
20-24	splay package	4.0	> 75
25-36.5	channel buildups (unit around North Head Point)	11.5 (total) 4-6.5 (indiv.)	> 150
39.5-46.5	channel (lacks lateral accretion sets)	7	> 100
57-65	channel (lacks lateral accretion sets)	8	$\simeq 40$
71.5-73.5	channel with point bar, lateral accretion sets	2.5	> 100
87-93	channel with two fining-upward cycles	6	> 75
113.8-124	stacked (point-bar) channels (two) with lateral migration sets	11	> 150
150-155	splay sequence: proximal and distal	5	> 75
163-174	stacked channels (three) with point-bar, lateral migration sets	11 (total) 3-4.5 (indiv.)	> 125
185-195	splay sequence	10 (total) .5-1.0 (indiv.)	$\simeq 200$
203-211	channel buildup and lateral migration	8 (total) 3-5 (indiv.)	> 125
214-220	channel	6	> 100
240-250	splay sequence	10 (total)	> 100
265-end	splay sequence	25 (total)	$\simeq 300$

*The lateral extent of channel sandstone bodies cannot be determined in many cases, because they extend laterally beyond the cliff exposure. On the basis of Collinson's (1978b) relationship, they should be $\simeq 700$ m wide.

Table 13. Lateral extent of channels (i.e., correlations >3 measured sections)

Figure	Location on Fig. Part	Area	Interval with thickest sequence		Correlations, lateral extent (km)*	
App. B, Fig. 1, Zone A	lower	eastern	SH:05-15m	- 10m	DE to M	6.4 km
	upper	western	NW:25-37m	- 12m	VM to NW	
App. B, Fig. 3, Zone C	lower	central	DW:70-83m	- 13m	GBW to DE	10 km
	upper	western	NW:87-93m	- 6m	NW to GBW	3 km
App. B, Fig. 4, Zone D	lower	central	GBW:107-117m	-10m	NW to GBE	4.7 km
App. B, Fig. 5, Zone E	lower	western	NW:163-174m	-11m	NW to GBW	3 km
	lower	western	NW:203-211m	- 8m	NW to GBW	3 km
	lower	western	NW:215-220m	- 5m	NW to GBW	3 km
App. B, Fig. 6, Zone E	upper	central	GBE:163-171m	- 8m	GBE to GBW	4 km
	upper	western	NW:254-260m	- 6m	NW to GBW	3 km

*Because lateral extent is much wider than can be determined from cliff exposure (Table 12), this table indicates that 1)cliff exposure is probably only partial and/or 2)most of the sandstone channel bodies are laterally amalgamated.

Table 14. Some examples of vertical coal (swamp)/backswamp sequences

Section	Figure*	Interval (m)	Vertical facies change observed
Victoria Mines	1	93- 96	coal overlain by floodplain package
New Waterford	2	55- 63	coal overlain by fluvial channel accumulation
New Waterford	2	80- 86	coal overlain by coarsening-upward lacustrine splay package
New Waterford	2	97-105	coal overlain by proximal channel package exhibiting flooding of series of upright tree trunks
New Waterford	2	184-190	coal overlain by interstratified backswamp and coarsening-upward splay deposit
Glace Bay West	3	19- 24	coal overlain by coarsening-upward lacustrine sequence
Glace Bay East	4	26- 32	coal overlain by pond deposit enclosed in a floodplain sequence
Donkin West	5	120-130	minor coal seams interstratified with floodplain, pond and splay deposits
Donkin East	6	33- 40	coal overlain by channel accumulation
Schooner Head	7	49- 54	coal overlain by coarsening-upward crevasse-splay deposits
Morien North	8B	74- 78	coal capping an abruptly abandoned distributary channel

* Figures refer to those of Appendix A.

Table 15. A) Classification of Fluvial Channel Systems (from Rust, 1978a)

	Single-channel system (braiding parameter 1)	Multichannel system (B.P. 1)
low sinuosity (1.5)	Straight	BRAIDED
High sinuosity (1.5)	MEANDERING	Anastomosing

B) Differences between the Deposits of Braided and Meandering Rivers (from Miall, 1977b)

Criterion	Braided Rivers	Meandering Rivers
lateral accretion deposits	rare, in point bars, linguoid bars, low water bar accretion	common in fining-upward point bars (including epsilon cross beds)
vertical accretion deposits	channel floor bed forms sheet flood deposits bar-top deposits minor overbank deposits	overbank deposits channel lag deposits
type of scour surface	channel erosion	meander widening
channel abandonment behaviour	progressive, as a result of aggradational fill	sudden, as a result of meander neck cutoff, chute cutoff or avulsion
channel abandonment deposit	fining-upward cycle	fine-grained fill or fining-upward sequence (see Walker and Cant, 1984)
Facies occurrence:		
Gm	common (longitudinal bar deposit)	rare to common (generally as a thin lag deposit)
Gt, Gp	rare to common	absent
St	common	common
Sp	common	generally rare
Sh, Sr	common	common
Fl, Fm	common abundant	common moderate
Channel-fill sequences	rarely 3 m	commonly 3 m

Table 16. Facies transition significance - decreasing order of importance

Transition facies interpretation	Difference value*
Se - St	0.917
St - St lam	0.640
St lam - Sr	0.444
Ls-f - Ls-m	0.383
Ls-m - Fl/m	0.308
Fm sid - Fl/m	0.217
Ls-m - Ls-f	0.202
C - Fl/m	0.194
C - Ls-f	0.183
Sh - Fl/m	0.178
St - Se	0.172
Ls-f - Fl/m	0.153
Sr - Fl/m	0.147
Fl/m - Sr	0.087
Fl/m - C	0.074
Sh - Sr	0.064
Ls-f - C	0.041
Fl/m - Sh	0.037

*Transitions with difference values $\leqslant$ 0.025 were not considered of significance. Total Transition Count Matrix for all measured sections is 3266. Detailed distribution is given in Fig. 19.

Table 17. Parameters of cycles ≥ 1.5 m (recorded for all sections)

Section	Thickness (m)	Fining-upward cycles: Total number of cycles	Fining-upward cycles: Thickness (m) Range*	Fining-upward cycles: Thickness (m) Average	Coarsening-upward cycles: Total number of cycles	Coarsening-upward cycles: Thickness (m) Range	Coarsening-upward cycles: Thickness (m) Average
Victoria Mines	117	6	3-7	4.3	1	2.5	2.5
New Waterford	285	18	1.5-11	4.4	14	1.5-4	2
Glace Bay West	280	9	1.5-7	3.7	6	1.5-5	3.2
Glace Bay East	210	12	1.5-8	2.9	7	1.5-3.5	1.9
Donkin West	134	14	1.5-8.5	2.8	4	1.5-2	1.6
Donkin East	133	13	1.5-4.0	2.4	3	1.5	1.5
Schooner Head	60	4	1.5-7	4.6	4	1.5-2.5	1.9
Morien South	103	9	1.5-4.5	2.8	3	1.5-2.0	1.7
Morien North	113	15	1.5-6	2.4	4	1.5	1.5
Total	1435	100	1.5-11	3.4	46	1.5-5	1.9

*Range of FU sequence.

Table 18. Distribution and number of paleocurrent measurements (of all types). Sydney Mines Formation

Structures measured	Sections									
	VM	NW	GBW	GBE	DW	DE+ SH	MS	MN	Total	%
Trough cross-stratal axis direction	77	87	53	64	57	80	55	62	535	55.5
Channel direction	--	17	6	7	7	5	3	4	49	5.1
Rippled cross-lamination direction	15	19	20	--	4	3	5	13	79	8.2
Rippled cross-laminated crest axis	52	33	28	11	6	4	7	3	144	14.9
Primary current lineation	10	4	20	23	7	5	3	11	83	8.6
Sole marks, flute casts, groove casts	5	--	2	3	--	--	3	20	33	3.4
Elongated clasts, lag features, etc.	27	8	--	6	--	--	--	--	41	4.3
$\sum n$	186	168	129	114	81	97	76	113	964	100

Table 19. Location of some limestone from the Sydney Mines Formation

Section	Location Figure*	Location Interval (m)	Type of physiographic features
Victoria Mines	1	1- 3	composite lacustrine unit interstratified with marly sequence
		64- 66	pedogenic calcrete deposit
New Waterford	2	6- 10	lacustrine delta deposit
		108-114	lacustrine deposit overlain by poorly drained swamp and coal
		128-130	small-size lacustrine/pond within fluvial floodplain
		174-183	well-developed lacustrine and marginal lacustrine deposit (stromatolitic with oncolites and mudstone-packstone)
		222-231	ephemeral lacustrine within floodplain with fluctuating water table upward into floodplain with minor coal
		240-244	coarsening-upward lacustrine delta and splays
Glace Bay West	3	19- 25	lacustrine sequence overlying coal
		29- 36	microgranular limestone within marly sequence and interstratified with thin splay units
		40- 43	coarsening-upward lacustrine sequence overlying coal seam
		65- 66	fossiliferous capping of coal
		118-120	isolated pond
		130-131	fossiliferous capping of coal
		174-185	lacustrine sequence of interstratified homogeneous limestone and highly calcareous sandy beds exhibiting soft-sediment deformation
Glace Bay East	4	2- 5	lacustrine splay deposit
		9- 11	isolated pond
		27- 32	small-scale lacustrine/pond within poorly drained swamp
		104-107	small lacustrine deposit within poorly drained swamp
Donkin West	5	89- 92	pond within poorly drained swamp
Donkin East	6	124-127	pond within poorly drained swamp

* Figures refer to those of Appendix A.

Table 20. Lateral extent of major limestone physiographic features of the Sydney Mines Formation (i.e., correlation across two sections or more)

Zone	Figure App. B	Observed distance	Reference unit (m)	Correlated extent (sections)	Type of deposition
C	4	11 km	6BE:38-41	NW to DE	major lacustrine inundation
C	4	11 km	6BW:118-122	NW to DE	major lacustrine inundation passing upward into coal swamp
E	5	7.7 km	NW:178-181	NW to 6BE	deltaic splay passing laterally into marginal lake deposits
E	5	7.7 km	NW:182-190	NW to 6BE	lacustrine deposit exhibiting deltaic and splay deposits
E	5	3 km	NW:201-203	NW to 6BW	lacustrine deposit with correlated fossiliferous beds and coal development in upper part

Figure 1

Location map of Sydney Basin, Cape Breton Island.

Locations of measured sections:

1. Victoria Mines; 2. New Waterford; 3. Glace Bay West; 4. Glace Bay East; 5. Donkin West and East and Schooner Head; 6. Morien South and North.

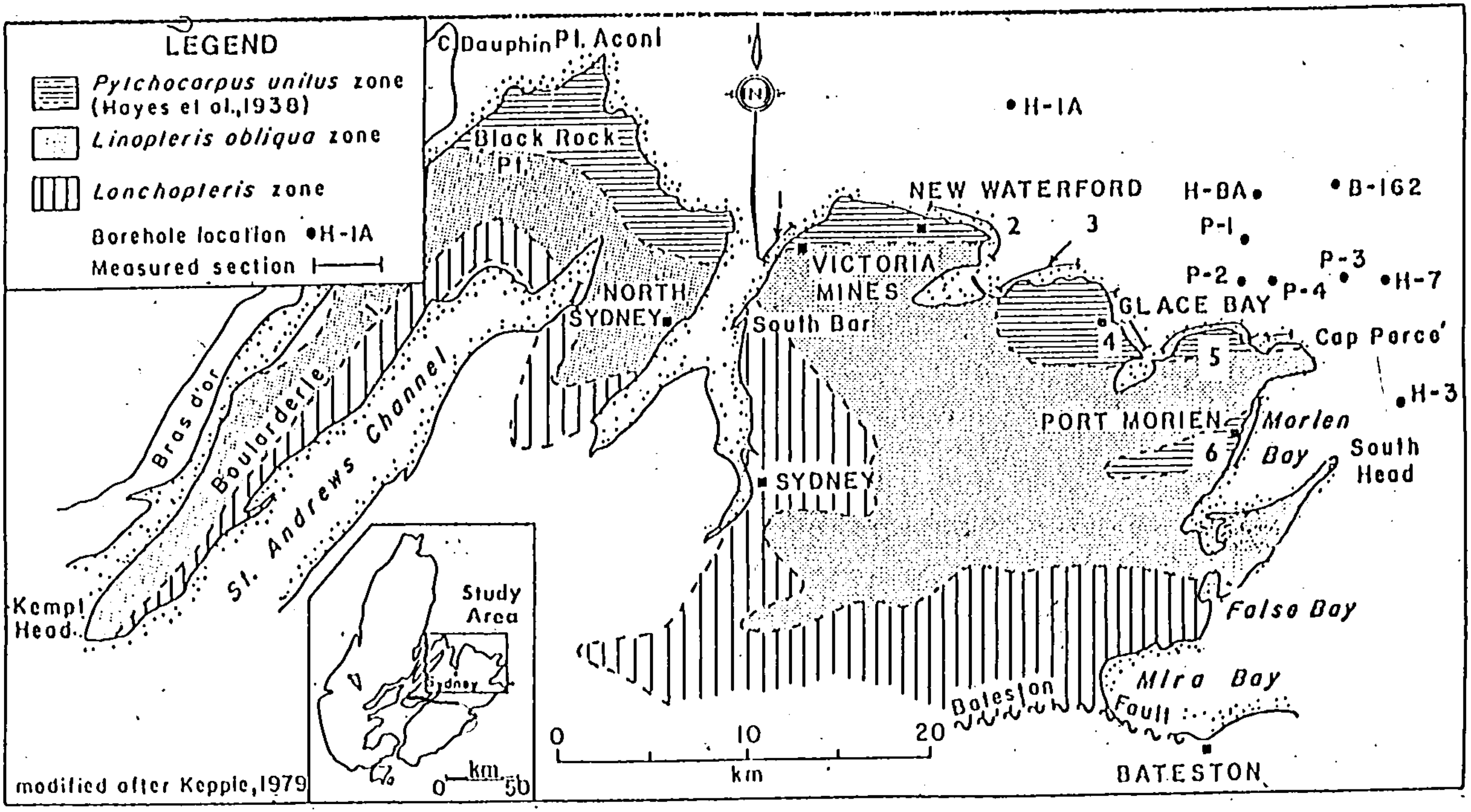
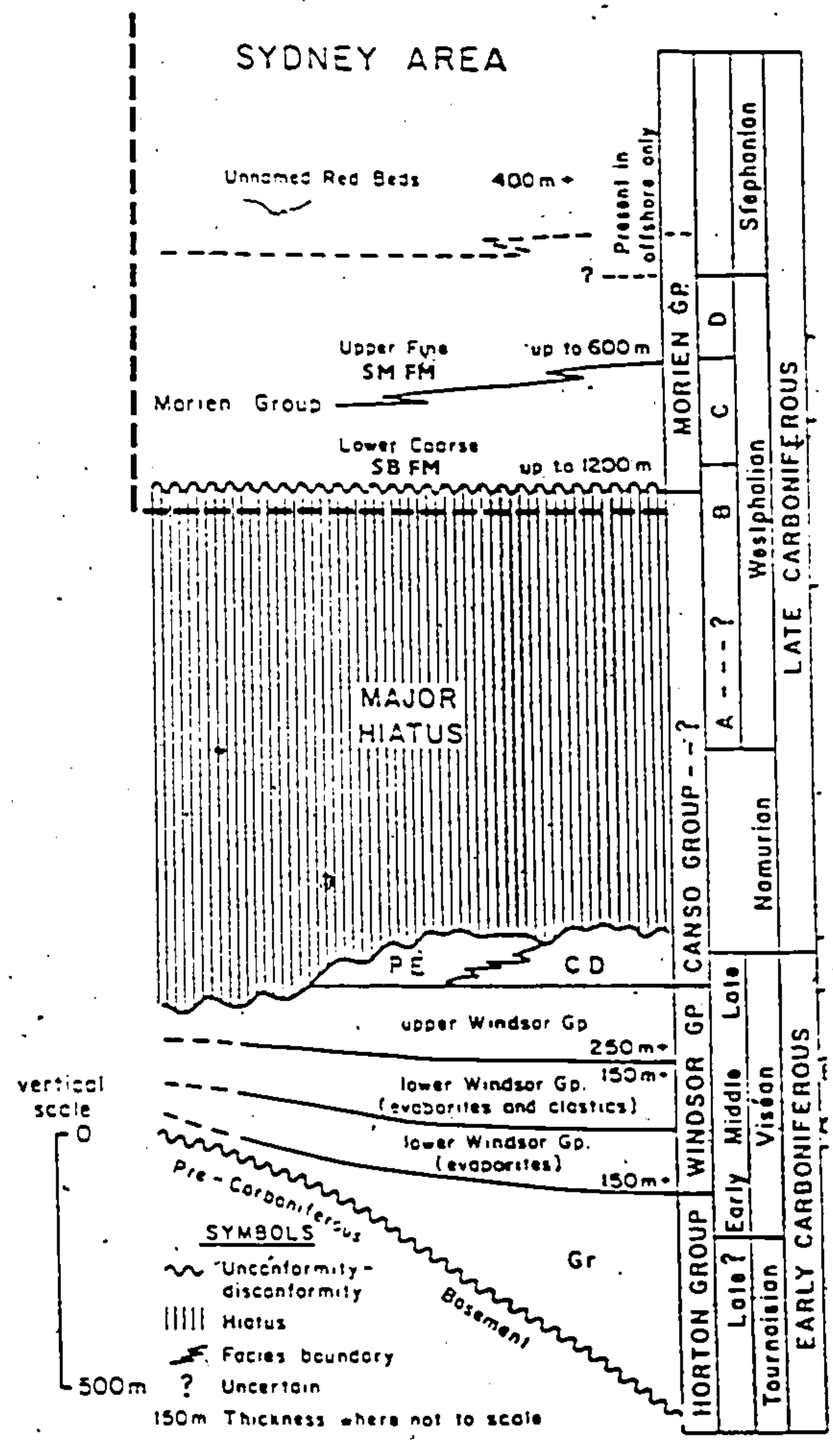

LEGEND
Pytchocarpus unitus zone (Hayes et al.,1938)
Linopteris obliqua zone
Lonchopteris zone
Borehole location •H-1A
Measured section
C Dauphin
Pt. Aconi
Black Rock Pt.
NORTH SYDNEY
Bras d'or
Boulardarie
St. Andrews Channel
Kempt Head
H-1A
NEW WATERFORD
VICTORIA MINES
South Bar
SYDNEY
H-8A
B-162
P-1
P-2
P-3
P-4
H-7
H-3
GLACE BAY
Cap Perce'
PORT MORIEN
Morien Bay
South Head
False Bay
Mira Bay
Bateston Fault
BATESTON
Study Area
Sydney
0 10 20
km
modified after Kepple, 1979

Figure 2

Summary of stratigraphy of the Sydney Basin (Boehner, 1984).

Rock units:-Gr - Grantmire Formation; PE - Point Edward Formation; CD - Cape Dauphin Formation; SB FM - South Bar Formation; SM FM - Sydney Mines Formation. Area enclosed by ----- represents location of Figure 3.



SYDNEY AREA
Unnamed Red Beds
400m+
Present in offshore only
?
Upper Fine
SM FM
up to 600m
Morien Group
Lower Coarse
SB FM
up to 1200m
MAJOR
HIATUS
PE
CD
upper Windsor Gp
250m+
150m+
lower Windsor Gp.
(evaporites and clastics)
lower Windsor Gp.
(evaporites)
150m+
Pre-Carboniferous
Basement
Gr
vertical scale
0
500m
SYMBOLS
Unconformity - disconformity
Hiatus
Facies boundary
? Uncertain
150m Thickness where not to scale
MORIEN GP
CANSO GROUP - - ?
WINDSOR GP
HORTON GROUP
D
C
B
A - - - ?
Late
Middle
Early
Late ?
Stephanian
Westphalian
Namurian
Viséan
Tournaisian
LATE CARBONIFEROUS
EARLY CARBONIFEROUS

Figure 3

Summary of stratigraphy of the Morien Group (after Boehner, 1984).

S.M. Fm = Sydney Mines Formation

S.B. Fm = South Bar Formation

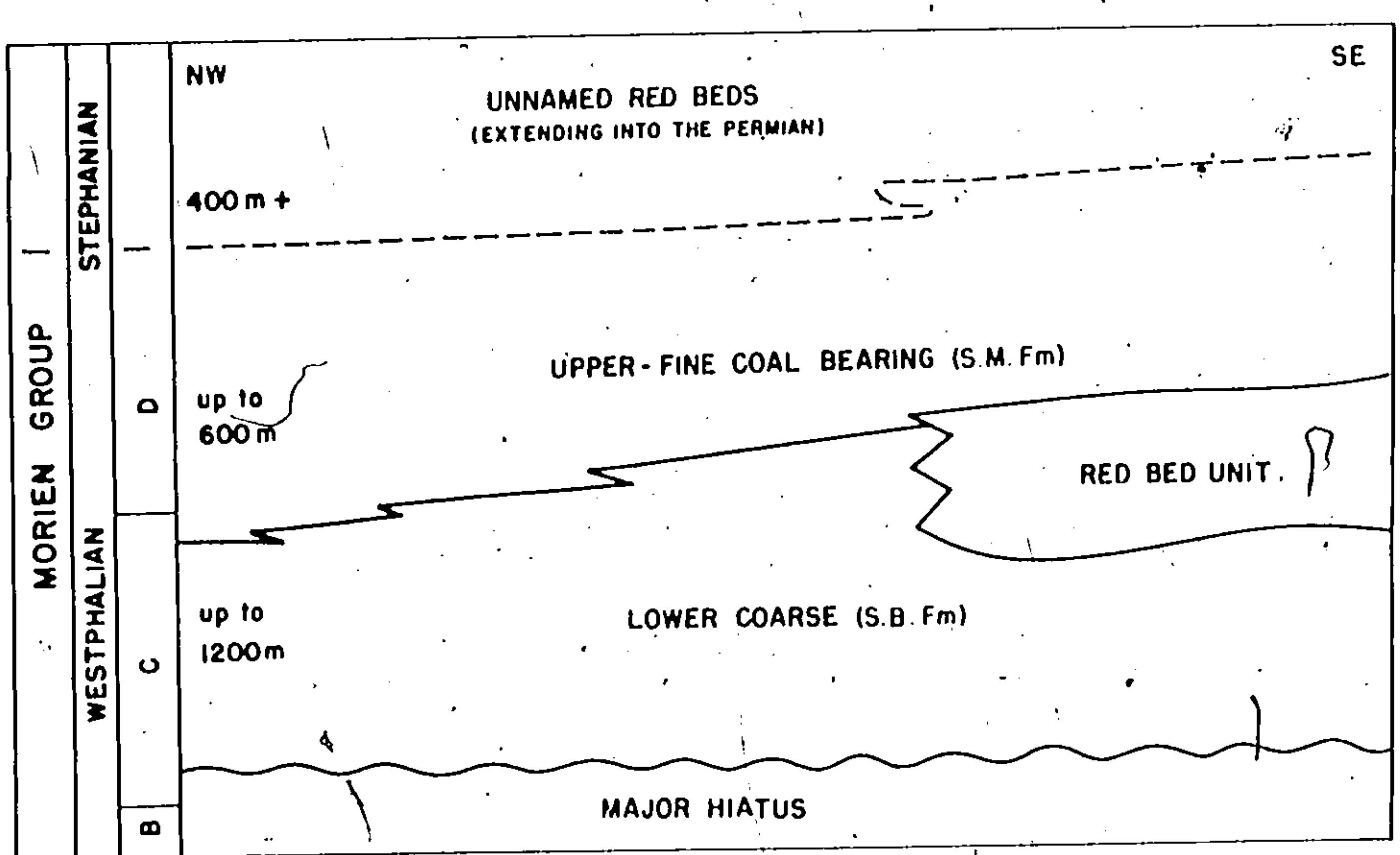

MORIEN GROUP
STEPHANIAN
WESTPHALIAN
D
C
B
NW
SE
UNNAMED RED BEDS
(EXTENDING INTO THE PERMIAN)
400 m +
UPPER - FINE COAL BEARING (S.M. Fm)
up to
600 m
RED BED UNIT.
LOWER COARSE (S.B. Fm)
up to
1200 m
MAJOR HIATUS

Figure 4

Distribution and correlatable lateral extent of the informal lithostratigraphic zones of the Sydney Mines Formation, upper Morien Group.

Environments of deposition are interpreted as:

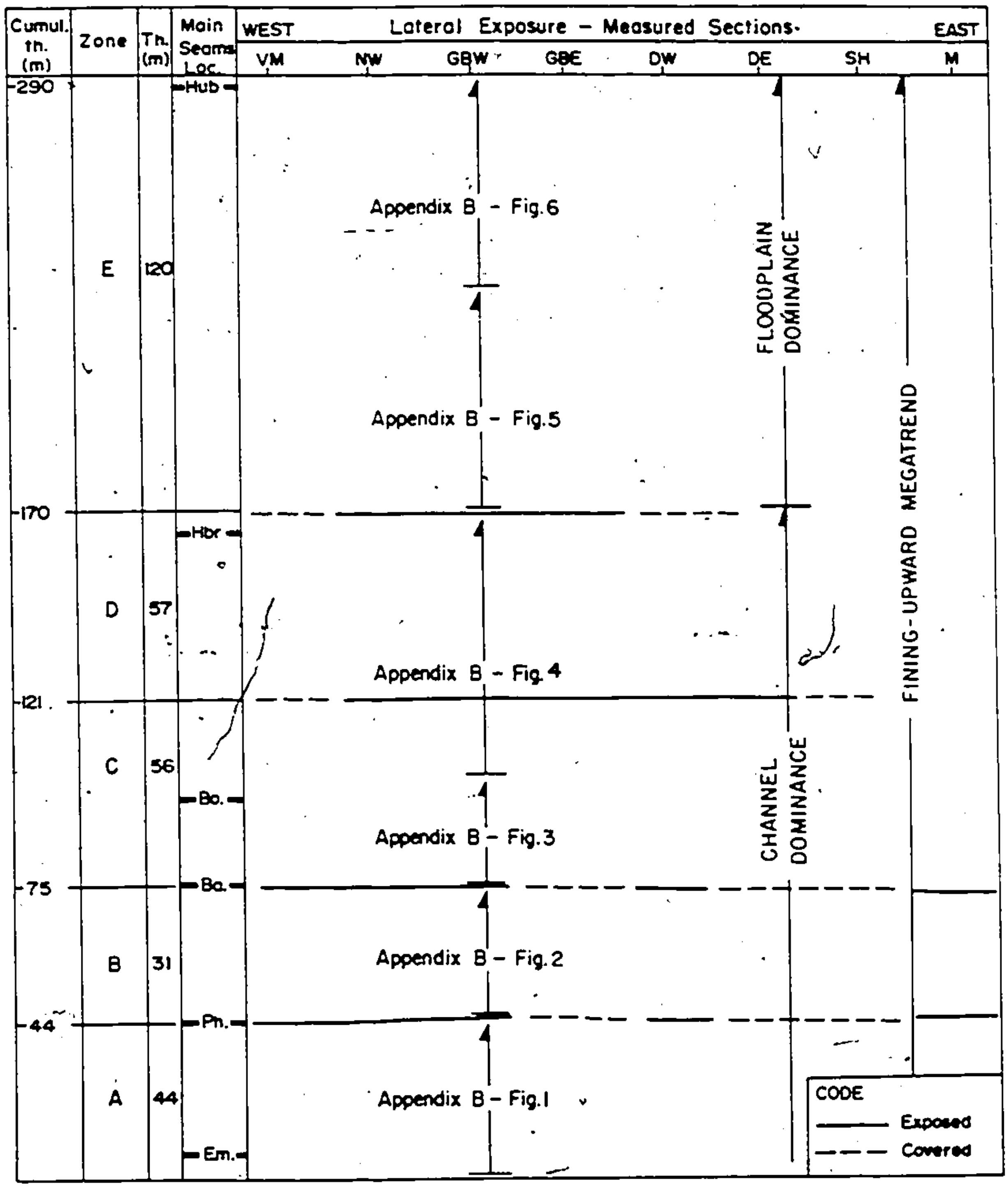
A,C - fluvial-channel-dominated with floodplain;

B,D - fluvial-channel and floodplain-dominated with local lacustrine limestone beds;

E - floodplain-dominated with minor distributary channels and lacustrine limestone beds.

Abbreviations: Em (Emery), Ph (Phalen), Ba (Backpit), Bo (Bouthillier), Hbr (Harbour), VM (Victoria Mines), NW (New Waterford), GBW (Glace Bay West), GBE (Glace Bay East), DW (Donkin West), DE (Donkin East), SH (Schooner Head), M (Morien South and Morien North sections).

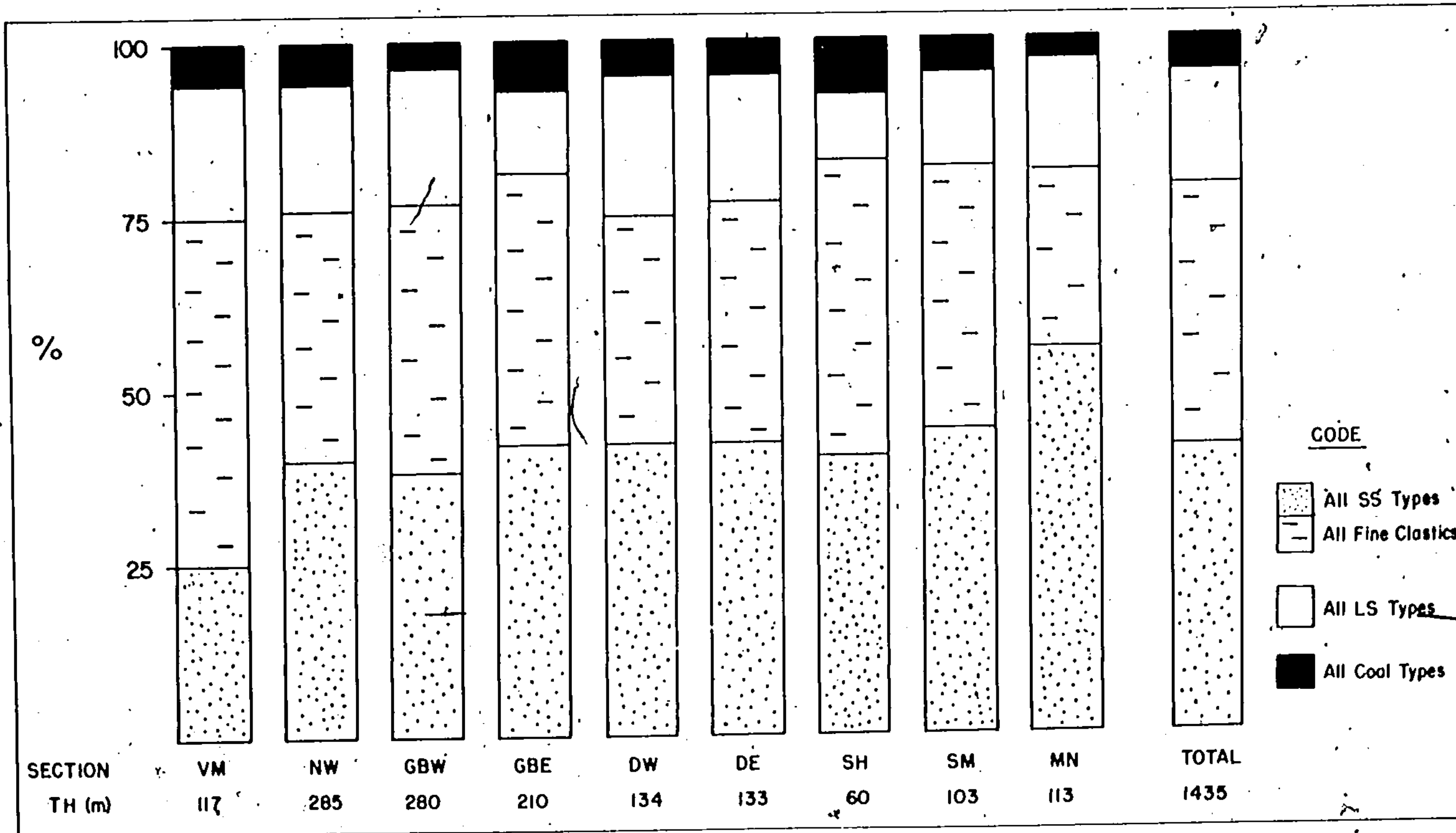
Thickness is that of New Waterford section. Location and lateral extent of figures from Appendix B are shown.



Cumul. th. (m)
Zone
Th. (m)
Main Seams Loc.
WEST
Lateral Exposure – Measured Sections
EAST
VM
NW
GBW
GBE
DW
DE
SH
M
290
Hub
E
120
Appendix B – Fig. 6
Appendix B – Fig. 5
FLOODPLAIN DOMINANCE
170
Hbr
D
57
Appendix B – Fig. 4
FINING-UPWARD MEGATREND
121
C
56
Bo.
Appendix B – Fig. 3
CHANNEL DOMINANCE
75
Ba.
B
31
Appendix B – Fig. 2
44
Ph.
A
44
Appendix B – Fig. 1
Em.
CODE
Exposed
Covered

Figure 5

Distribution and percentage of main lithological groups in sections measured.



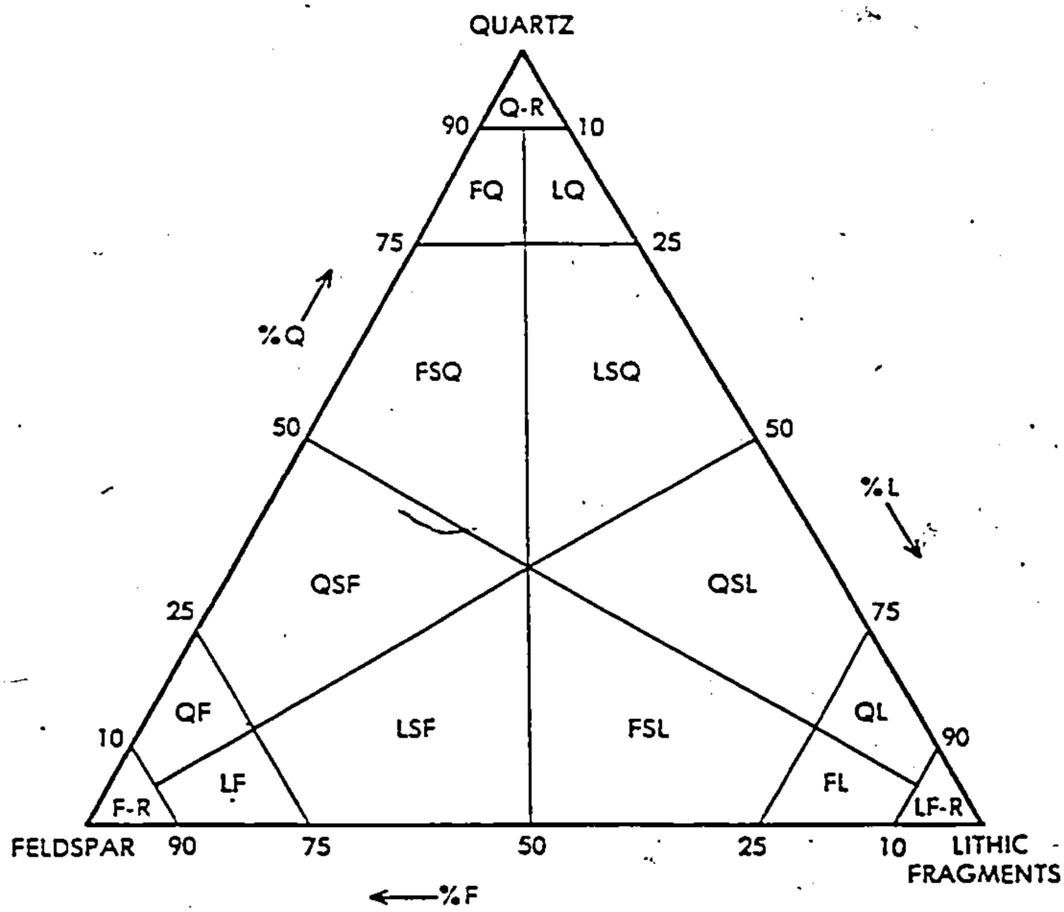
100
75
50
25
%
SECTION
TH (m)
VM
117
NW
285
GBW
280
GBE
210
DW
134
DE
133
SH
60
SM
103
MN
113
TOTAL
1435
CODE
All SS Types
All Fine Clastics
All LS Types
All Coal Types

Figure 6

Classification and nomenclature of the sandstones from the Sydney coalfield (from Mansfield and Ahlbrandt, 1978).

QFL TRIANGLE

SECONDARY SUBREGIONS



QUARTZ POLE	FELDSPAR POLE	LITHIC-FRAGMENT POLE
Q-R = Quartz-rich	F-R = Feldspar-rich	LF-R = Lithic fragment-rich
FQ = Feldspathiquartzose	QF = Quartzofeldspathic	QL = Quartzolithic
LQ = Lithiquartzose	LF = Lithifeldspathic	FL = Feldspathilithic
FSQ = Feldspathisubquartzose	QSF = Quartzosubfeldspathic	QSL = Quartzosublithic
LSQ = Lithisubquartzose	LSF = Lithisubfeldspathic	FSL = Feldspathisublithic

Highly specific classification and nomenclature of sandstones. Either the names or the letter-symbols may be used.

Figure 7

Example 1. Point-bar fining-upward sequence. Location: Donkin West section, interval 24-28 m. See General Code for Appendix A for signification of symbols.

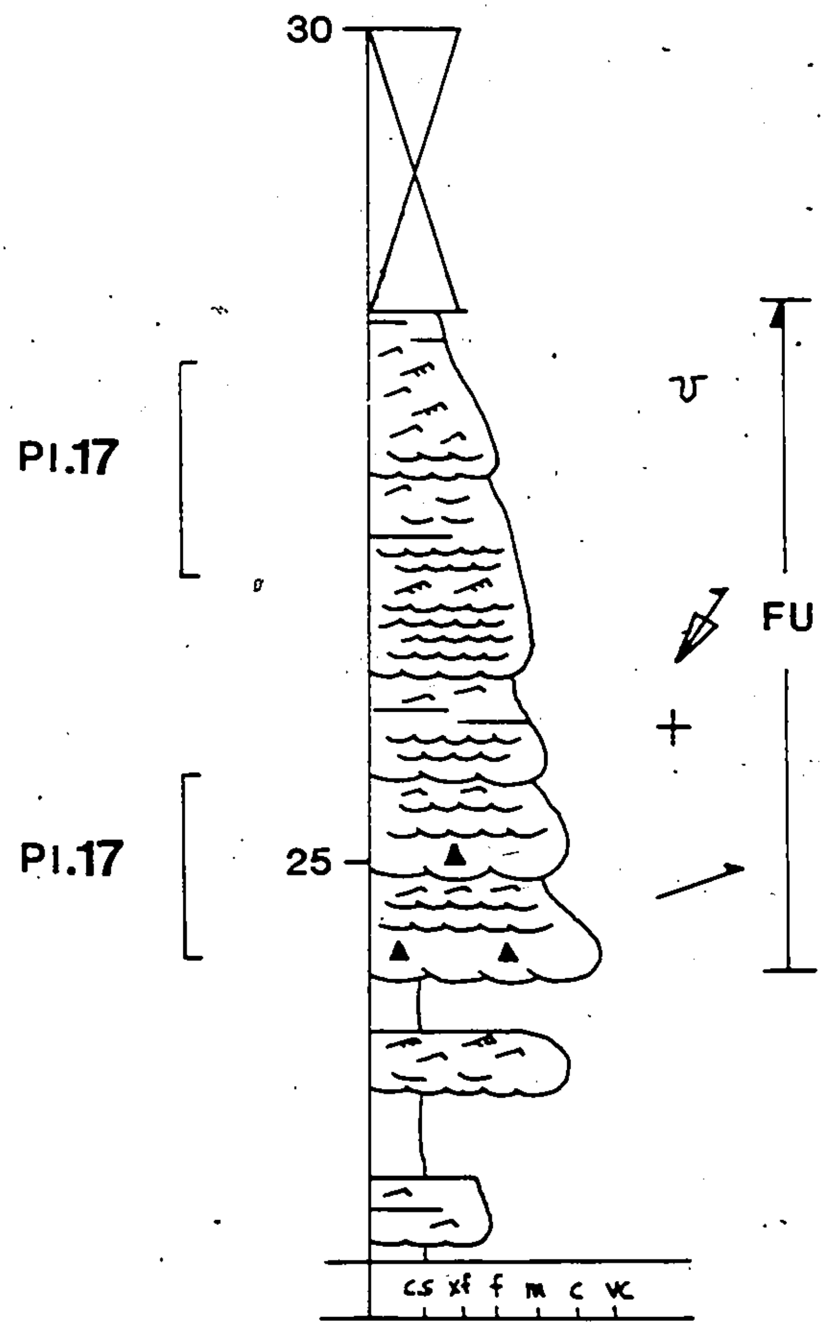

30
Pl.17
Pl.17
25
FU
cs xf f m c vc

Figure 8

Example 2. Point-bar fining-upward sequence. Location: Donkin East section, interval 72-77 m. See General Code for Appendix A for signification of symbols.

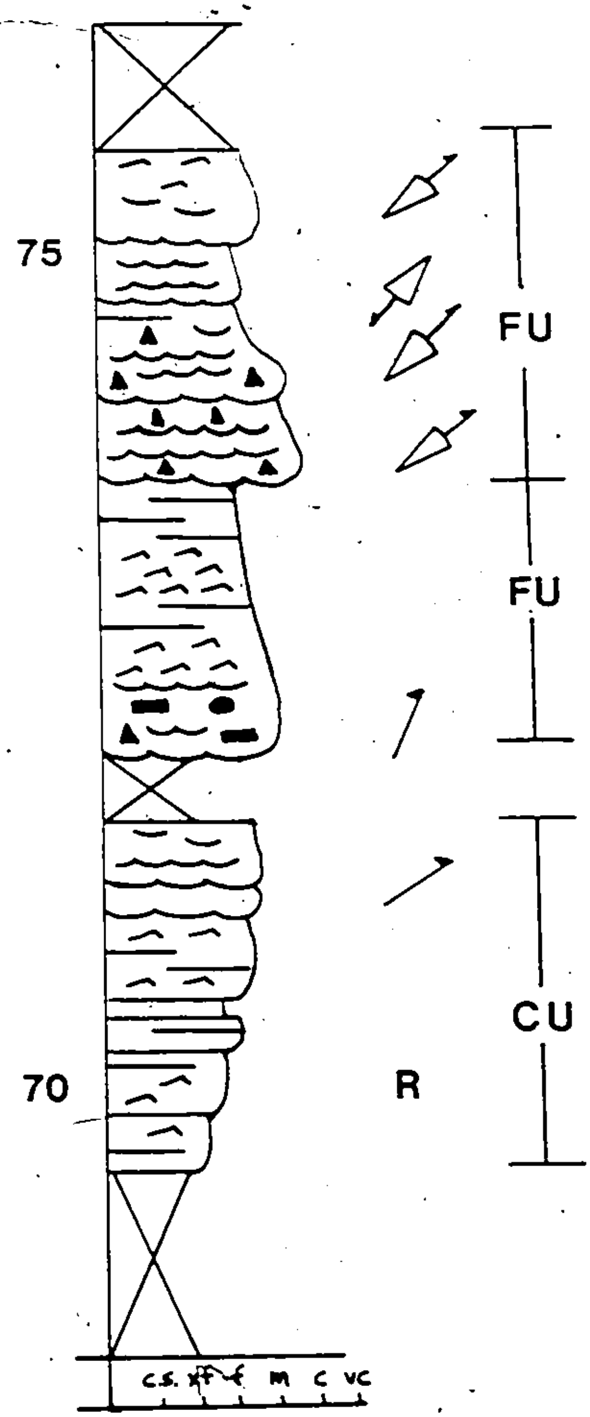
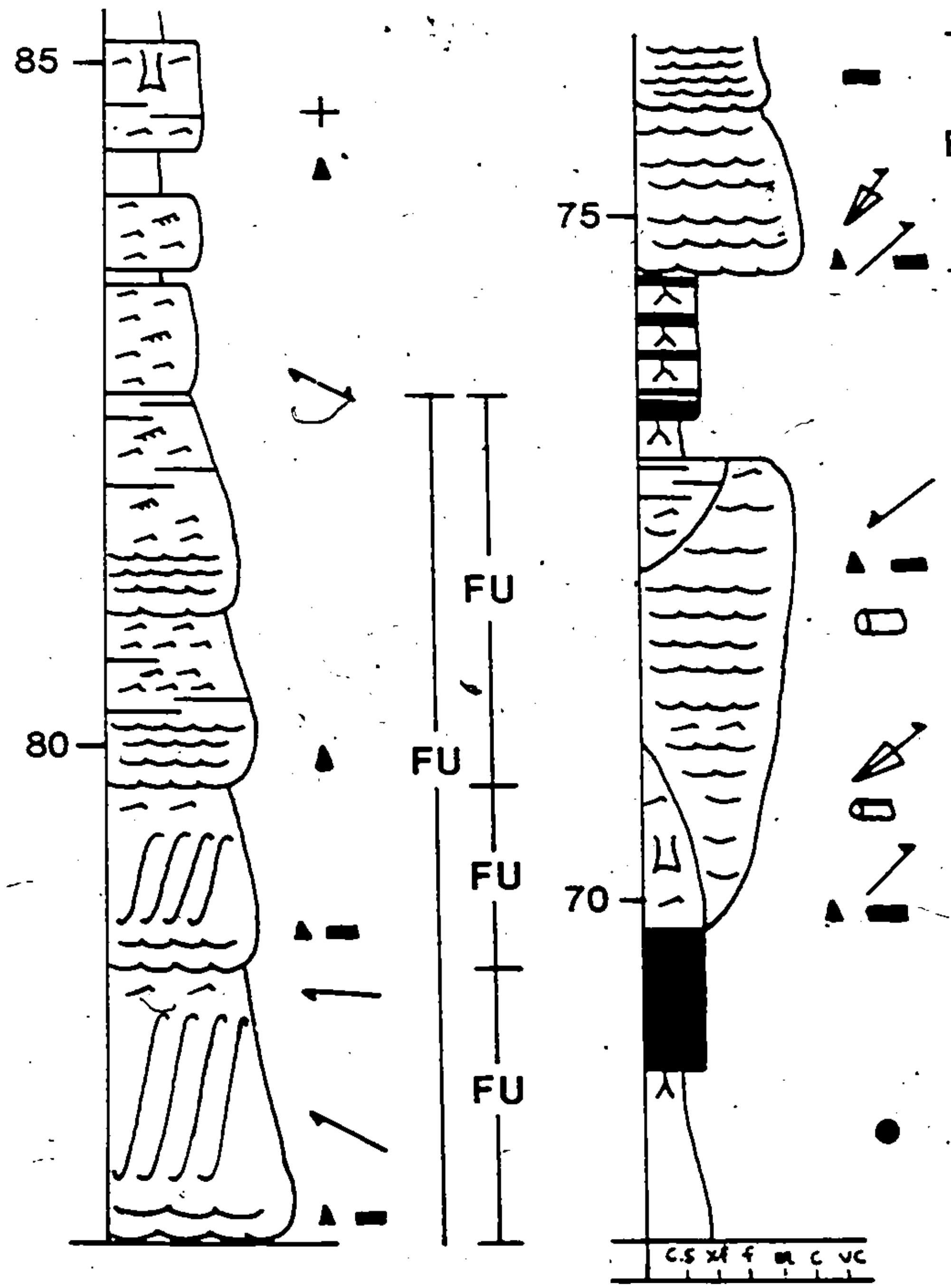

75
70
FU
FU
CU
R
c.s. vf f m c vc

Figure 9

Example 3. Lateral filling of channel with epsilon cross-strata.

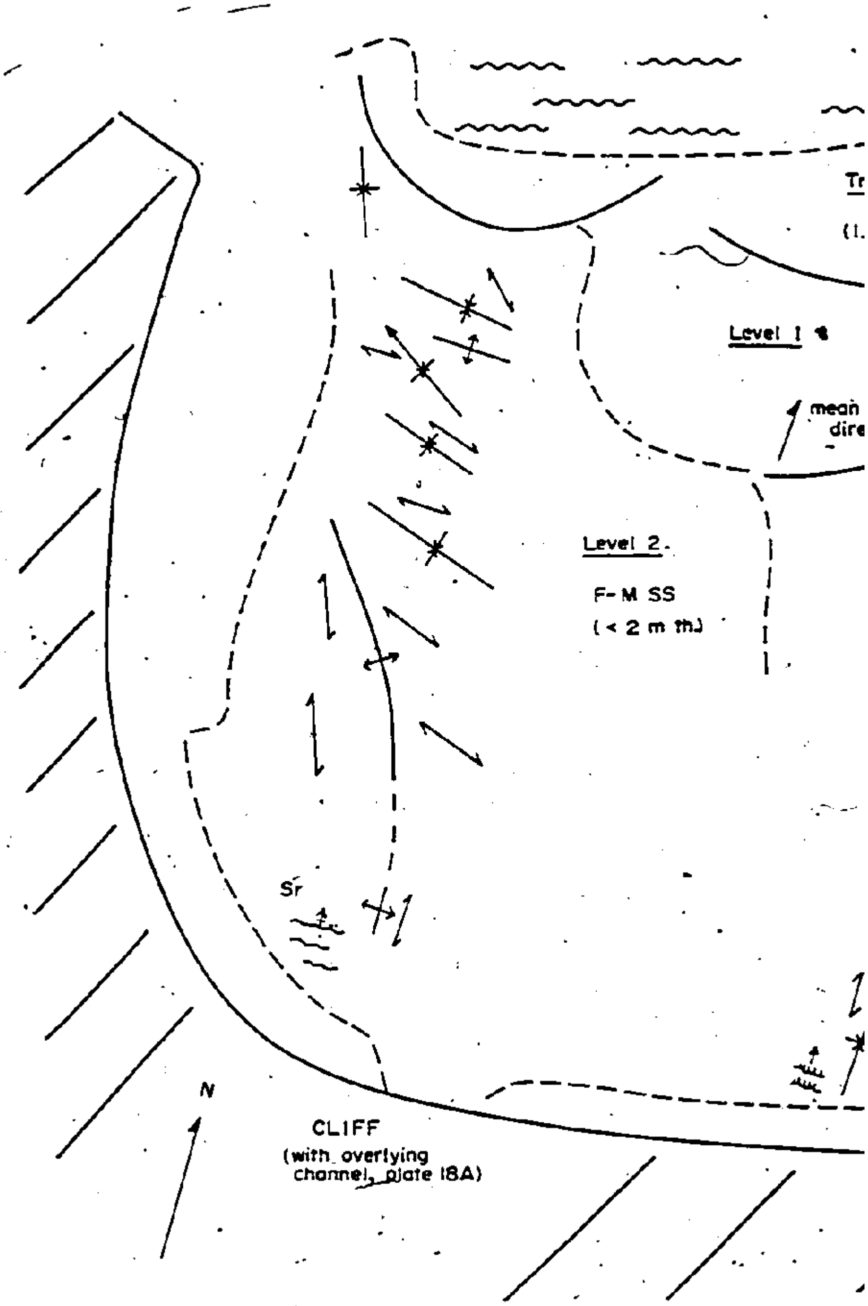
Location: Donkin West section, interval 75-83.5 m. See General Code for Appendix A for signification of symbols.



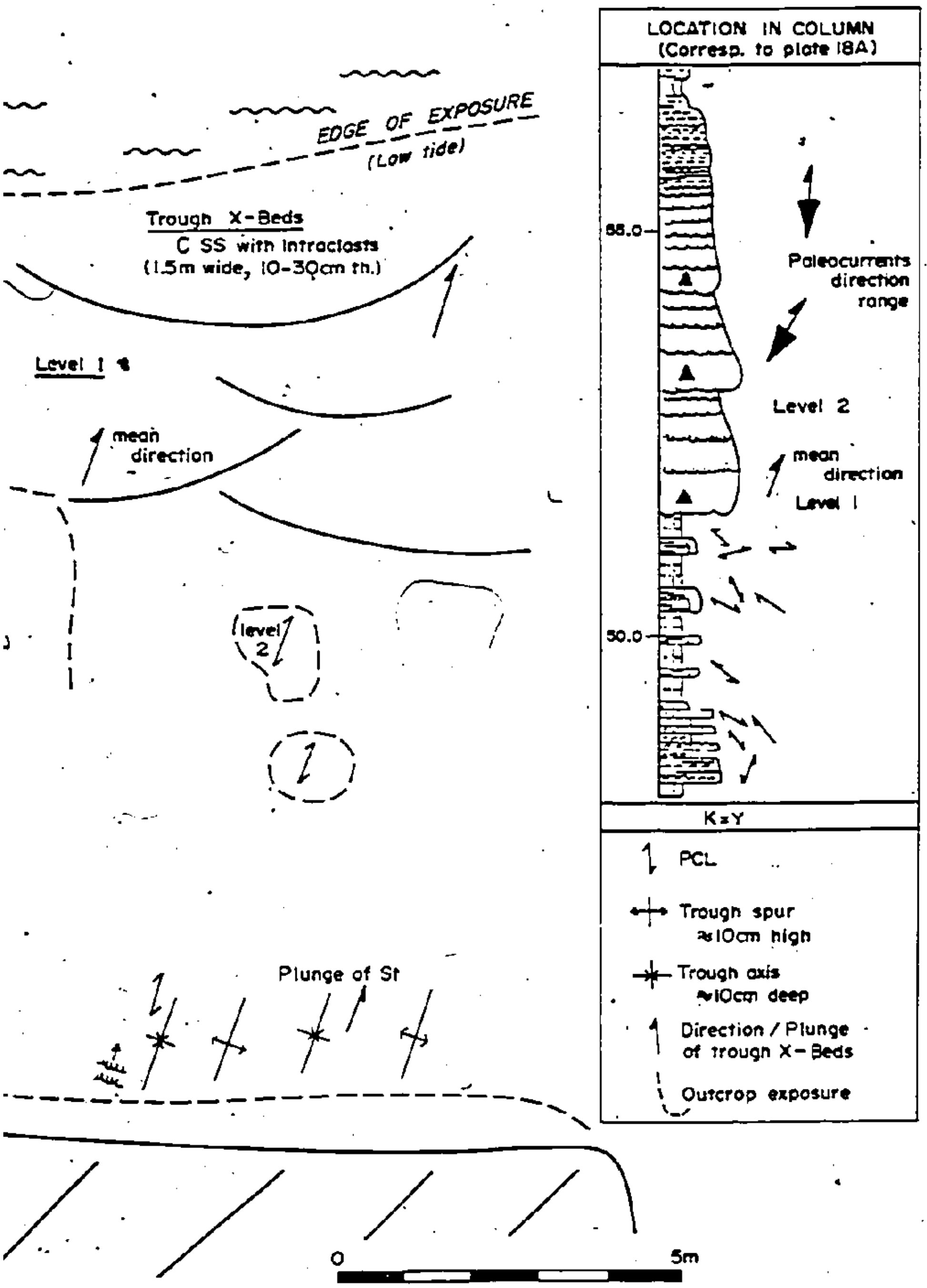
85
80
75
70
FU
FU
FU
FU
FU
c.s xf f m c vc

Figure 10

Example 4. Homogeneous channel fill deposit. Location: Morien North section, interval 50-57 m.



MORIEN NORTH 50-57m — Underlying units and



ying units and laterally exposed bases of channels.

Figure 11

Example 5. Pebbly-granular sand wave deposit. Location: Donkin West section, interval 14-20 m.

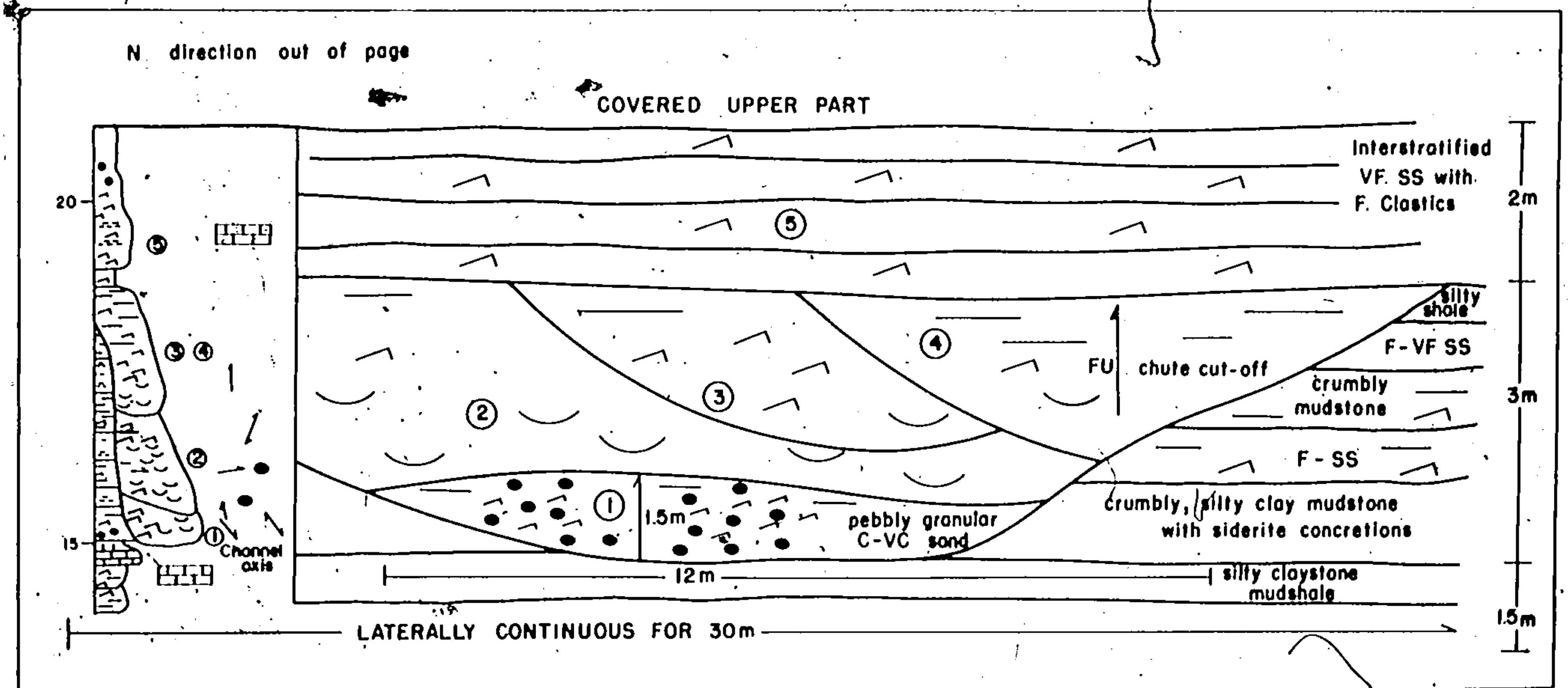

N direction out of page
COVERED UPPER PART
Interstratified VF. SS with F. Clastics
silty shale
F-VF SS
FU
chute cut-off
crumbly mudstone
F - SS
crumbly, silty clay mudstone with siderite concretions
pebbly granular C-VC sand
1.5m
12m
silty claystone mudshale
Channel axis
20
15
2m
3m
1.5m
LATERALLY CONTINUOUS FOR 30m

Figure 12

A) Example 6. Channel abandonment filling: gradual abandonment (chute cutoff) deposit. Location: Morien North section, interval 14-17.5 m.

B) Example 7. Channel abandonment filling: avulsion abandonment (neck cutoff) deposit. Location: Morien North section, interval 3-6 m.

See General Code for Appendix A for signification of symbols.

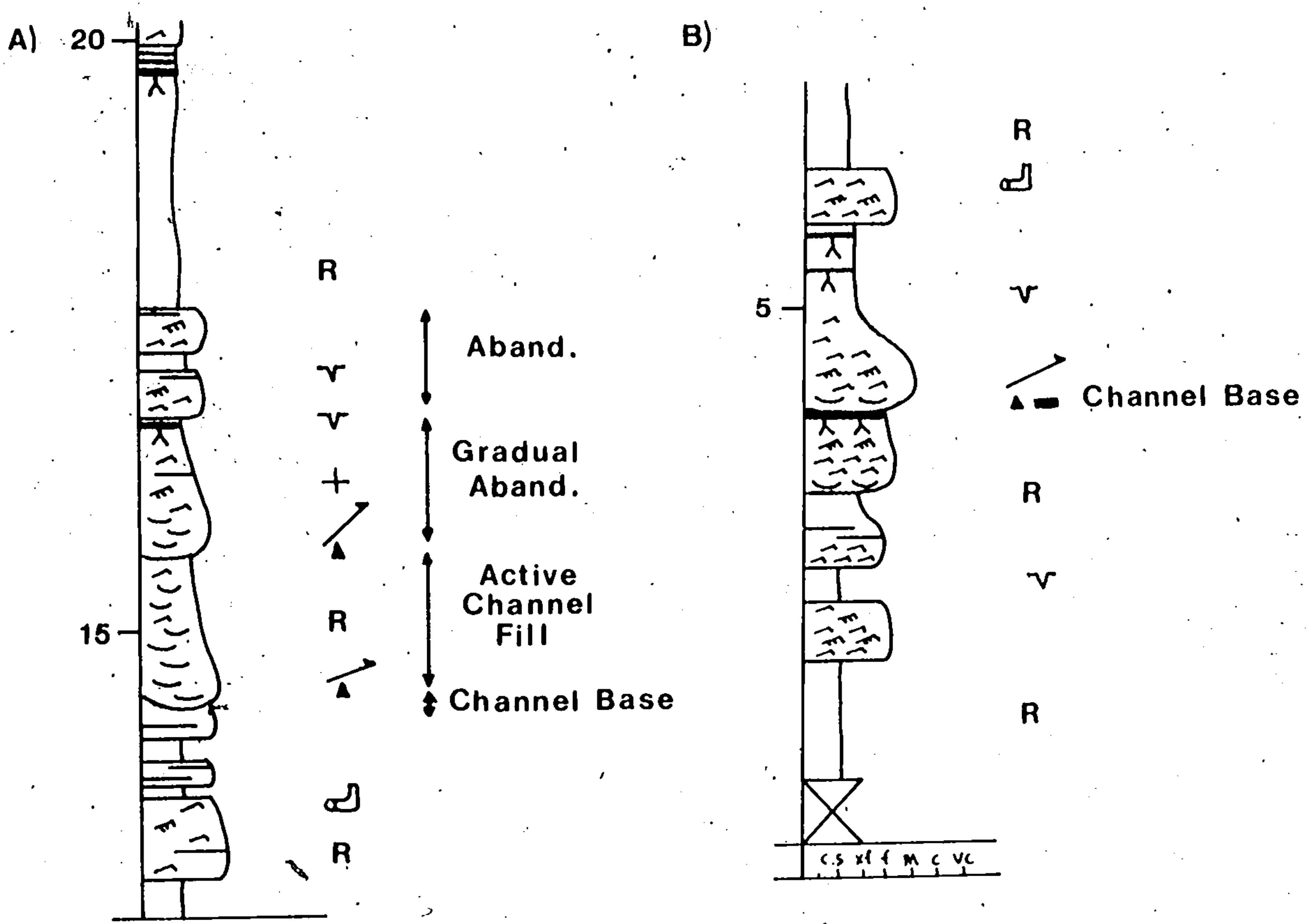
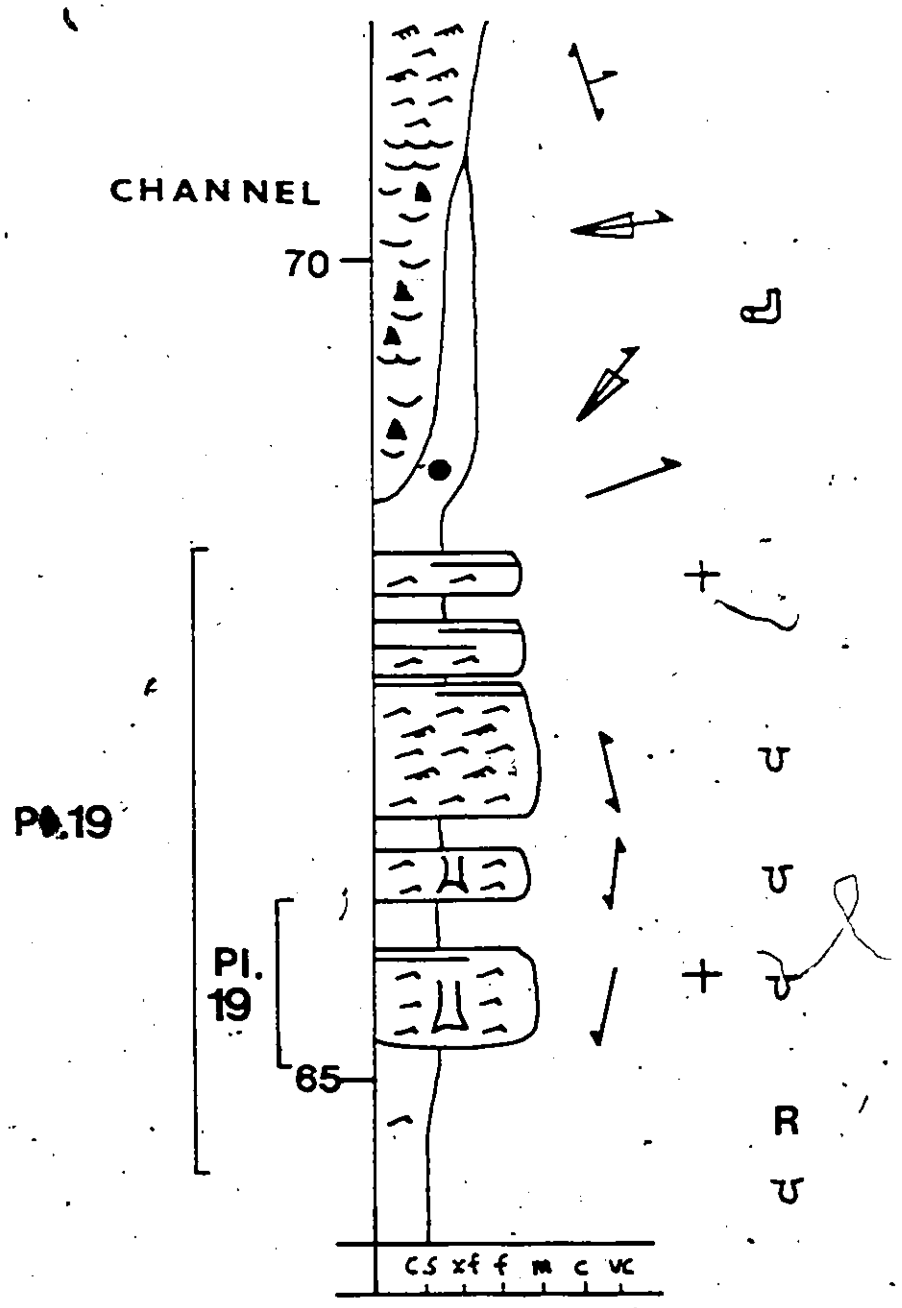

A)
20
15
R
R
R
Aband.
Gradual
Aband.
Active
Channel
Fill
Channel Base
B)
5
R
R
R
Channel Base
c.s xf f m c vc

Figure 13

Example 8. Overbank deposits: channel margin and levee deposits.

Location: Morien North section, interval 64-68 m.

See General Code for Appendix A for signification of symbols.



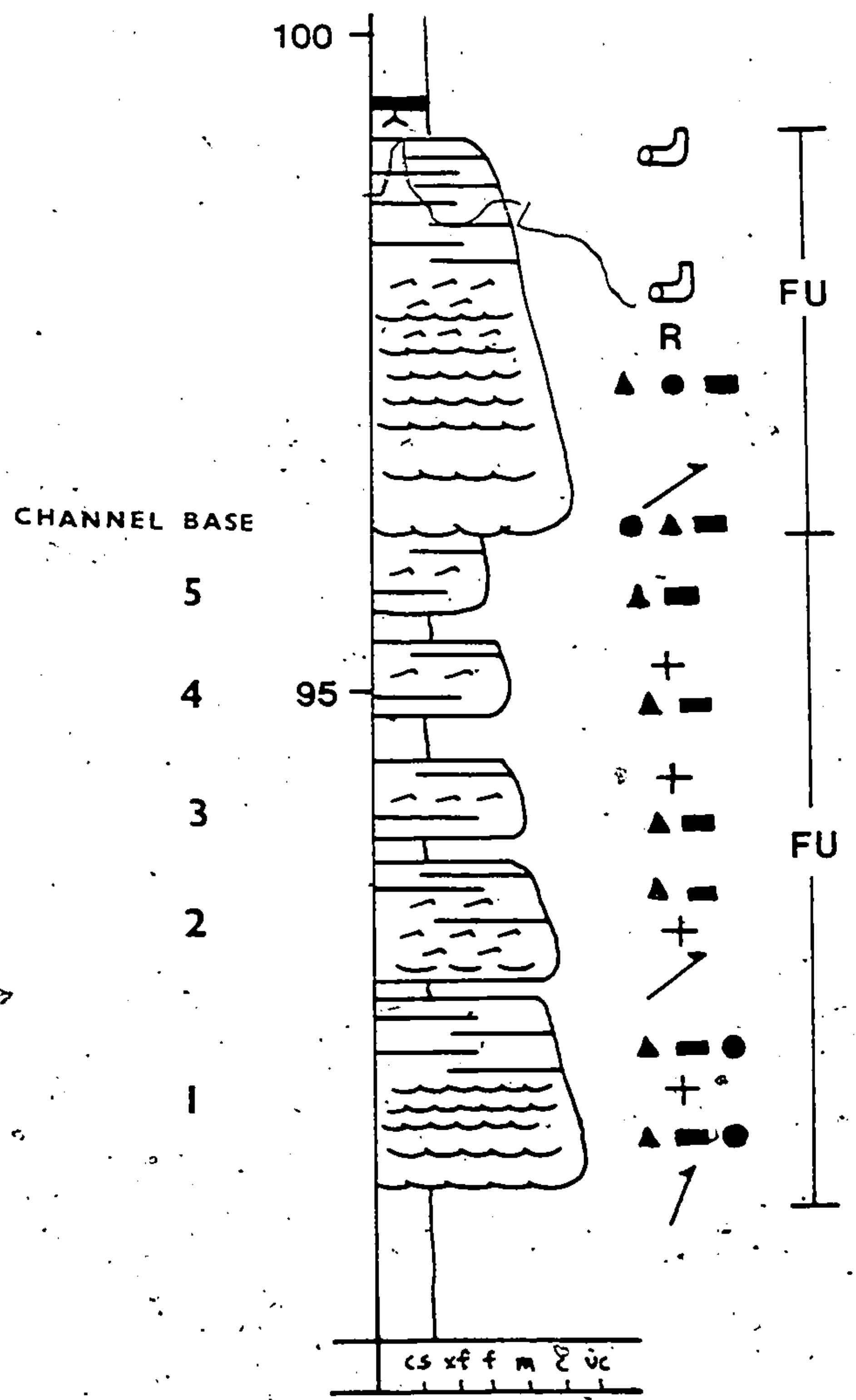
CHANNEL
70
Pl.19
Pl.
19
65
R
cs xf f m c vc

Figure 14

Example 9. Overbank deposits: pebbly sheet splay deposits.

Location: Morien North section, interval 91-96 m.

See General Code for Appendix A for signification of symbols.



100
FU
R
CHANNEL BASE
5
4
95
3
FU
2
1
cs xf f m c vc

Figure 15

Example 10. Overbank deposits: crevasse-splays with distributary channel deposits. Location: Glace Bay East section, interval 117-139 m.

See General Code for Appendix A for signification of symbols.

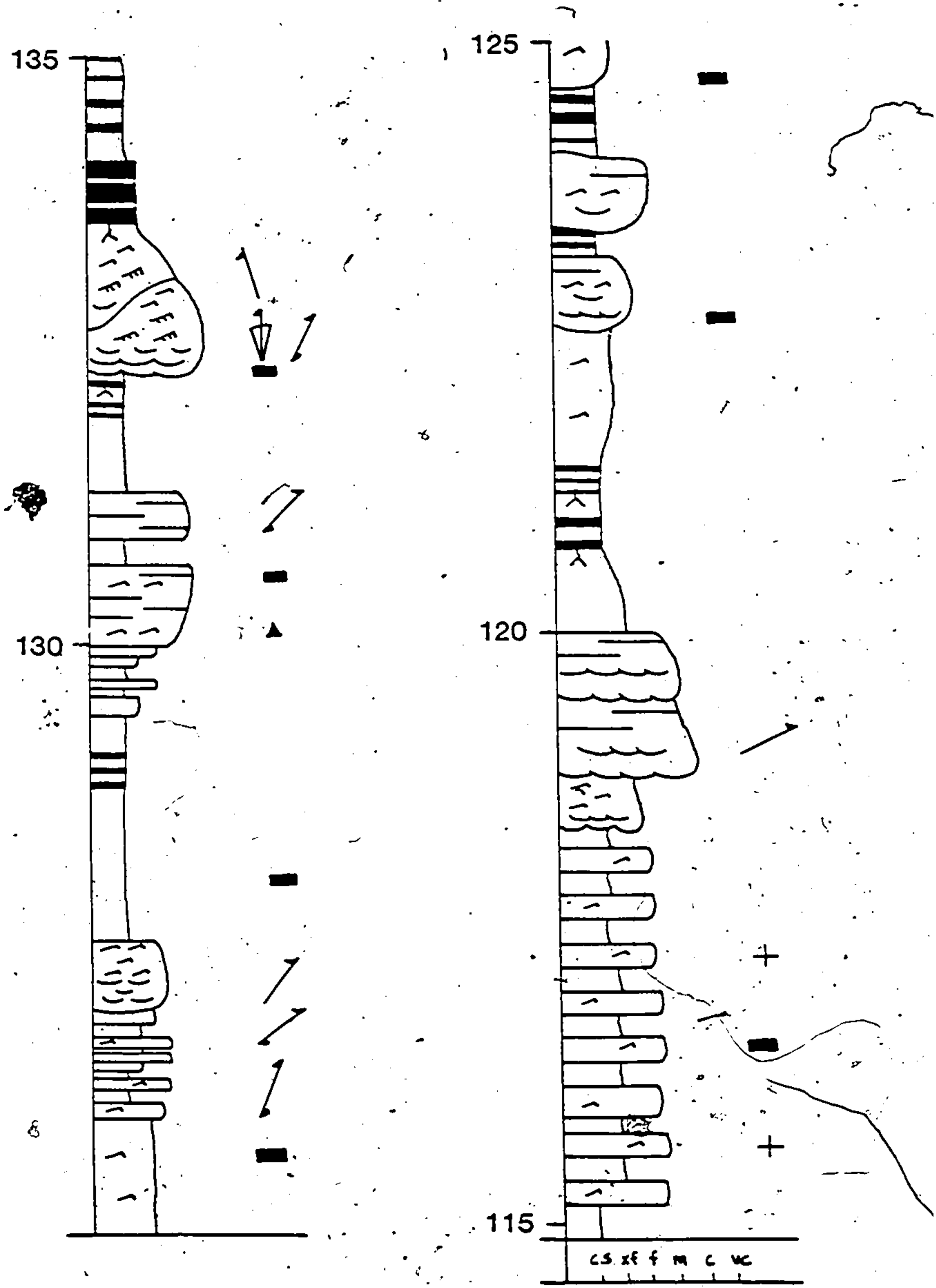
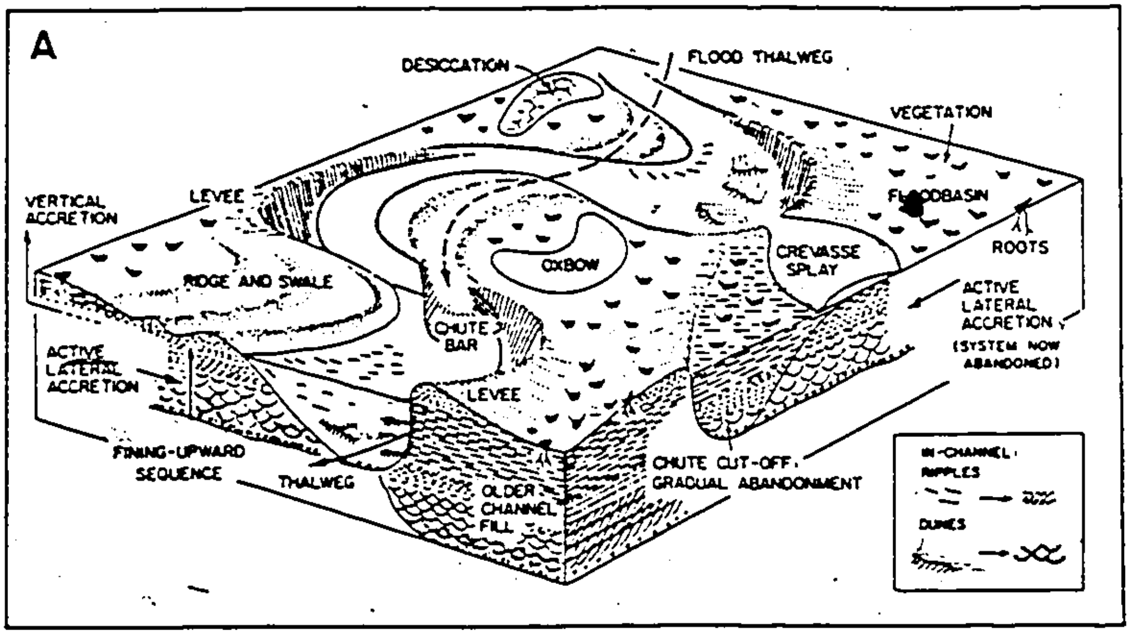

135
130
125
120
115
cs xf f m c vc

Figure 16

Major morphological elements of river systems (after Walker and Cant, 1984, Figs. 1 and 14).

A) A meandering river system. Erosion on the outside bend of meander loops leads to lateral accretion on the opposite point bar - the dunes and ripples in the channel giving rise to trough cross-bedding and ripple cross-lamination respectively (inset, lower right), which are preserved in a fining-upward sequence. Characteristic are: overbank levees, splays and flood basin deposits.

B) A braided river system based on the South Saskatchewan River. Stippled areas exposed, all other features under water. Bar in left corner is being driven laterally against a vegetated island and is separated from the island by a slough in which mud is being deposited. Sandflat 1 is complex, with dissection features and flood-stage sandwaves generating stacked Sp sets. Sinuous-crested dunes generate St in main channel.


A
DESICCATION
FLOOD THALWEG
VEGETATION
FLOODBASIN
ROOTS
VERTICAL ACCRETION
LEVEE
RIDGE AND SWALE
OXBOW
CREVASSE SPLAY
ACTIVE LATERAL ACCRETION (SYSTEM NOW ABANDONED)
CHUTE BAR
ACTIVE LATERAL ACCRETION
LEVEE
FINING-UPWARD SEQUENCE
THALWEG
OLDER CHANNEL FILL
CHUTE CUT-OFF, GRADUAL ABANDONMENT
IN-CHANNEL:
RIPPLES
DUNES

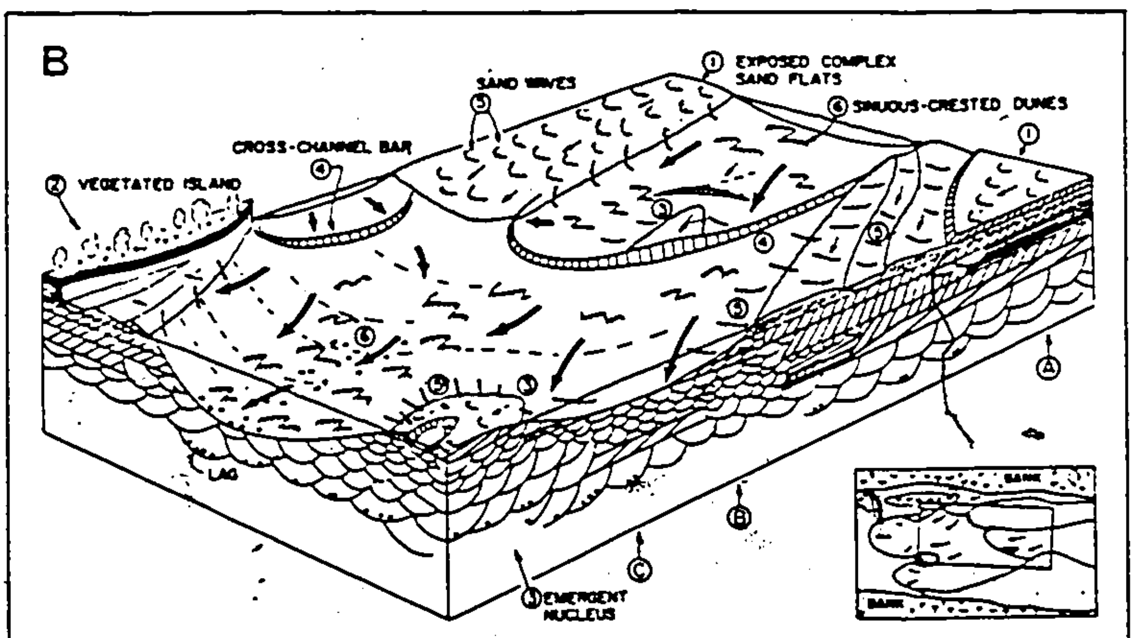

B
① EXPOSED COMPLEX SAND FLATS
SAND WAVES
⑥ SINUOUS-CRESTED DUNES
CROSS-CHANNEL BAR
② VEGETATED ISLAND
LAG
③ EMERGENT NUCLEUS
BANK
BANK

Figure 17

General lithogenetic model for the main environments of deposition of the Port Hood Formation (from Gersib and McCabe, 1981). The model is applicable to the Sydney Mines Formation.

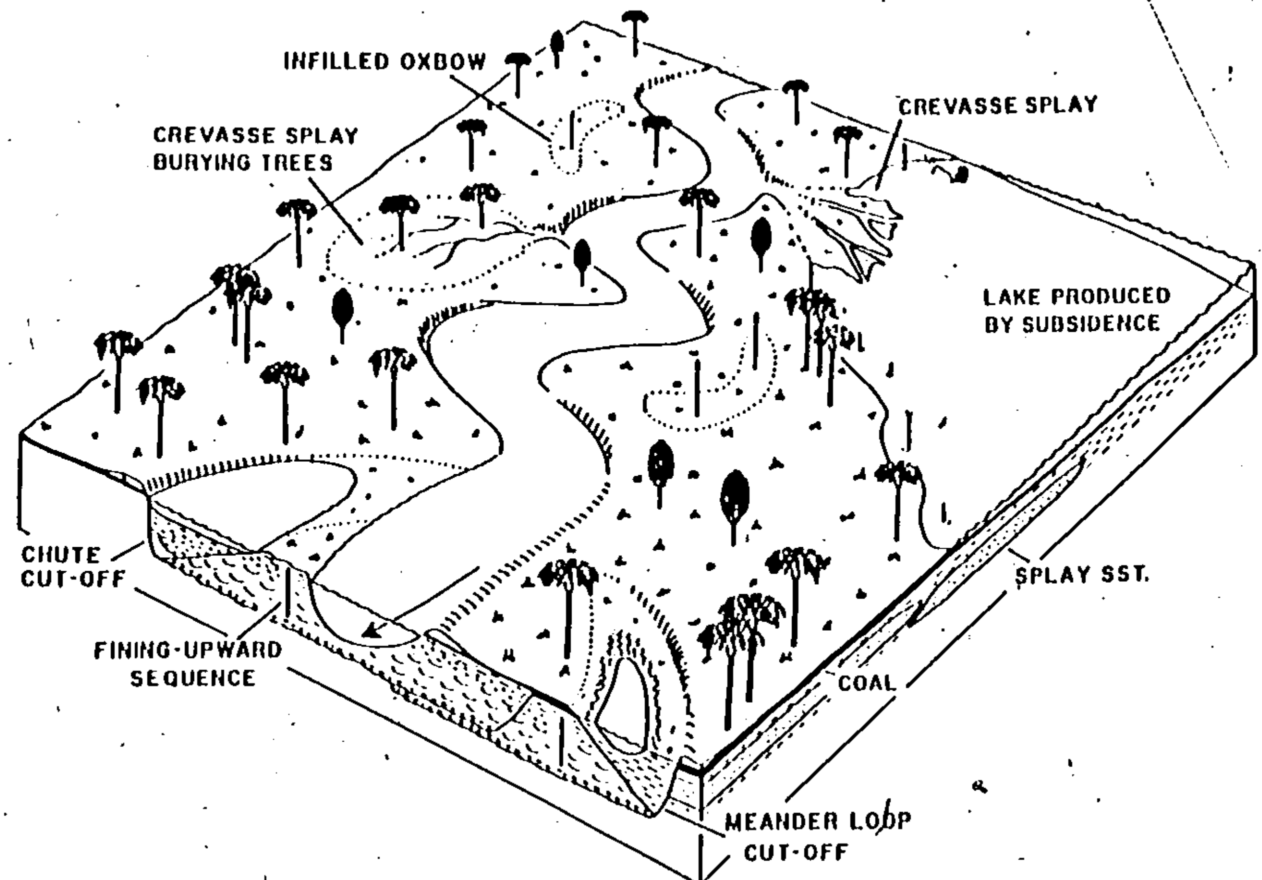

INFILLED OXBOW
CREVASSE SPLAY
CREVASSE SPLAY
BURYING TREES
LAKE PRODUCED
BY SUBSIDENCE
CHUTE
CUT-OFF
FINING-UPWARD
SEQUENCE
SPLAY SST.
COAL
MEANDER LOOP
CUT-OFF

Figure 18

Facies Transition Diagram, Sydney Mines Formation, and Meandering River Facies Model (adapted from Allen, 1970, and Walker and Cant, 1976).

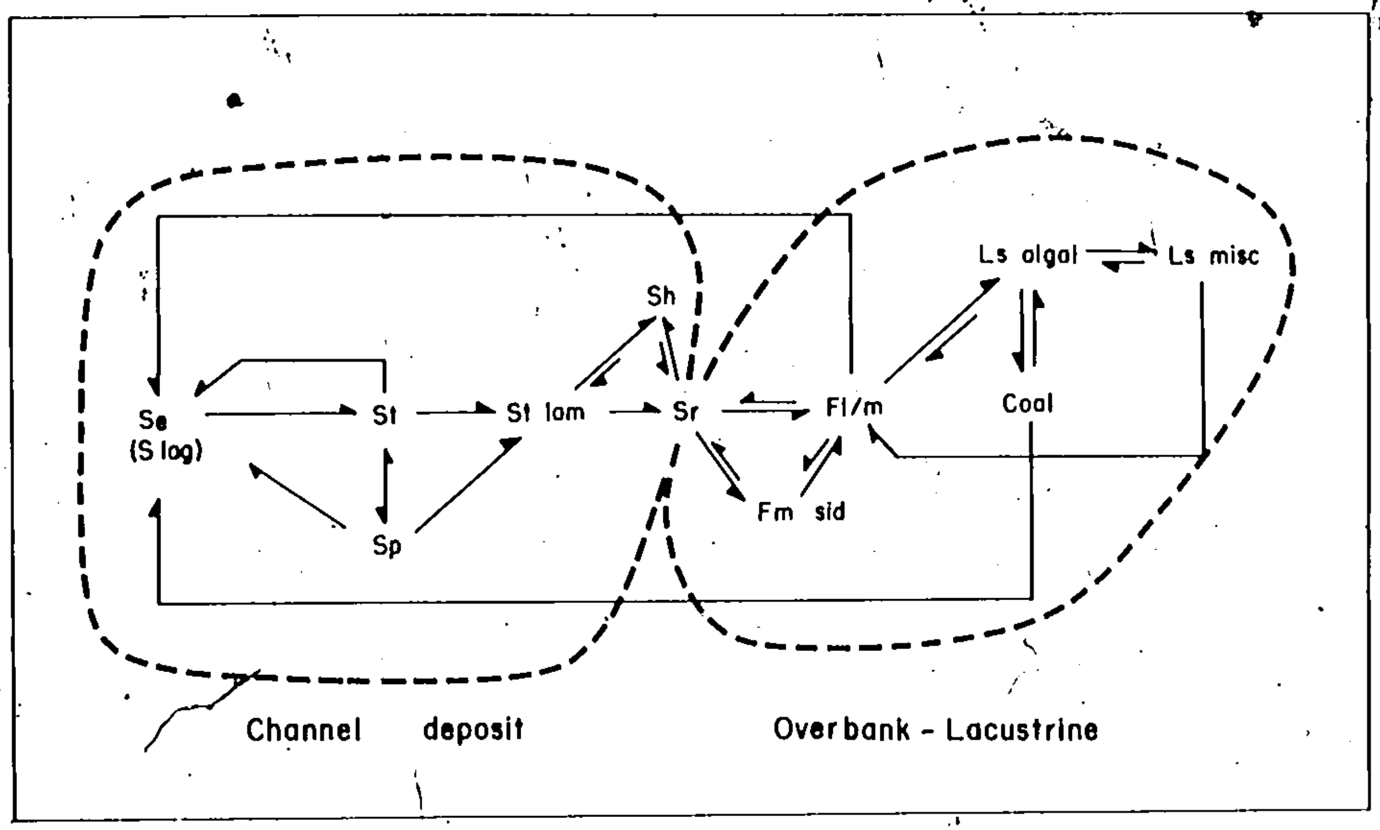

Se
(S log)
St
Sp
St lam
Sh
Sr
Fl/m
Fm sid
Ls algal
Ls misc
Coal
Channel deposit
Overbank - Lacustrine

Figure 19

Transition Count Matrix (10 units) for all measured sections of the study area.

	Se	St	St lam	Sr	Sh	Fl/m	C	Fm sid	Ls-f	Ls-m
Se		94			2					
St	40		146	4	5	2				
St lam	9	28		231	34	7		1		
Sr	16	30	96		170	476	7	78	1	16
Sh	8	8	15	159		212	1	16	1	2
Fl/m	16	22	41	430	200		123	44	13	33
C	6	5	5	15	1	68		9	28	2
Fm sid	3	3	7	44	11	79	6			1
Ls-f			1	3		26	5			24
Ls-m		1	1	6	1	46		5	17	

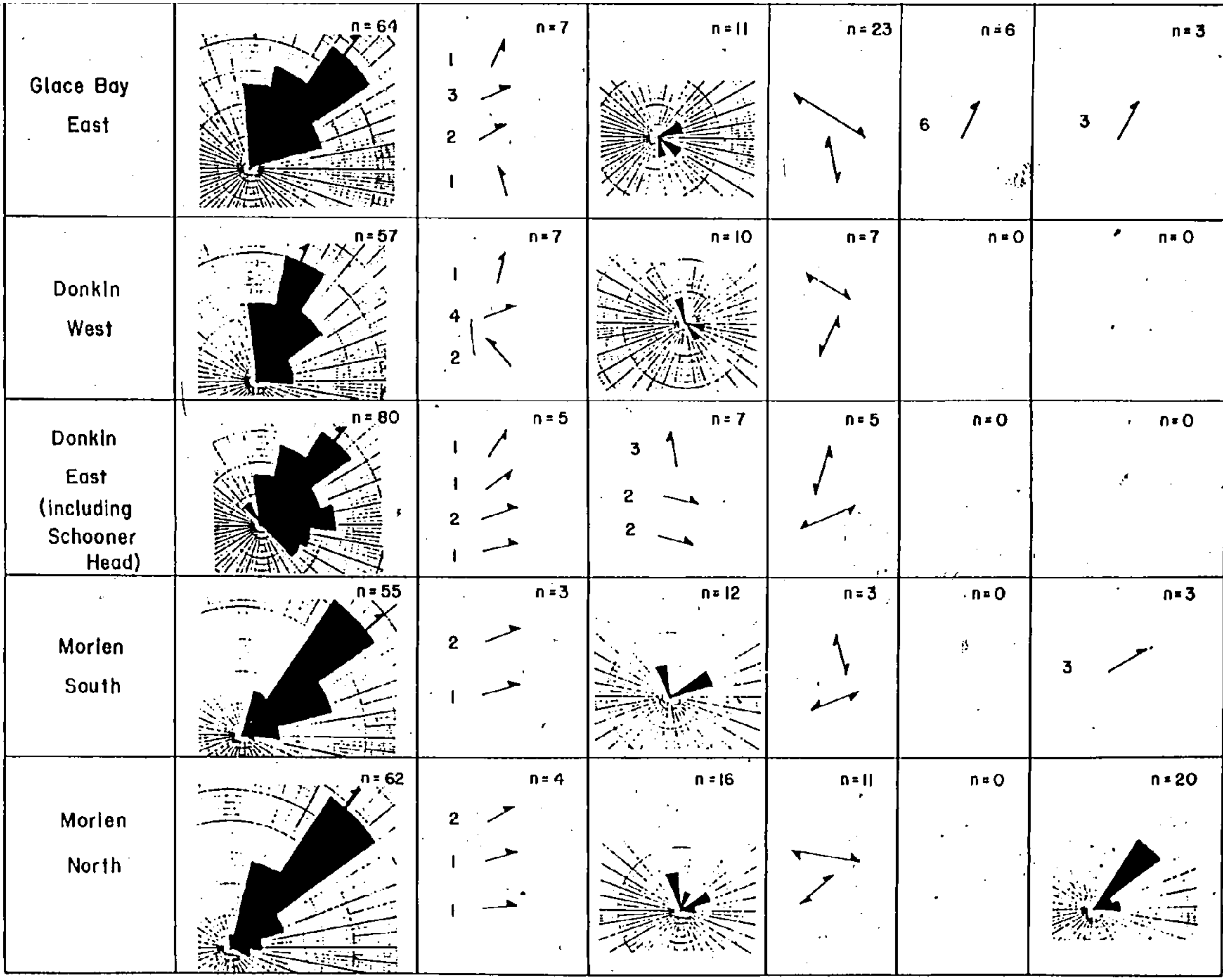
Total transitions: 3266

Total frequencies: 3267

Figure 20

Paleocurrent directions for paleocurrent types for each section measured. Where n $<$ 10, individual readings are represented by an arrow. PCL values are trends observed. North is up page in all cases.

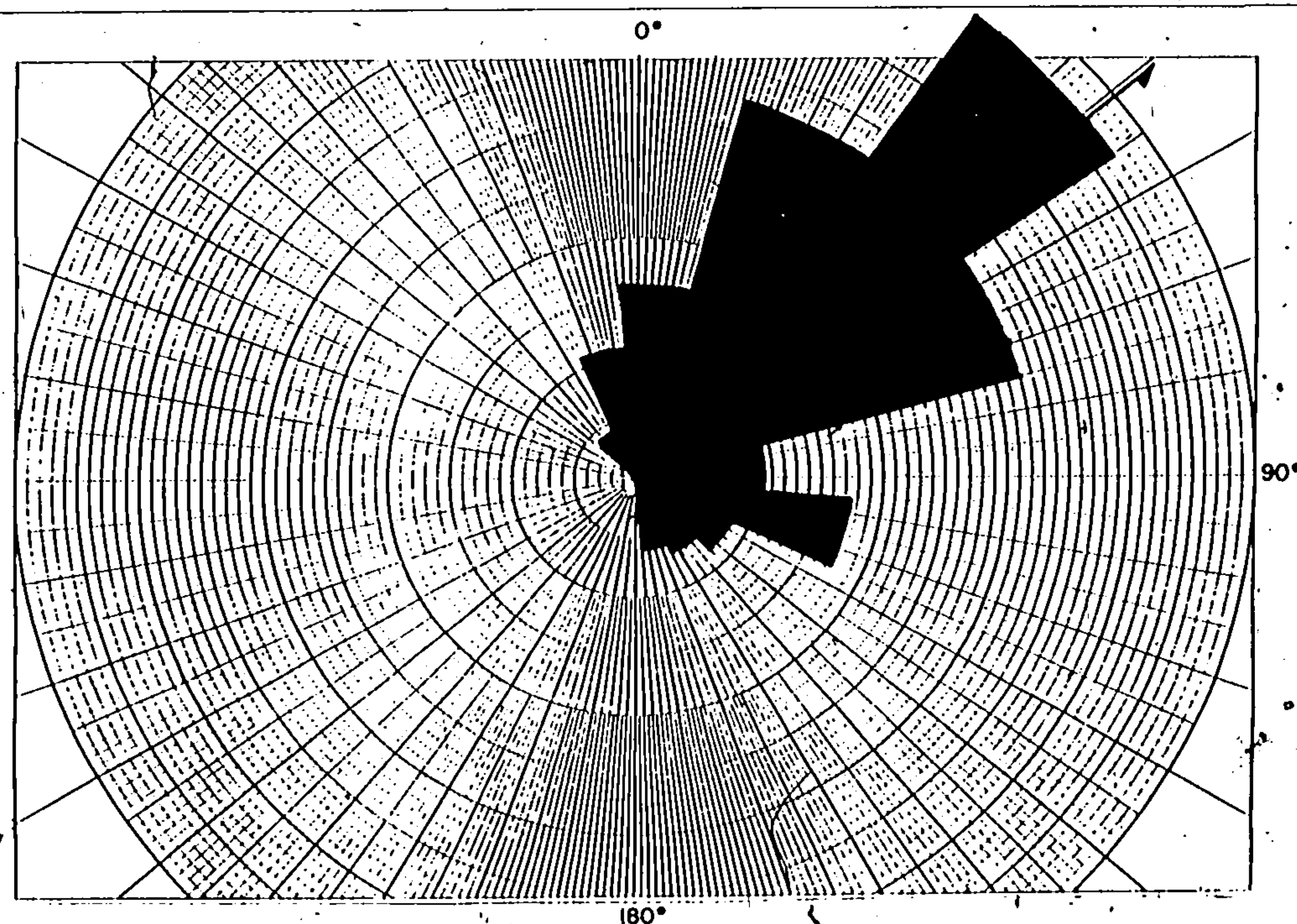
SECTION \ STRUCT.	Trough X-Beds Axis Direction	Channel Axis Direction	Ripple-Cross Laminations	PCL Planar X-Beds	Elongated Lags	Scour Features
Victoria Mines	n = 77	n = 0	n = 67	n = 10	n = 27	n = 5
New Waterford	n = 87	n = 17	n = 52	n = 4	n = 8 (5, 3)	n = 0
Glace Bay West	n = 53	n = 6 (2, 2, 1, 1)	n = 48	n = 20	n = 0	n = 2 (2)
Glace Bay East	n = 64	n = 7 (1, 3, 2, 1)	n = 11	n = 23	n = 6 (6)	n = 3 (3)



Glace Bay East
n=64
n=7
1
3
2
1
n=11
n=23
n=6
6
n=3
3
Donkin West
n=57
n=7
1
4
2
n=10
n=7
n=0
n=0
Donkin East (including Schooner Head)
n=80
n=5
1
1
2
1
n=7
3
2
2
n=5
n=0
n=0
Morien South
n=55
n=3
2
1
n=12
n=3
n=0
n=3
3
Morien North
n=62
n=4
2
1
1
n=16
n=11
n=0
n=20

<u>Figure 21</u>

Paleocurrents for all sections, 20° intervals, values $\leq$10 not plotted.



$\Sigma n = 807$

TROUGH X BED = 538

CHANNELS DIR. = 49

RIPPLES X LAM. = 223

AZIMUTH DIRECTION
OF MEAN VECTOR
50.42°

MAGNITUDE OF
RESULTANT VECTOR
$\gamma = 544.8$

VECTOR MAGNITUDE
L% = 67.5%

Figure 22. Selected stratigraphic sequences of lacustrine facies of the Sydney Mines Formation

Section	Interval (m)	Plate	Type of deposit
A) Victoria Mines	1- 4	29	lacustrine deposit - algal laminated predominant
B) New Waterford	108-110	31A	well-developed lacustrine deposit - interstratified stromatolitic and mudstone-packstone subfacies
C) New Waterford	177-181	31B	marginal lacustrine deposit - interstratified stromatolites with oncolites and minor mudstone-packstone subfacies
D) New Waterford	186-190	32	lacustrine delta and splay deposits
E) Glace Bay West	176-183	30	lacustrine deposit - interstratified tabular beds with soft-sediment deformation

Note: legend is same as in Appendix A.

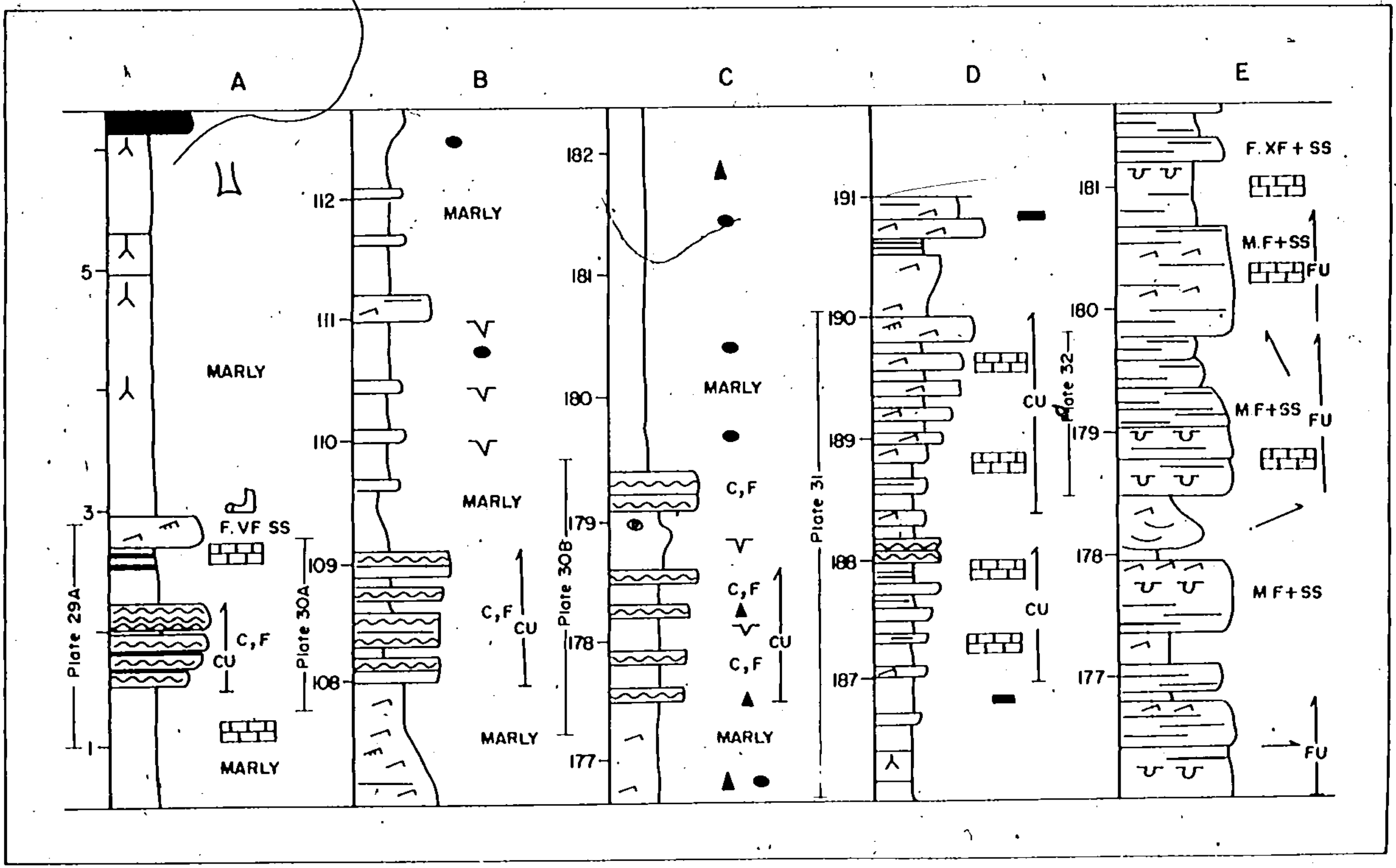
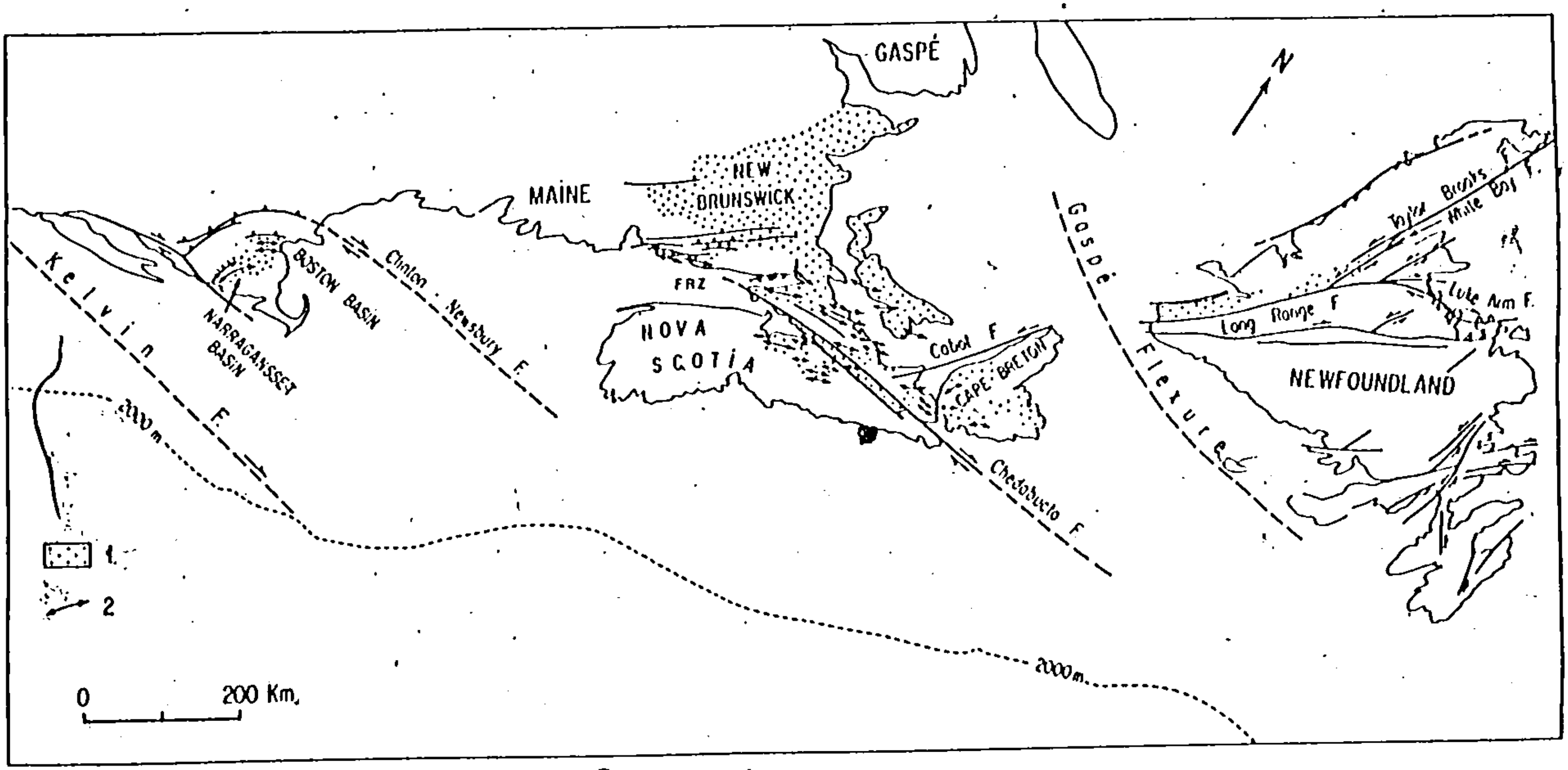

A
B
C
D
E
MARLY
F. VF SS
C, F
CU
Plate 29A
Plate 30A
Plate 30B
Plate 31
Plate 32
M.F+SS
FU
F. XF + SS
M F+SS
5
3
1
112
111
110
109
108
182
181
180
179
178
177
191
190
189
188
187

Figure 23

Late Hercynian (Variscan equivalent) structures in Northern and Maritime Appalachians. The area is a junction between the late Variscan shear zone and the Southern Appalachian folded belt. Folds and thrusts transform the offset of (mainly right-lateral) strike-slip faults.

FRZ: Fundy Rift Zone.

Legend: 1) Carboniferous deposits; 2) folds (from Arthaud and Matte, 1977; Bradley, 1982).



GASPÉ
N
MAINE
NEW BRUNSWICK
FRZ
NOVA SCOTIA
Cabot F
CAPE BRETON
Chedabucto F.
Gaspé Flexure
NEWFOUNDLAND
Long Range F
Lake Arm F.
Mille Bay F.
Clinton - Newbury F.
BOSTON BASIN
NARRAGANSSET BASIN
Kelvin F.
2000m
1
2
0
200 Km.

Figure 24

Basins, structural sub-basins and faults of the Fundy Basin System (modified after McCabe and Schenk, 1982).

Legend: Basins - 1) Cumberland; 2) Minas; 3) Moncton; 4) Sydney (study area); 5) Antigonish; 6) Southwestern; 7) North Central.

Structural sub-basins - 8) Merigomish; 9) Stellarton; 10) Caledonia; 11) Cobequid; 12) Browns Mountain; 13) Cape Breton Highlands; 14) Louisbourg.

Faults: 15) Taylor Brook; 16) Long Range; 17) Hollow; 18) Cobequid-Chedabucto; 19) Belle Isle.

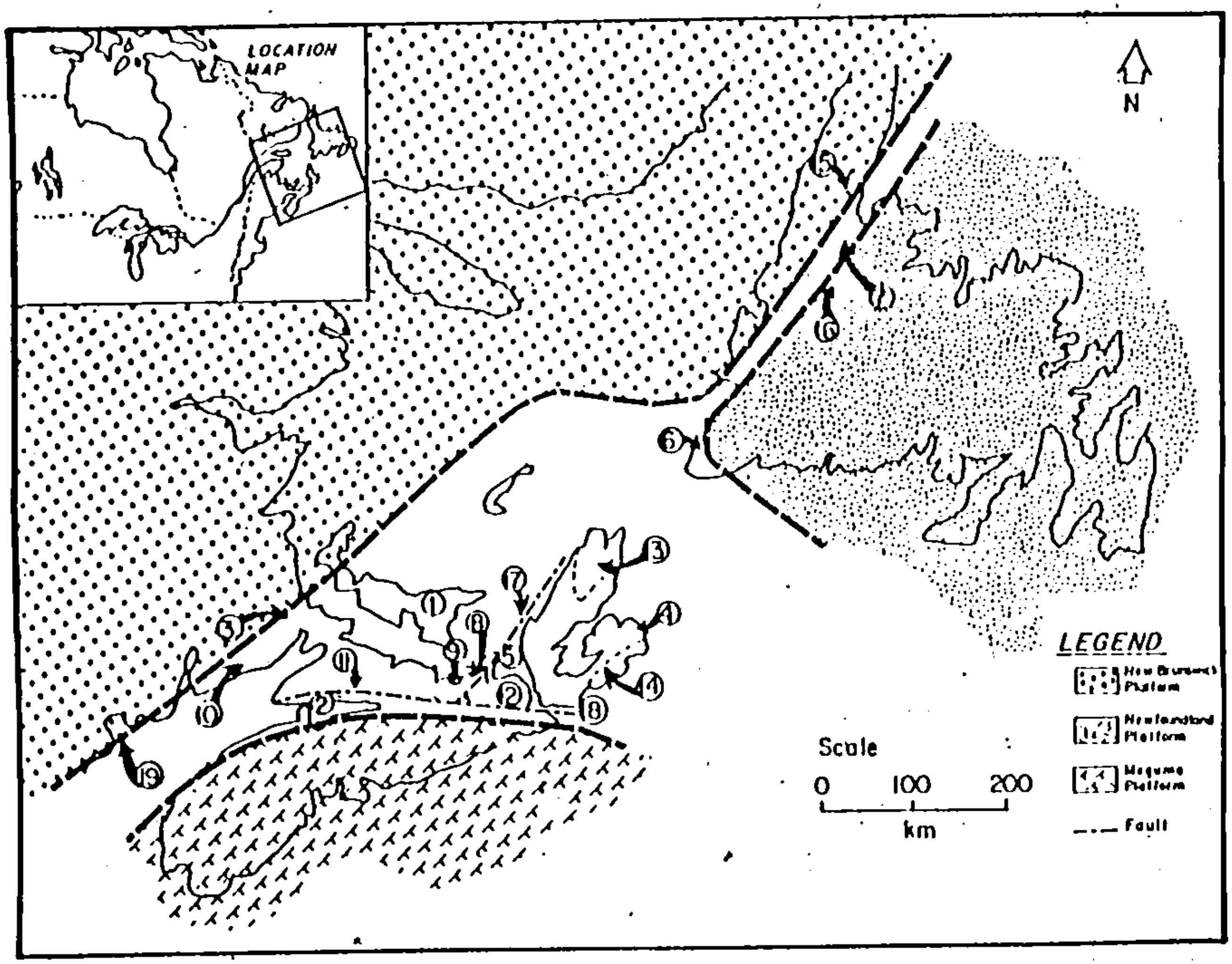

LOCATION MAP
N
LEGEND
New Brunswick Platform
Newfoundland Platform
Meguma Platform
Fault
Scale
0 100 200
km

Figure 25

Position of major strike-slip faults and other structural features active during the Upper Carboniferous (modified from McCabe and Schenk, 1982). Legend: 1) Caledonia Arch; 2) Moncton Basin; 3) Westmoreland Arch; 4) Belle Isle Fault; 5) Cumberland Basin; 6) Cobequid Arch; 7) Hopewell Fault; 8) Antigonish Massif; 9) Antigonish Basin; 10) Hollow Fault; 11) Mira Bay Fault; 12) Cobequid Fault.

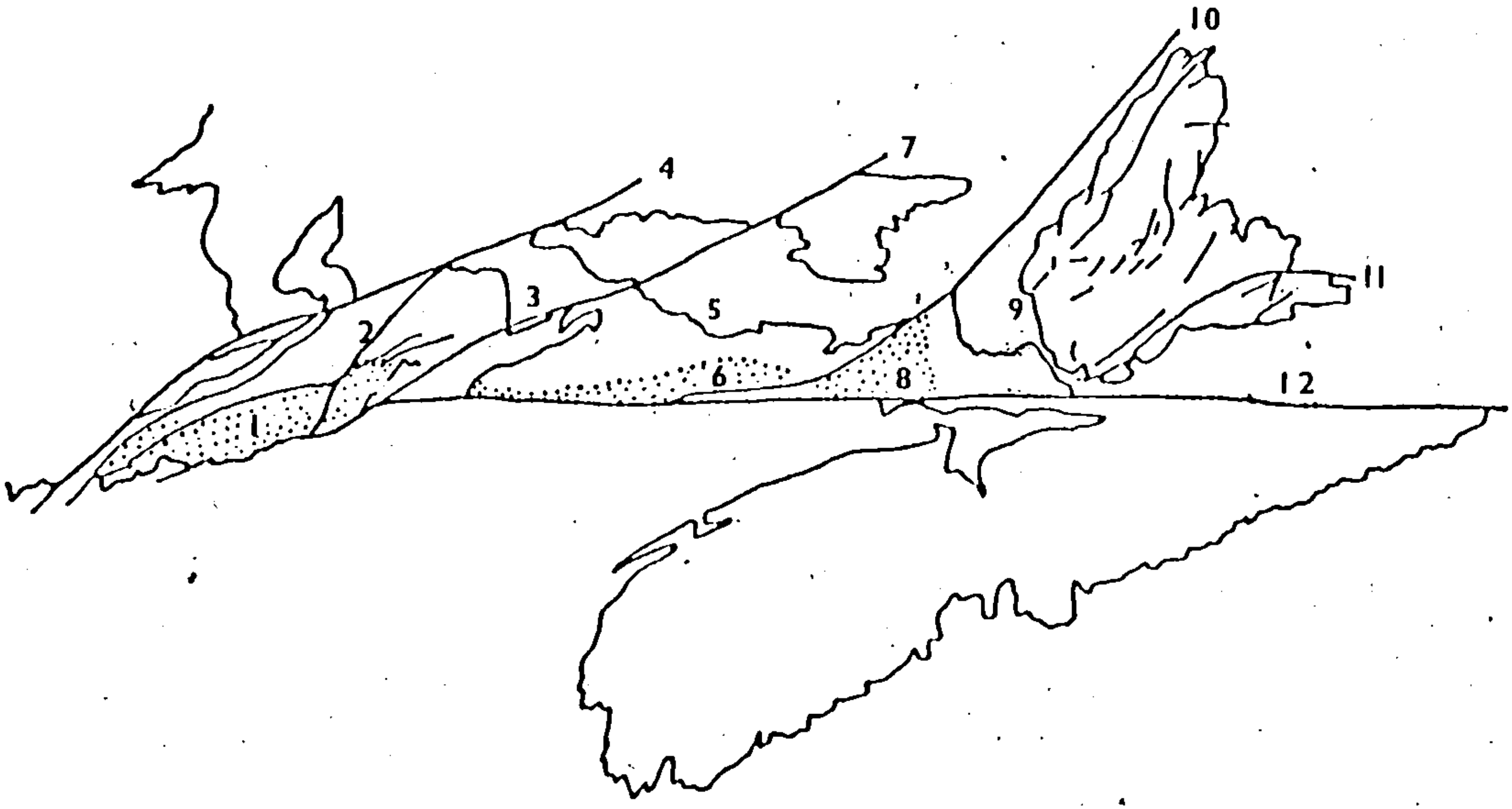

1
2
3
4
5
6
7
8
9
10
11
12

Figure 26

General structural features of the Sydney Synclinorium. Dotted area represents outcrop of upper Morien Group (SM FM) (modified after Giles, 1983).

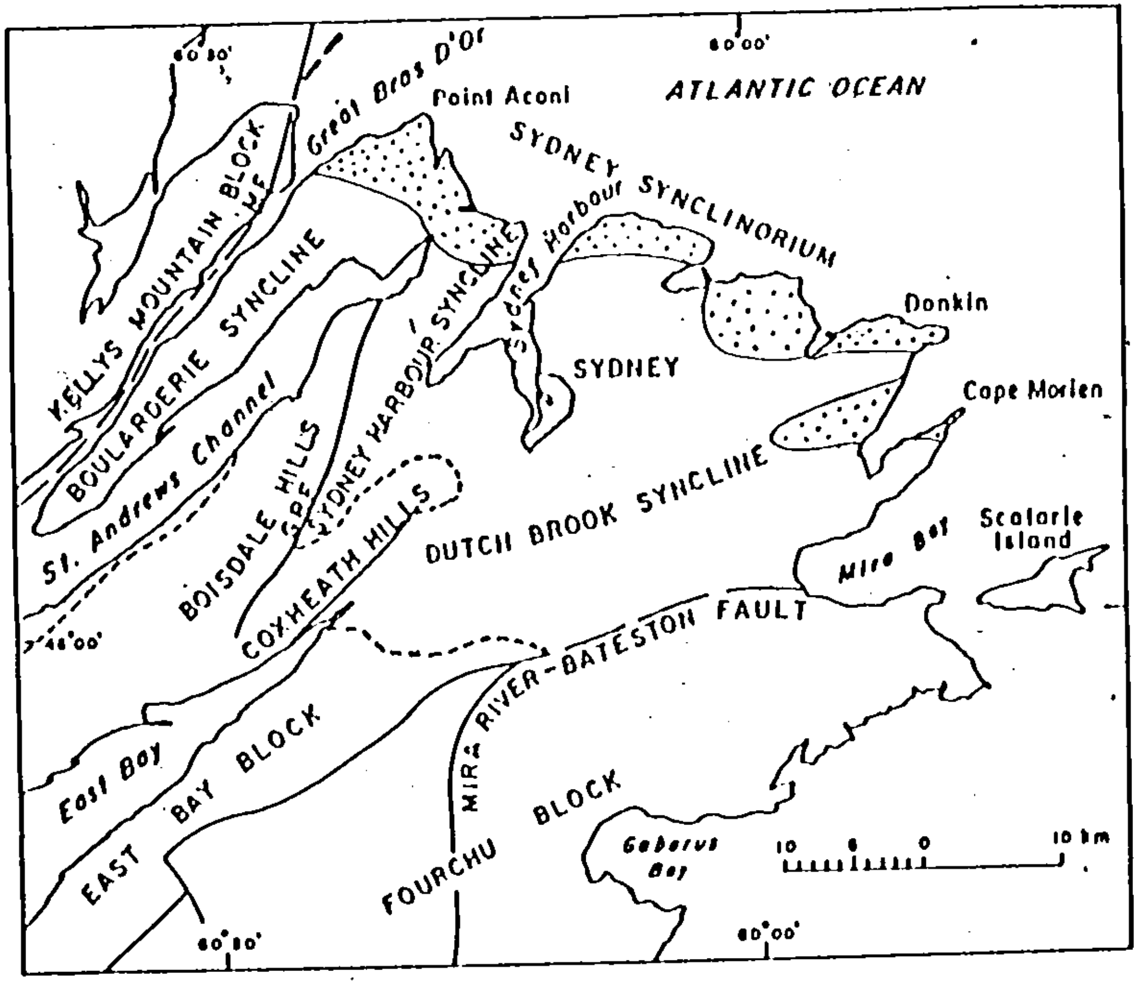
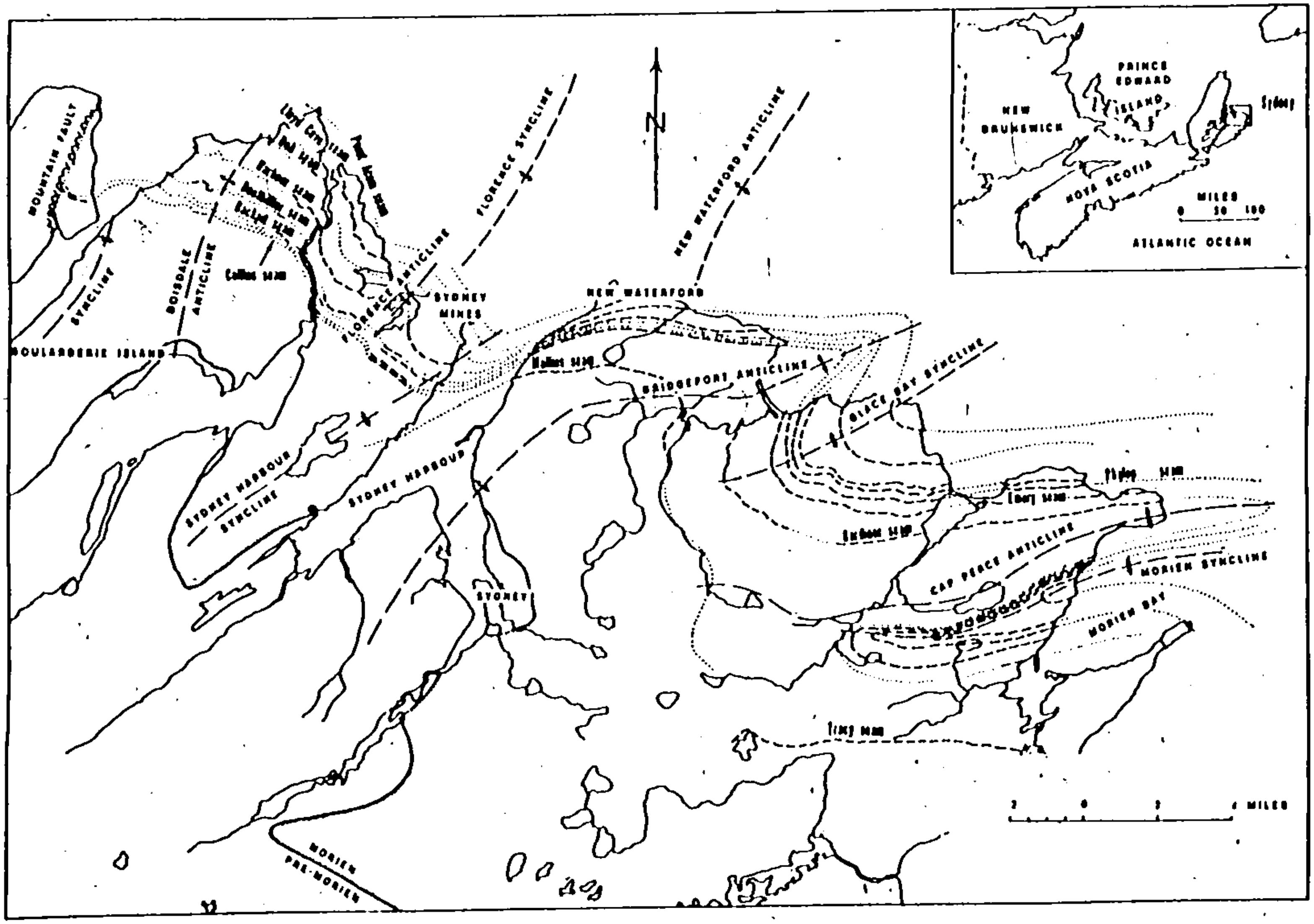

ATLANTIC OCEAN
Point Aconi
Great Bras D'Or
SYDNEY SYNCLINORIUM
Sydney Harbour
SYDNEY HARBOUR SYNCLINE
SYDNEY
Donkin
Cape Morien
Scatarie Island
Mira Bay
DUTCH BROOK SYNCLINE
COXHEATH HILLS
BOISDALE HILLS
St. Andrews Channel
BOULARDERIE SYNCLINE
KELLYS MOUNTAIN BLOCK
East Bay
EAST BAY BLOCK
MIRA RIVER-BATESTON FAULT
FOURCHU BLOCK
Gabarus Bay
60°30'
60°00'
46°00'
10 km

Figure 27

Fold pattern in the Sydney Coalfield, Nova Scotia (modified after Hacquebard and Donaldson, 1969).



MOUNTAIN FAULT
SYNCLINE
BOISDALE ANTICLINE
BOULARDERIE ISLAND
FLORENCE ANTICLINE
FLORENCE SYNCLINE
SYDNEY MINES
N
NEW WATERFORD ANTICLINE
NEW WATERFORD
BRIDGEPORT ANTICLINE
GLACE BAY SYNCLINE
SYDNEY HARBOUR SYNCLINE
SYDNEY HARBOUR
SYDNEY
CAP PERCE ANTICLINE
MORIEN SYNCLINE
MORIEN BAY
MORIEN
PRE-MORIEN
2 0 2 4 MILES
PRINCE EDWARD ISLAND
NEW BRUNSWICK
NOVA SCOTIA
MILES
0 50 100
ATLANTIC OCEAN

Plate I

Pebbly-conglomeratic to very coarse quartzolithic sandstone with mudstone, calcareous and sideritic nodules and clasts as lag deposit. Location: Morien North section 91.5 m. Clast identification: C - calcareous, M - mudstone and S - sideritic. Scale bar in cm.

Plate 2

Pebbly (conglomeratic) to very coarse quartzolithic to quartzosublithic sandstone, basal part of channel lag deposit with large siderite nodules and mud clasts.

Location: Morien North section 100-105 m. Scale bar in cm.


10 11 12 13 14 15 16 17 18 19 20 21

Plate 3

A) Medium to fine (coarse-medium in lower part) quartzolithic to lithi-subquartzose rippled sandstone with sand-filled burrows.
   Location: Morien North section 9.5 m. Scale bar 1 cm.

B) Medium to fine quartzosublithic to lithisubquartzose rippled sandstone.
   Location: Victoria Mines section 92.5 m. Scale bar 1 cm.

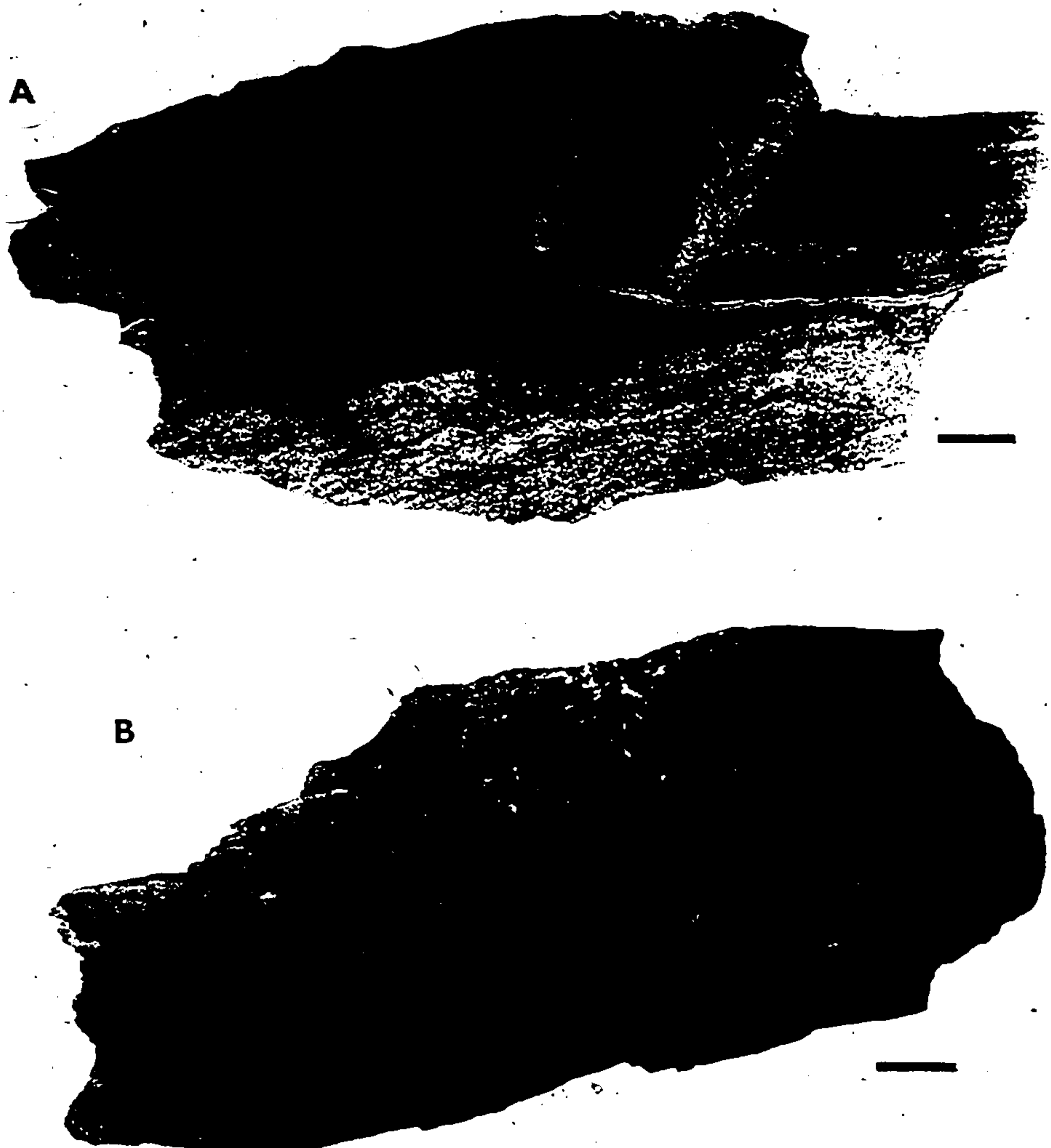

A
B

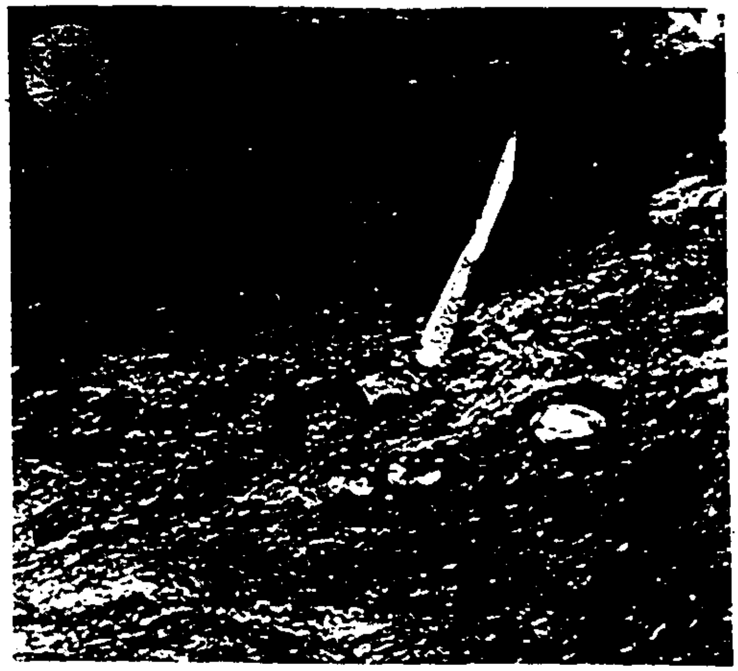
Plate 4

A) Disseminated and aligned iron-carbonate nodules from an undershale unit.

Location: Victoria Mines section 10-15 m. Knife is 17 cm long.

B) Septarian nodule with fractures filled by calcite cement.

Location: Morien North section 100 m. Scale bar in cm.



B

Plate 5

A) Vertical polished section through algal laminite.

Location: Victoria Mines section 2.0 m. Scale bar = 1.5 cm.

B) Thin section of algal stromatolite.

Location: New Waterford section 179 m. Scale bar = 5 mm.

C) Vertical polished section through oncoids. Upper surface is approximately parallel to bedding.

Location: New Waterford section 179.5 m. Scale bar = 1.5 cm.


A
B
C

Plate 6

Mudstone-packstone limestone subfacies.

Location: Donkin East 107 m. Scale bar = .5 cm.

Plate 7

A) Pedogenic calcrete unit.

Location: Victoria Mines section 63 m. Notebook = 15 cm long.

B) Internal fabric of pedogenic calcareous nodule.

Location: Victoria Mines section 21 m. Scale bar = 1 cm.

B

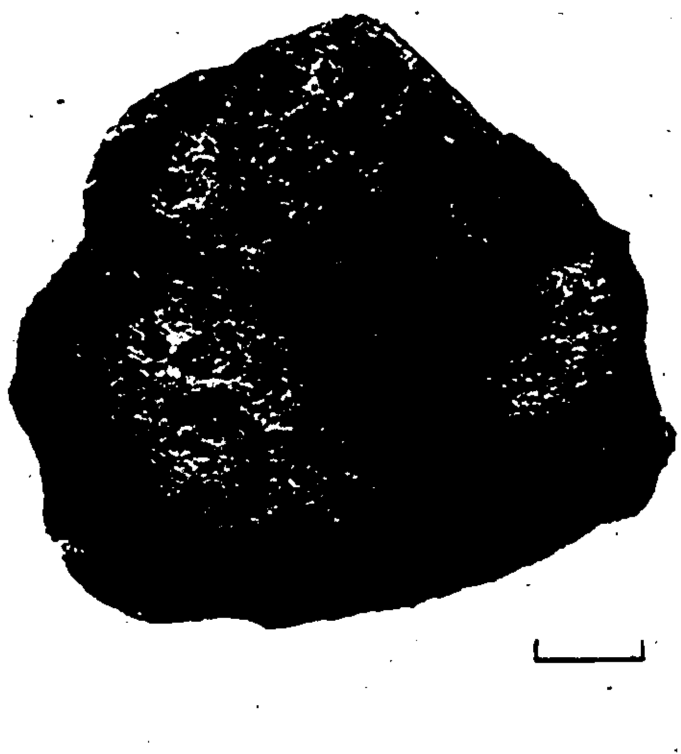


Plate 8

A) Conglomerate-breccia limestone subfacies from "rip-up" limestone unit. Variegated calcareous fragments and lithoclasts in a calcareous mud matrix. Microfractures are filled with calcite.

Location: Victoria Mines section 72 m. Scale bar = 1 cm.

B) Conglomerate-breccia limestone subfacies. Variegated calcareous fragments and lithoclasts in a silty to very fine sandy calcareous mud matrix.

Location: Morien North section 88 m. Scale bar in cm.

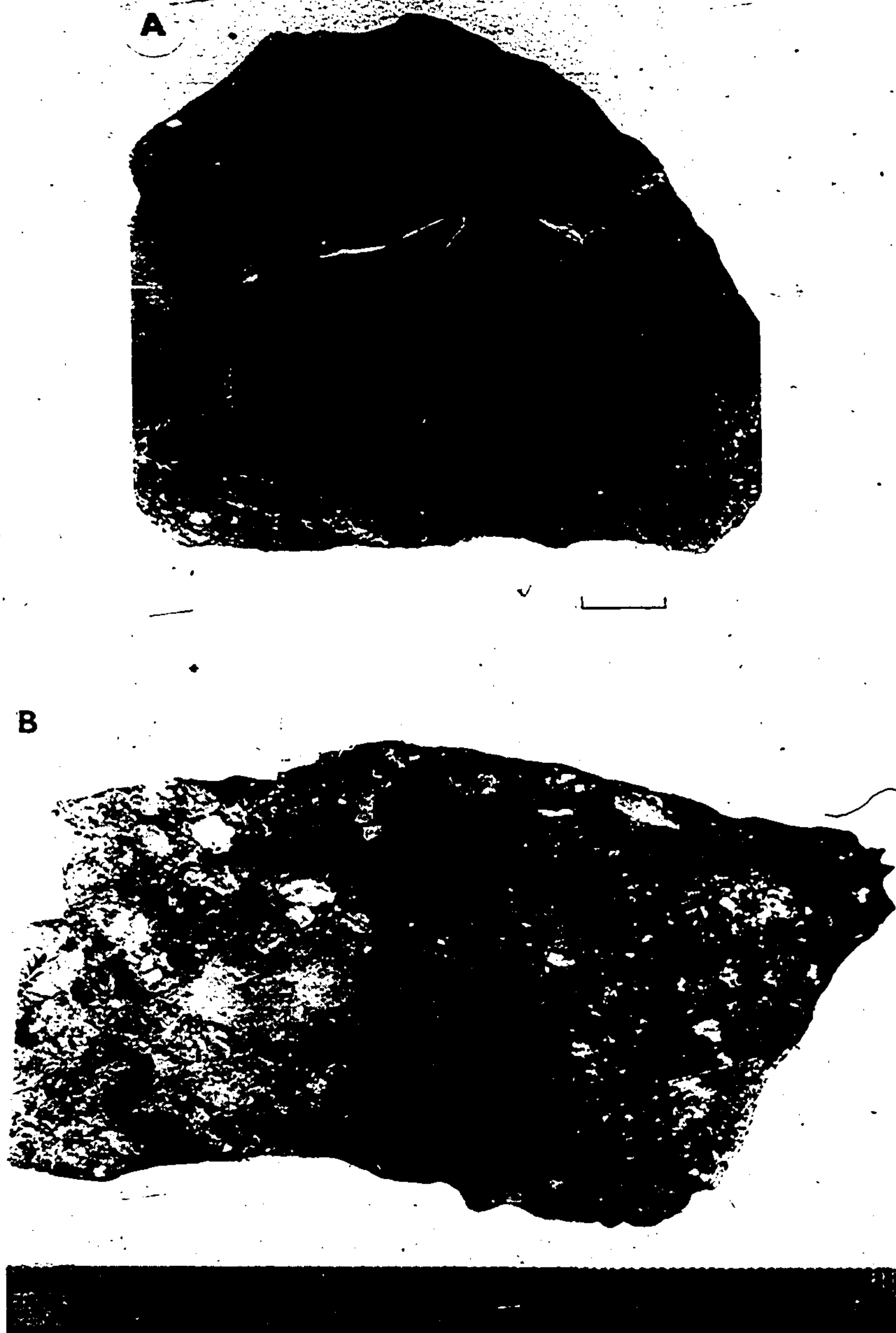

A
B

Plate 9

Fish microfauna from the Sydney Mines Formation. Scale bar is 0.5 mm in all cases.

Fig. 1. Xenacanth tooth, coronal view. Unit NW-20. Family Xenacanthidae, Genus Orthacanthus Agassiz.

Fig. 2. Xenacanth tooth, coronal view. Unit NW-20. Family Xenacanthidae, Genus Orthacanthus Agassiz.

Fig. 3. Xenacanth tooth, lingual view. Unit VM-14. Family Xenacanthidae, Genus Orthacanthus Agassiz.

Fig. 4. Orthacanthus, mucous membrane denticle. Unit NW-20.

Fig. 5. Pterygoid plates [= "upper jaw"] of lungfish, ventral view. Unit NW-20. Order Dipnoi, Family Ctenodontidae (Woodward), Monongahela stenodonta.

Fig. 6. Vomerine tooth fragment from lungfish, lateral view. Unit NW-20. Order Dipnoi, Family Ctenodontidae (Woodward), Monongahela stenodonta.

Fig. 7. Elasmobranch dermal denticle, lateral view. Unit NW-17. Unspecified family and genus.

Fig. 8. Elasmobranch compound dermal denticle assemblage. Unit NW-20. Unspecified family and genus.

Unit VM-14 is located at interval 2-3 m of Victoria Mines section, unit NW-17 at interval 108-110 m of New Waterford section, and unit NW-20 at interval 128-130 m of New Waterford section.


1
2
3
4
5
6
7
8

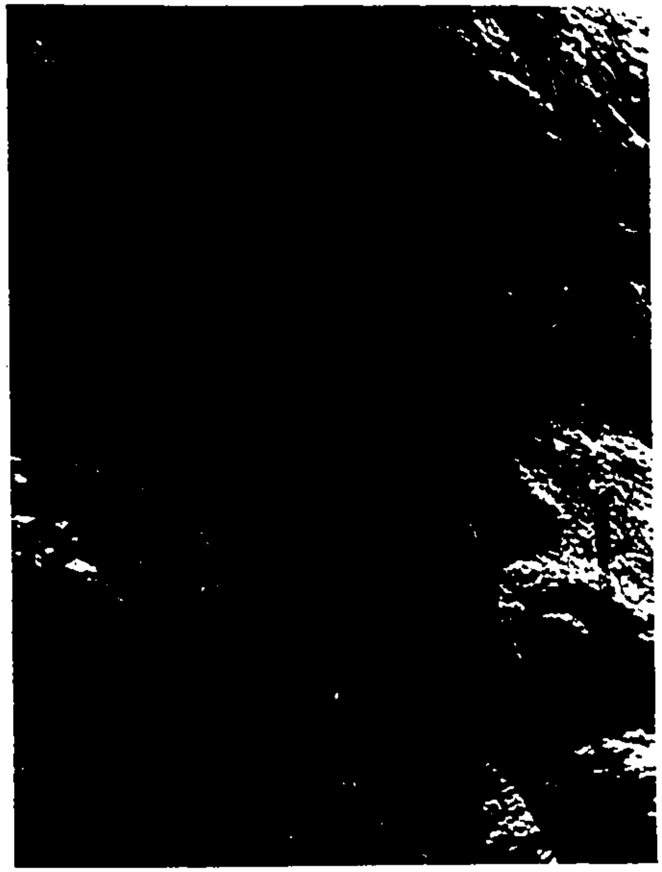
Plate 10

A) Bright-dull banded coal, Emery seam.

Location: Schooner Head section 34 m. Thickness of seam approximately 1.5 m.

B) Coal-carbonaceous shale-clay interlamination grading upward into bright-dull banded coal. Note prominent vertical and horizontal cleats. CL identifies the thin clay layers.

Location: Schooner Head section 50.5 m. Scale: bag is 30 cm x 30 cm.



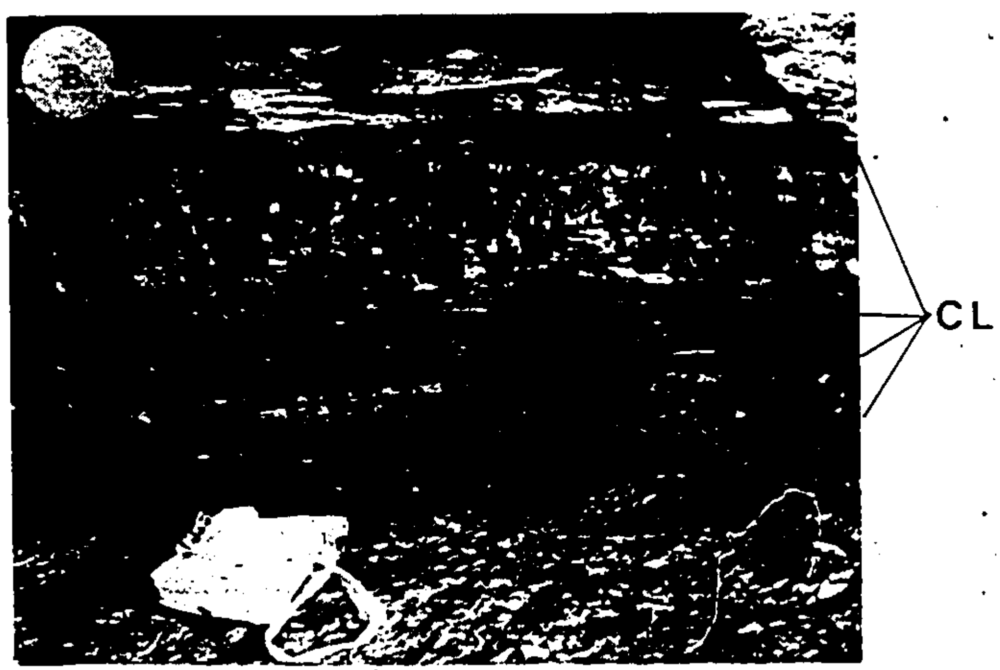

CL

Plate 11

A) Rooted zone in underclay.

Location: Donkin East section 34 m. Pencil = 15 cm.

B) Silty to very fine sandy isolated scour pocket (lighter area in center forefront of photo) preferentially cemented by limestone in rooted zone from underclay unit.

Location: Donkin West section 64 m. Calcareous pocket is 20 cm in diameter.


B

Plate 12

A) Interstratified coal (C) and carbonaceous shale.

Location: Donkin East section 102.5 m. Notebook = 10 x 17 cm.

B) Crevasse-splay sequence overlying Spencer seam (C and ruler).

Interstratified coal and carbonaceous shale (CS) coarsening upward to rippled sandstone (Sr).

Location: Morien South section 0-7 m. Ruler = 1.0 m.

C) Fining-upward channel sandstone overlying Backpit rider seam (C).

Location: Donkin West section, base of channel at 75 m.

Thickness of exposed coal below channel is 60 cm.

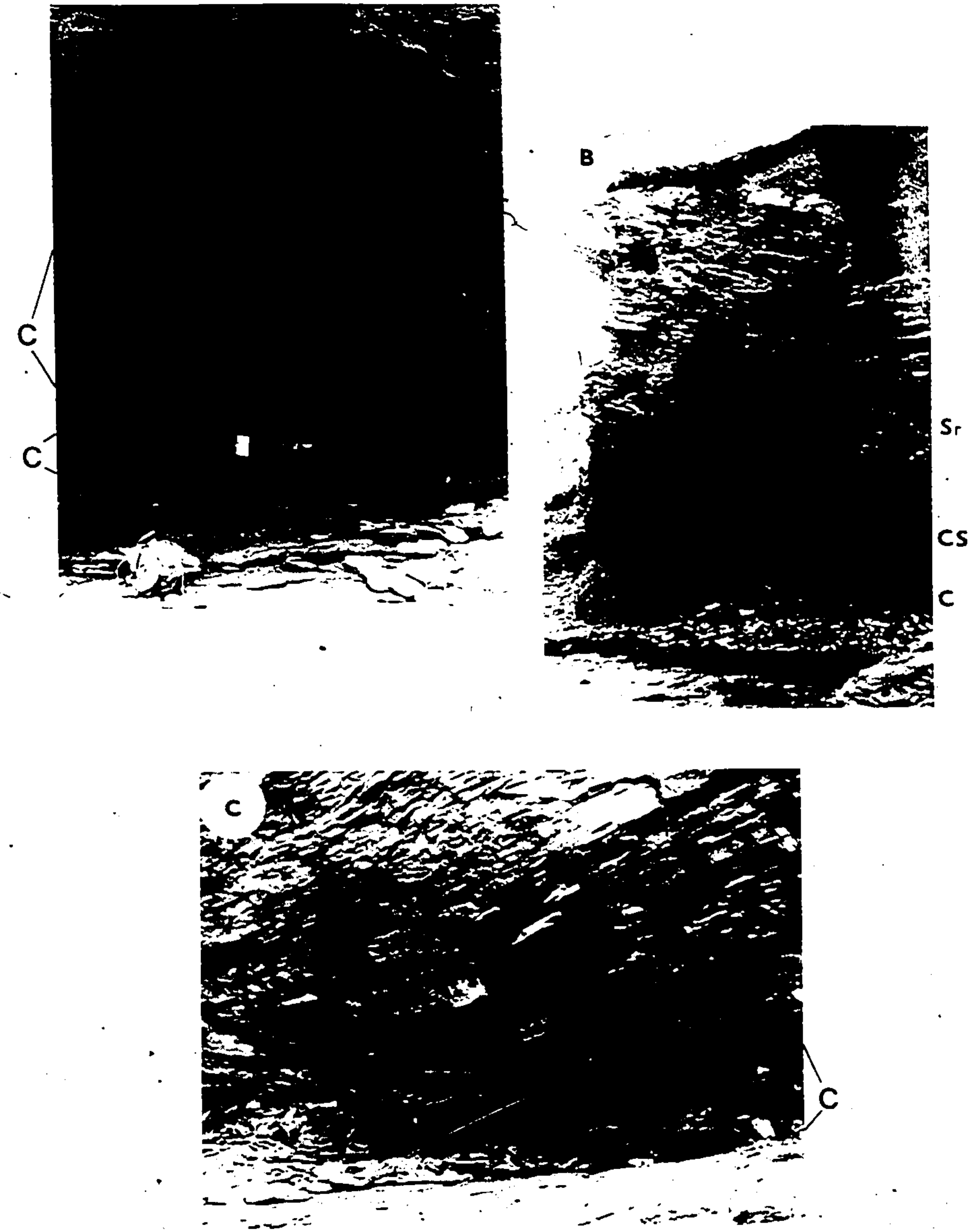

C
C
B
Sr
CS
C
C
C

Plate 13

A) Sigillarian Trunk with Syringodendron pattern.

Location: Victoria Mines section 110.5 m. Notebook is 10 cm x 17 cm.

B) Upright Calamites trunk in upper part of coarsening-upward sequence.

Location: New Waterford section 102 m. Trunk = 1.5 m high.

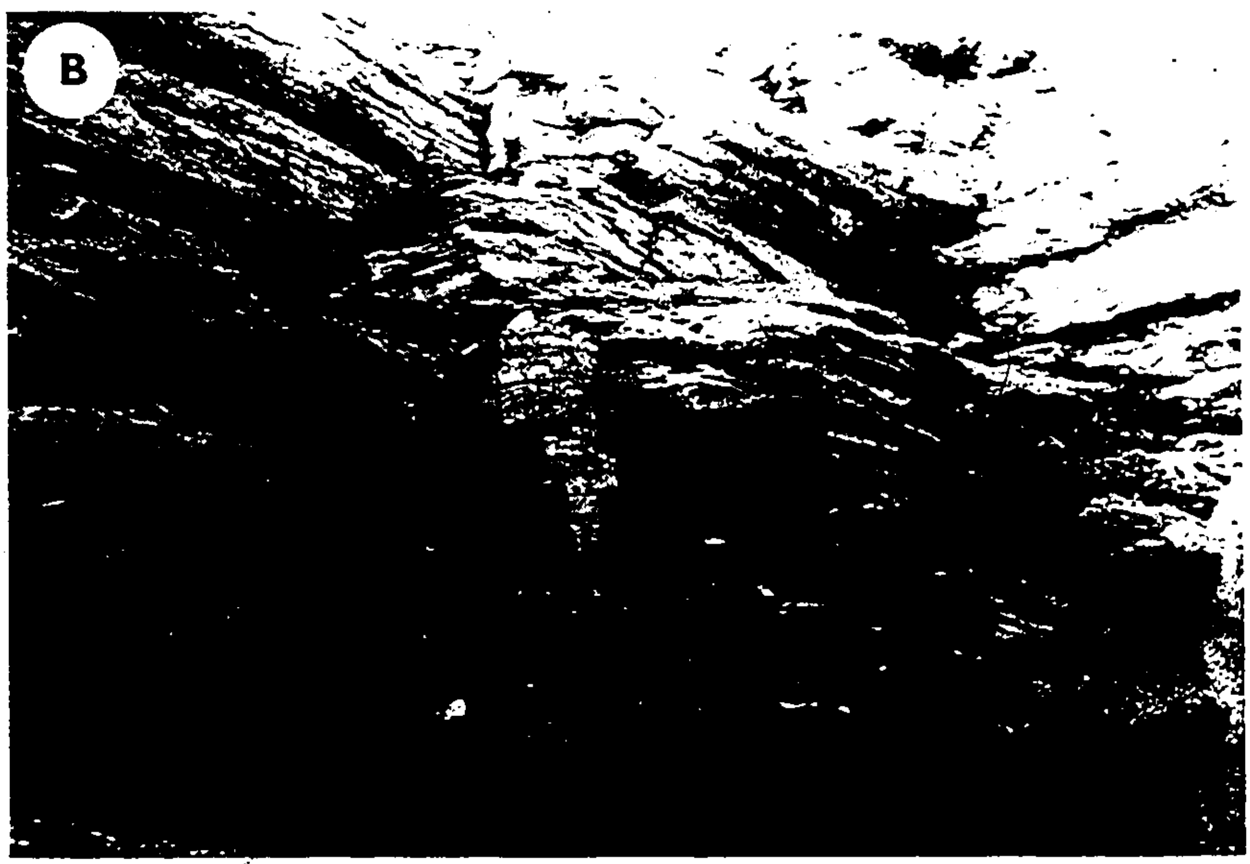

B

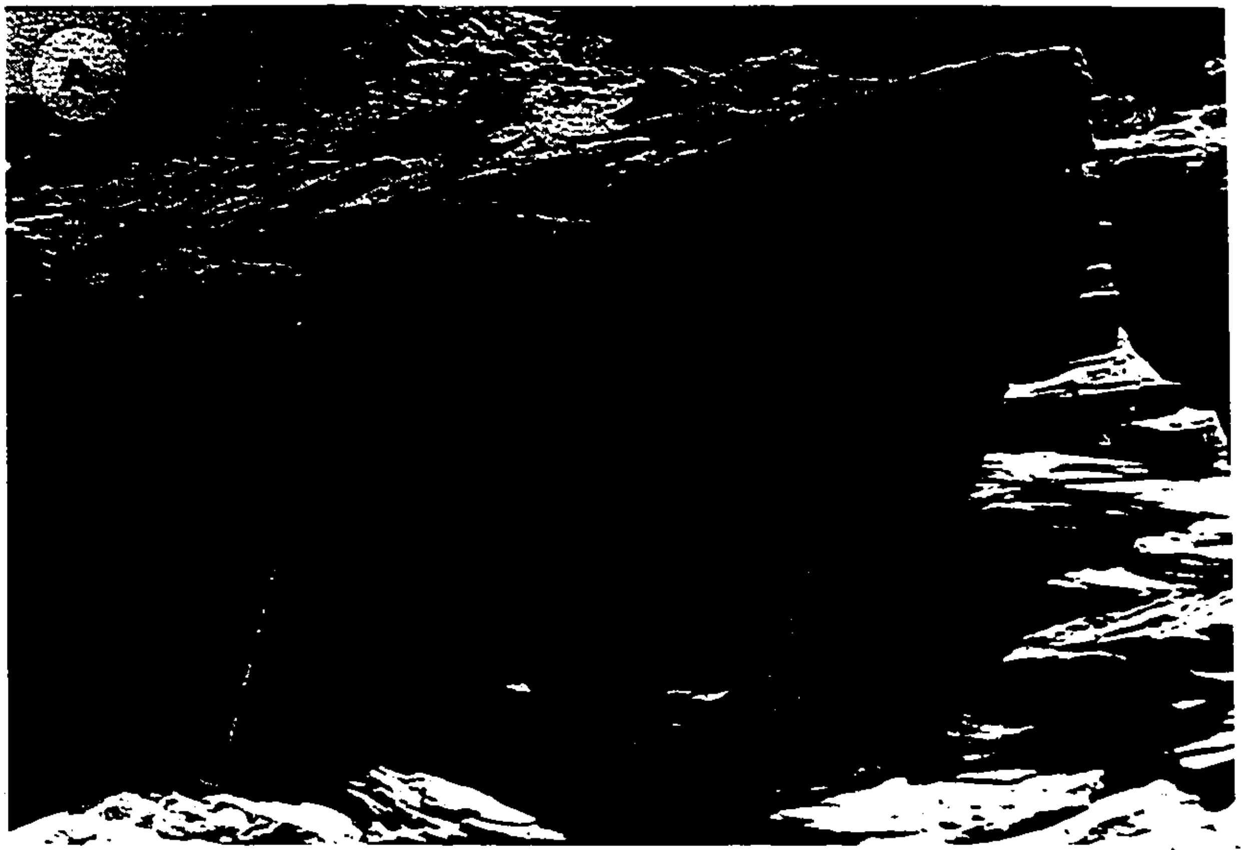
Plate 14

A) Trough cross-stratified sandstone (facies St) from middle part of channel fill. Base shows erosional surface and cross-cutting relationship of troughs. Scale 1 m.

Location: New Waterford section, channel from 256-260 m.

B) Horizontally stratified sandstone (facies Sh) interstratified with ripple cross-laminated sandstone (facies Sr) and minor Sp strata and underlain by trough cross-stratified sandstone (facies St) with lag (Se).

Location: Donkin East section 72-77 m. Scale 10 cm intervals.


A

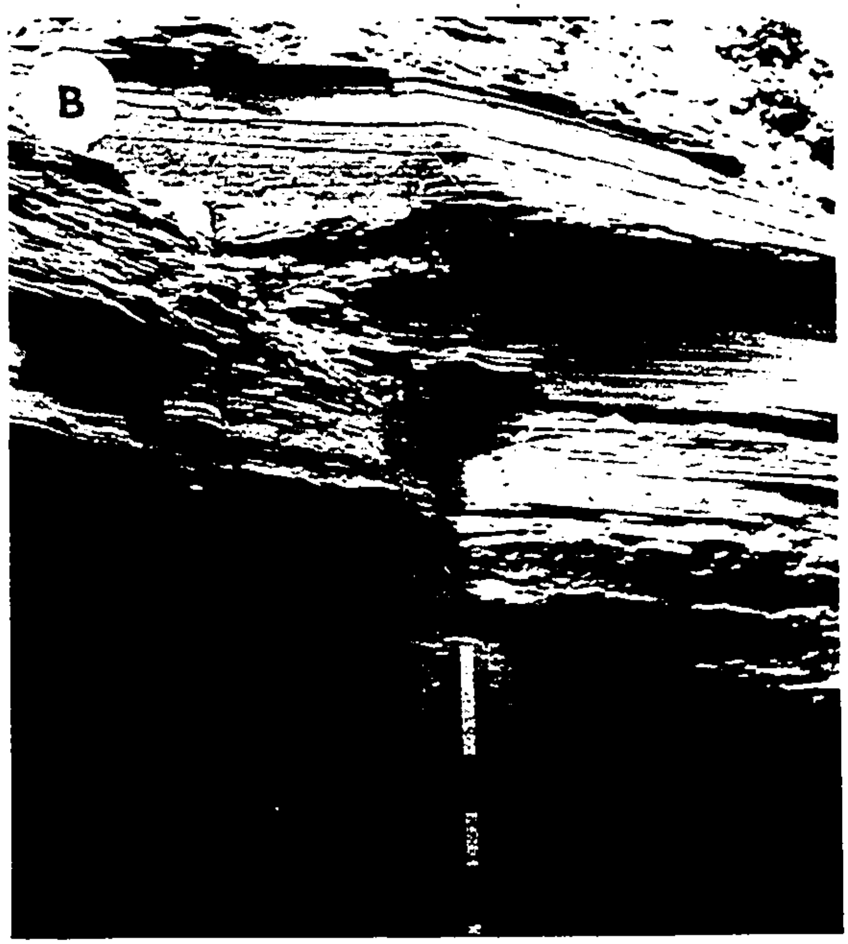

B
Sh
Sp
Sh
Sr
St
Se

Plate 15

A) Undulatory, climbing ripple cross-laminated sandstone (facies Sr). Laminations are enhanced by hematitic content. Note that ripple crests are out of phase in vertical sequence.

Location: Victoria Mines section 104.5 m. Hammer handle is 28 cm long.

B) Undulatory, climbing in-phase ripple cross-laminated sandstone (facies Sr). Section is oblique to bedding.

Location: Victoria Mines 44 m. Hammer handle is 18 cm long.

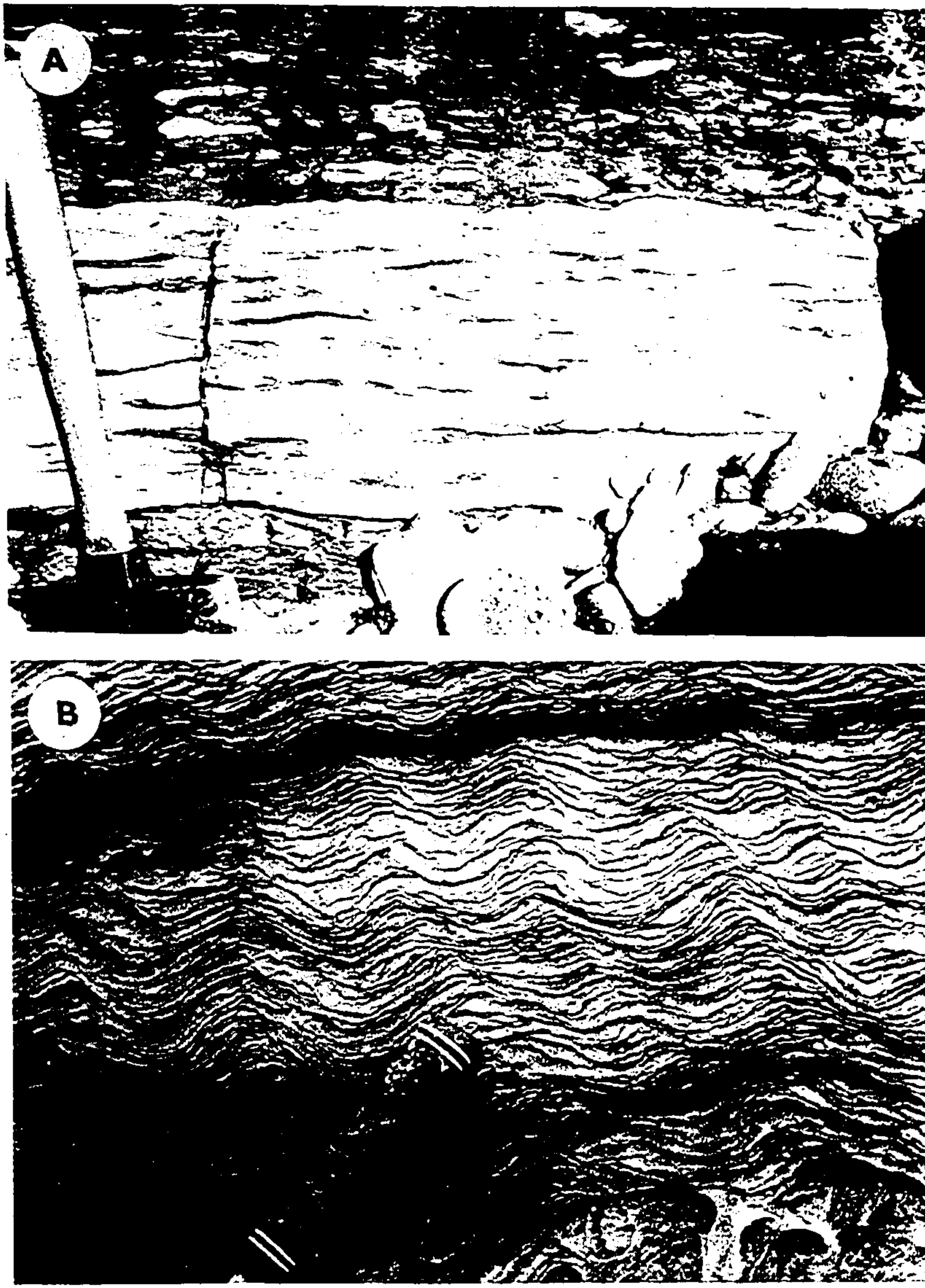
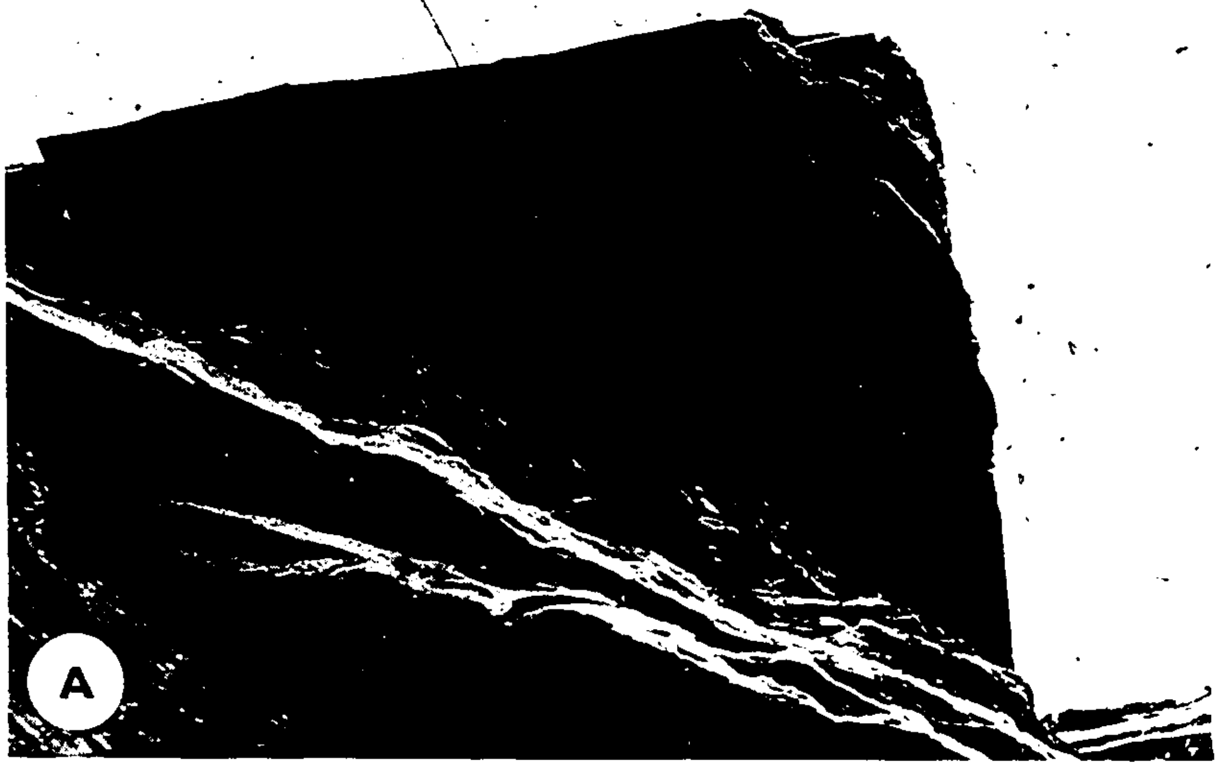

A
B

Plate 16

A) Horizontally laminated sandstone (facies Sh) exhibiting groove and tool marks on lower bedding surface. Scale: top slab 1.5 m wide. Current direction NE-SW. Location: Glace Bay East 127 m.

B) Horizontally to low-angle stratified very fine to coarse sandstone gradational into silty mudstone. Location: Morien South section 31-33 m. Scale 1 m long.


A

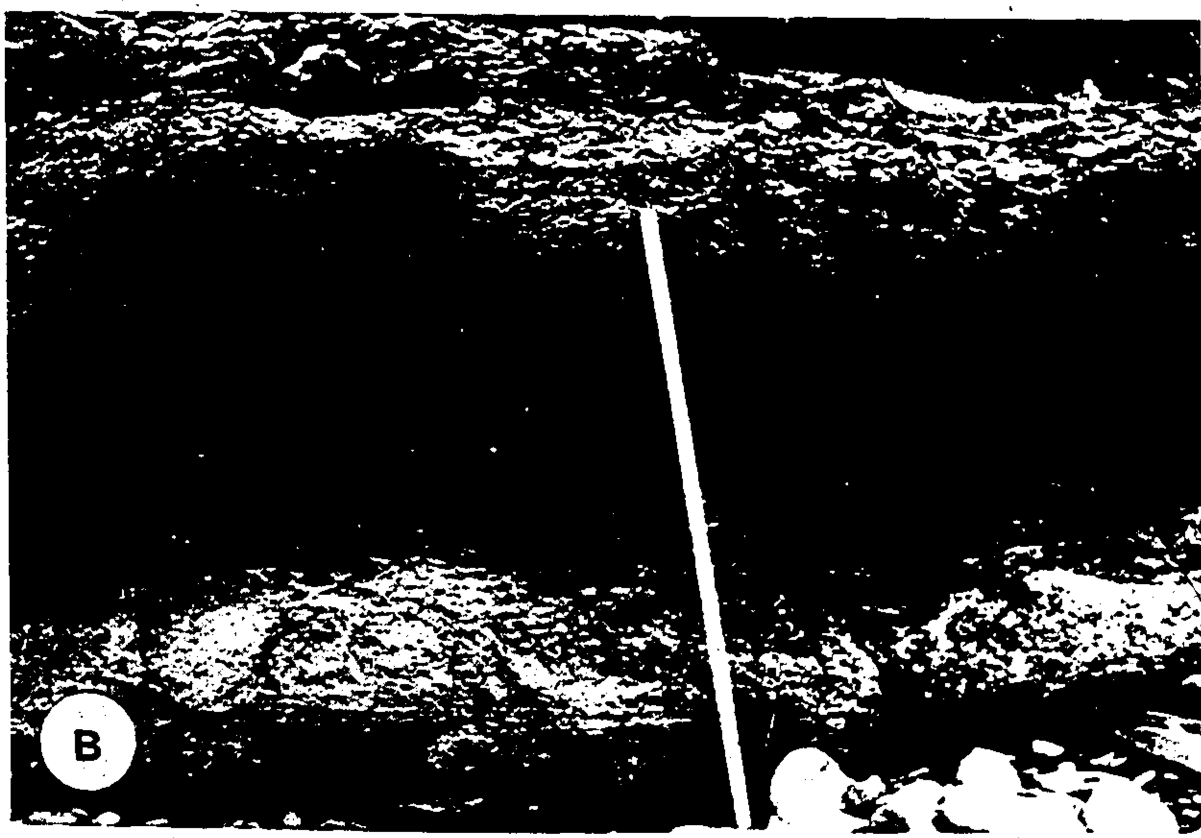
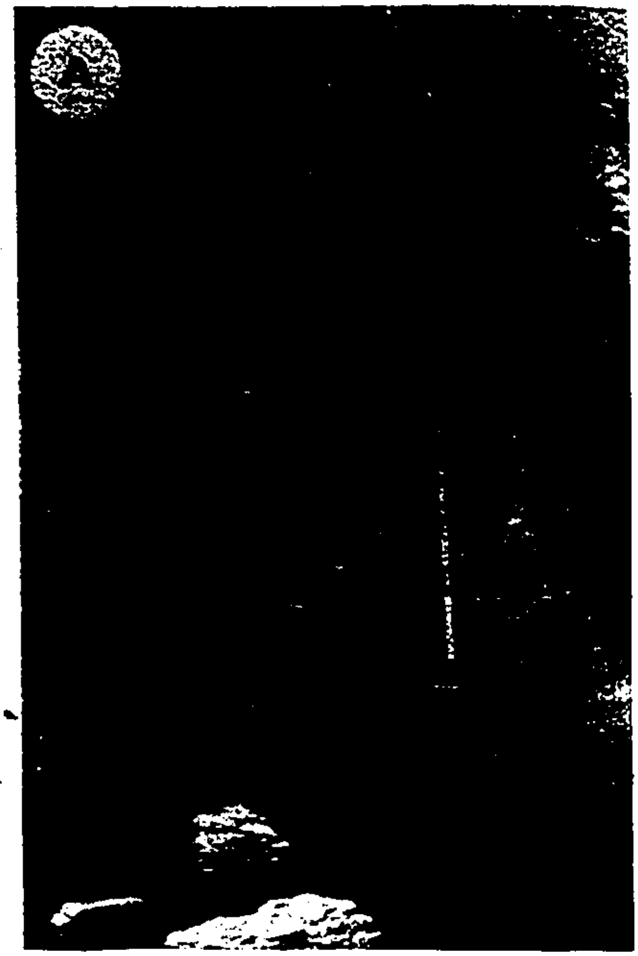

B

Plate 17

Example 1. Point-bar fining-upward sequence. Location: Donkin West section, interval 24-28 m.

A) Fining-upward point-bar sequence containing trough cross-bedded (St) to trough cross-laminated (St lam) to rippled sets (Sr). Scale 1 m long.

B) Laterally migrating trough cross-stratified sets. Scale 20 cm long.


A
Sr
St lam
St


B
St
Se

Plate 18

Example 4. Homogeneous channel fill deposit. Location: Morien North section, interval 50-57 m.

A) Channel filled by fining-upward trough sets as thick homogeneous sandstone units lacking lateral accretion structures. Facies indicated correspond to those listed in Table 9.

B) Similar channel filling as (A) but in New Waterford section, interval 202-211.5 m. Scale 1 m.


A
Sr
St
Fl
Sr
St
FU
Se
St
Se


B

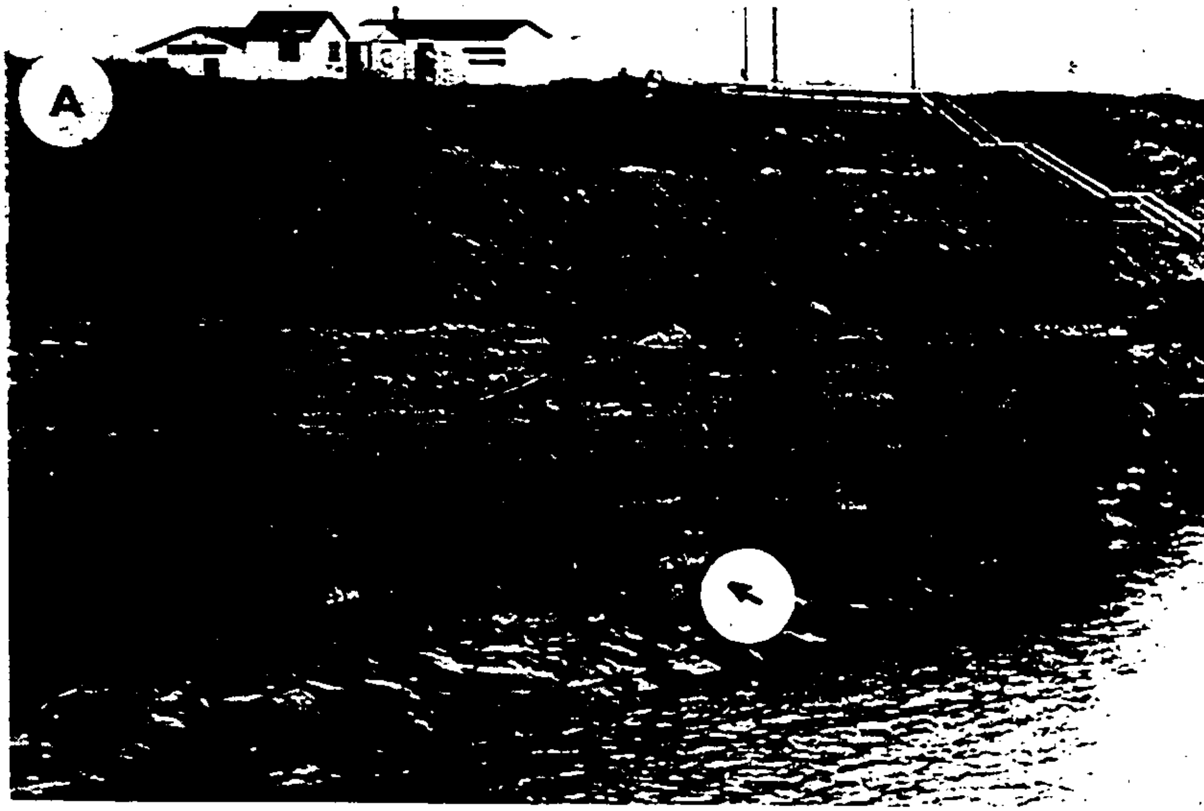
Plate 19

Example 8. Overbank deposits: channel margin and levee deposits.

Location: Morien North section, interval 64-68 m.

A) Channel margin and levee sequence including flooded upright tree trunks (close-up in (B)). Total height of cliff from grass to beach is approximately 13 m.

B) Interstratified tabular rippled sandstone, siltstone and silty shale enclosing upright tree trunks. Scale: upright trunk in center is 40 cm in height. Location of close-up is indicated in (A) by arrow.


A


B

Plate 20

Example 9. Overbank deposits: pebbly sheet splay deposit.

Location: Morien North section, interval 91-96 m.

A) Vertical sequence of lowermost 4 tabular bodies (numbered on plate) ranging in thickness from 1.5 m at base to 60 cm at the top.

B) Bedding plane view from the lowermost tabular bed of (A) of this pebbly-conglomeratic, very coarse to coarse sandy unit with a green to dark-grey muddy matrix. Scale: camera cap is 5 cm in diameter.

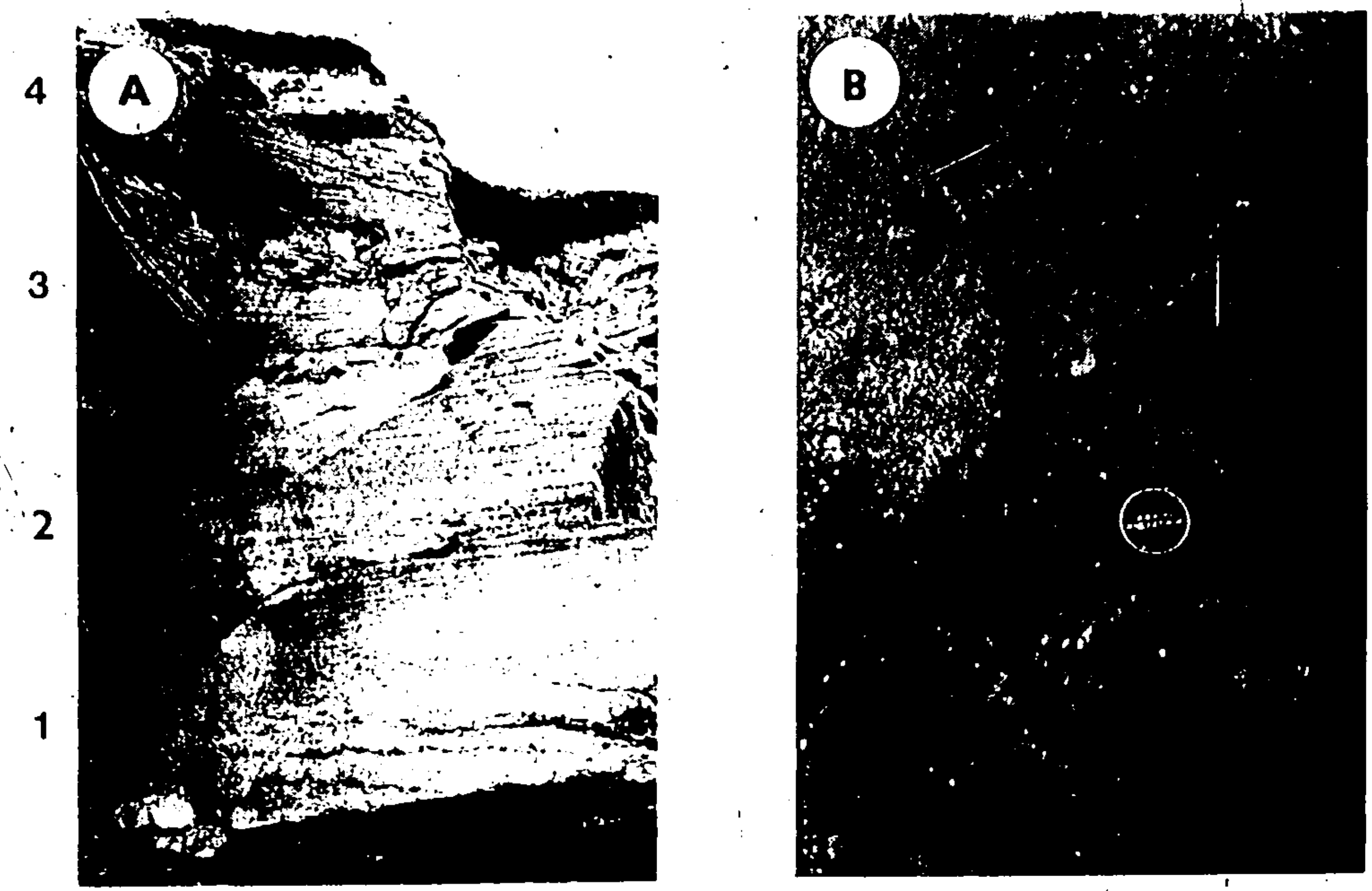

4
3
2
1
A
B

Plate 21

Example 10. Overbank deposits: crevasse-splays with distributary channel deposit. Location: Glace Bay East section, interval 117-139 m.

A) Splay channel with lateral accretion sets on left side of channel. Interval is 120 (base of ruler) to 126 m. Beds enclosing channel contain much disseminated plant debris and discontinuous thin coally lenses. Scale 1 m.

B) Splay channel from New Waterford section, channel located at interval 252-253 m. Channel is part of a sequence environmentally similar to (A). Scale 1 m.


A


B

Plate 22

Well-drained floodplain deposit with fluctuating water table. Variable interstratification of light olive grey/greyish green to purple hematitic (locally mottled) fine sandstone to fine clastic beds. Location: New Waterford section, interval 260-280 m. Cliff height approximately 15 m.

Plate 23

Poorly drained (organically dominated) coarsening-upward floodplain deposit. Interstratified dark olive grey to olive black, highly organic claystones/mudstones and thin to thick coal seams.

A) Location: Glace Bay East-section, interval 108-118 m. Cliff height 10.7 m.

B) Location: Glace Bay East section, interval 98-104 m. Cliff height 6 m.

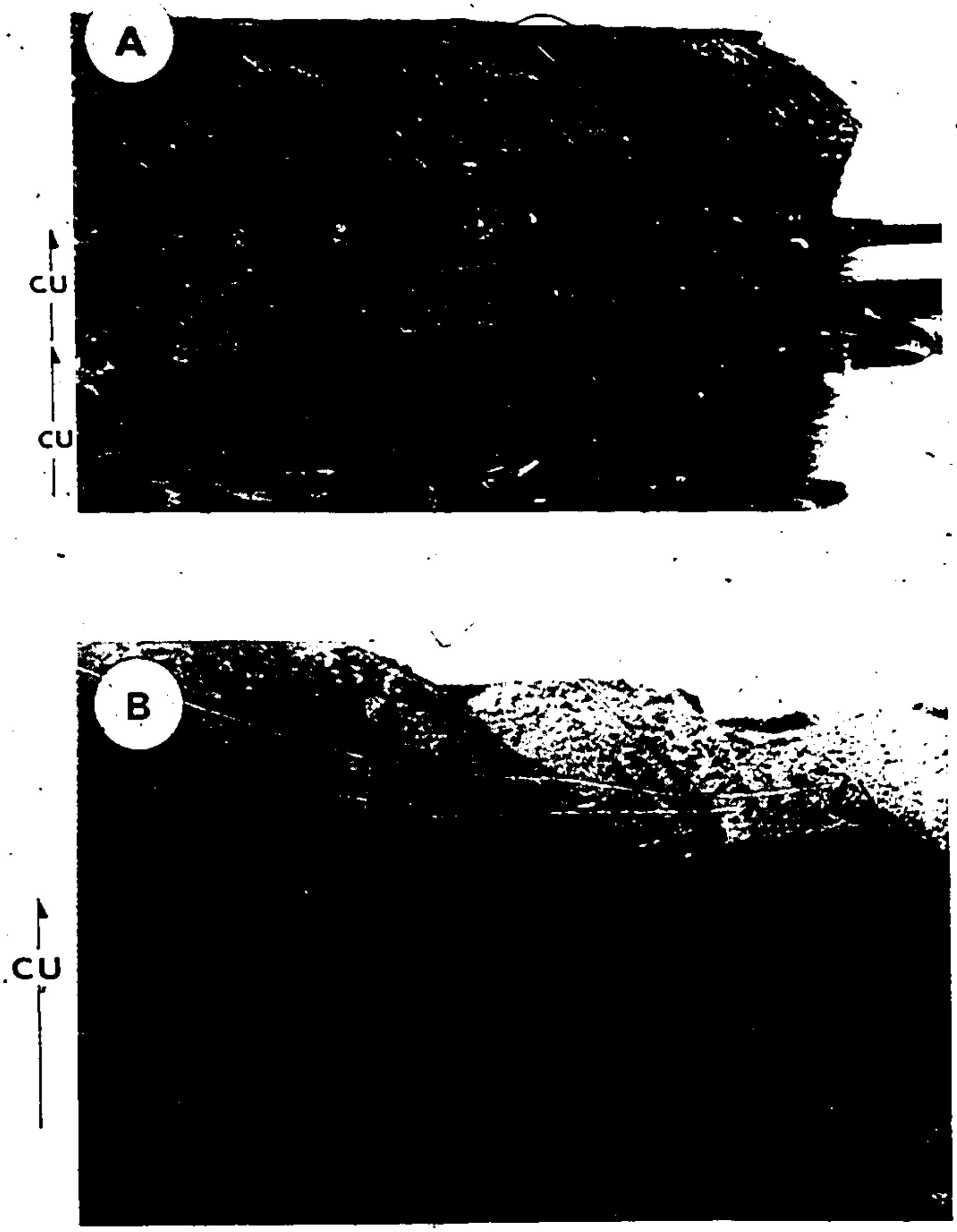
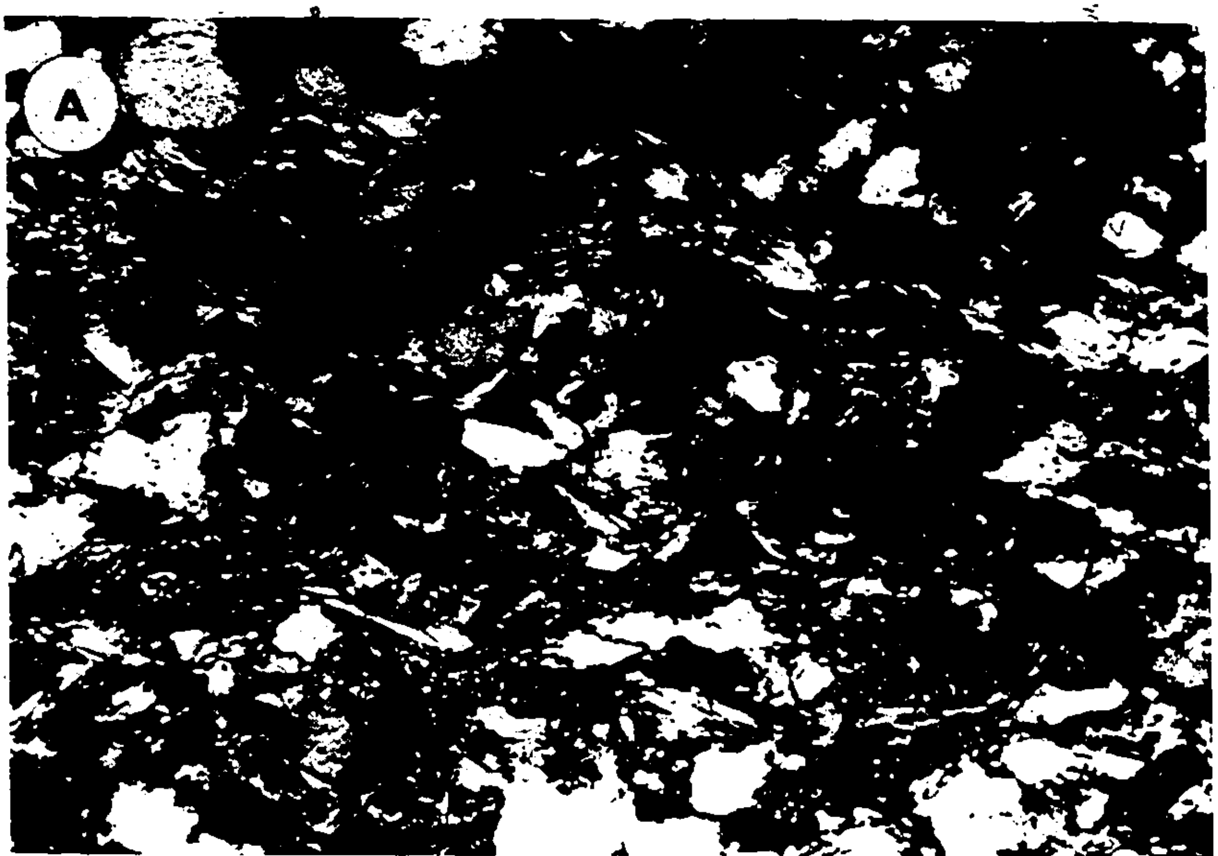

A
CU
CU
B
CU

Plate 24

Sandstone diagenesis: burial diagenesis and compaction.

A) Fracturing and bending of mica flakes and micaceous lithic clasts in a very fine to fine sandstone interlaminated with sandy siltstone. Location: Morien North section 22 m. Scale: average dimension of disseminated quartz grains is 0.15 mm.

B) Compaction effects (stylolites) in and carbonaceous mud clasts from an intraclastic calcareous bed. Location: Glace Bay East section 40 m. Scale: larger clast in center of photo is 5 mm in diameter.


A

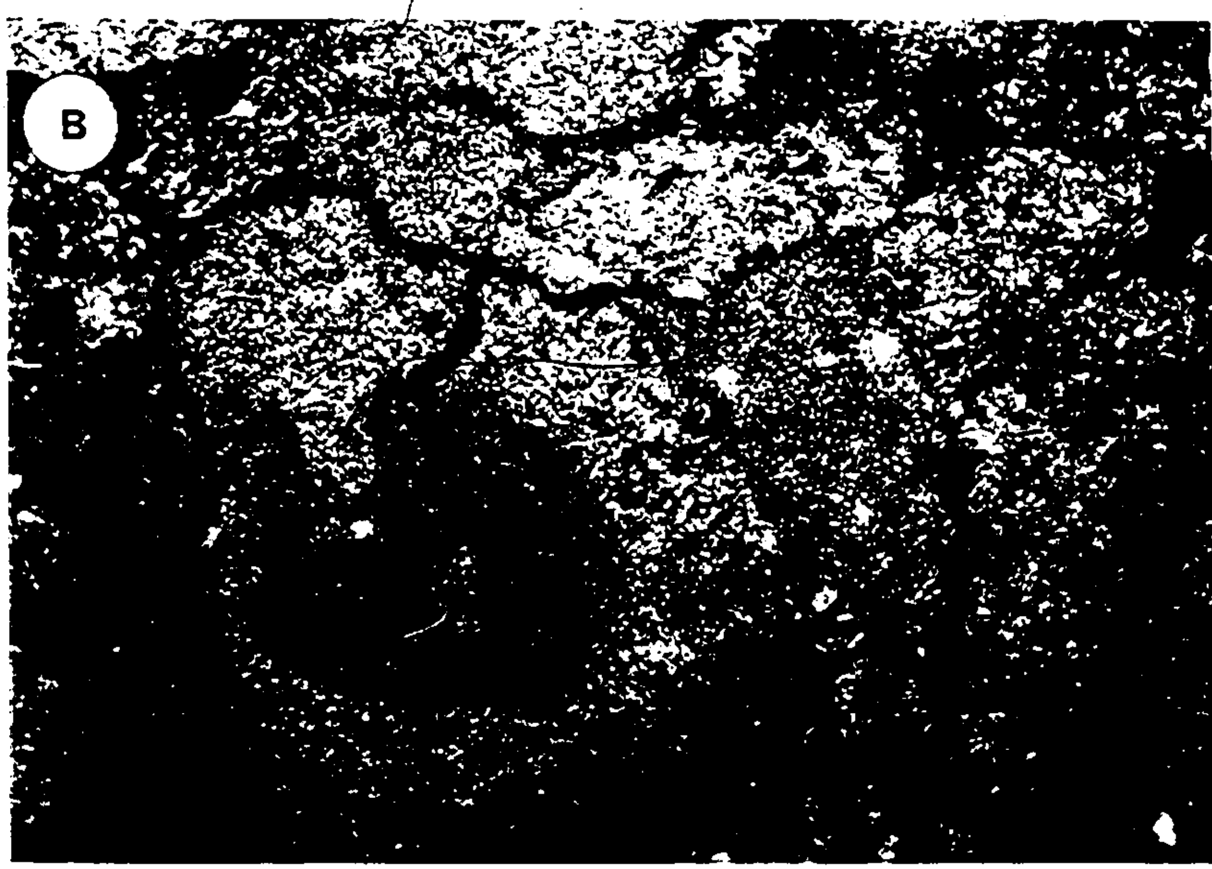
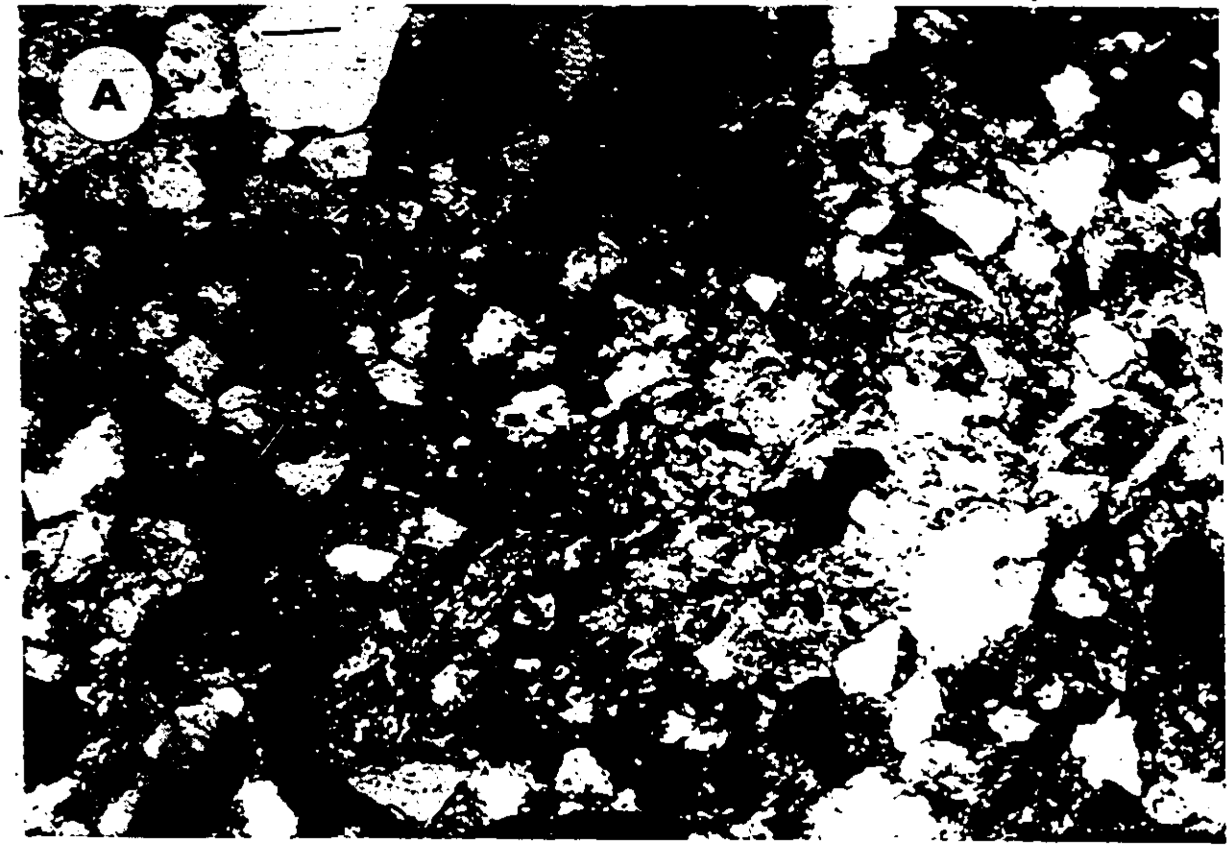

B

Plate 25

Sandstone diagenesis: primary and authigenic clay content.

A) Primary clay of pluri-mineralic clay assemblage exhibiting poorly defined outlines of crystals and clay aggregates and a low to moderate degree of crystallinity. Location: very fine to fine, calcareous, lithic sandstone from Donkin West section 64 m. Scale: average dimension of disseminated quartz grains is 0.15 mm.

B) Authigenic clay as fine crystalline aggregates and coating on the rims of detrital grains, in which the individual clay crystals exhibit some degree of orientation either parallel or perpendicular to the grain boundaries. This example is from a coarse-medium, salt and pepper sandstone with coarse-medium mica flakes and carbonaceous debris. Location: trough cross-stratified unit at Donkin West section 115.5 m.


A

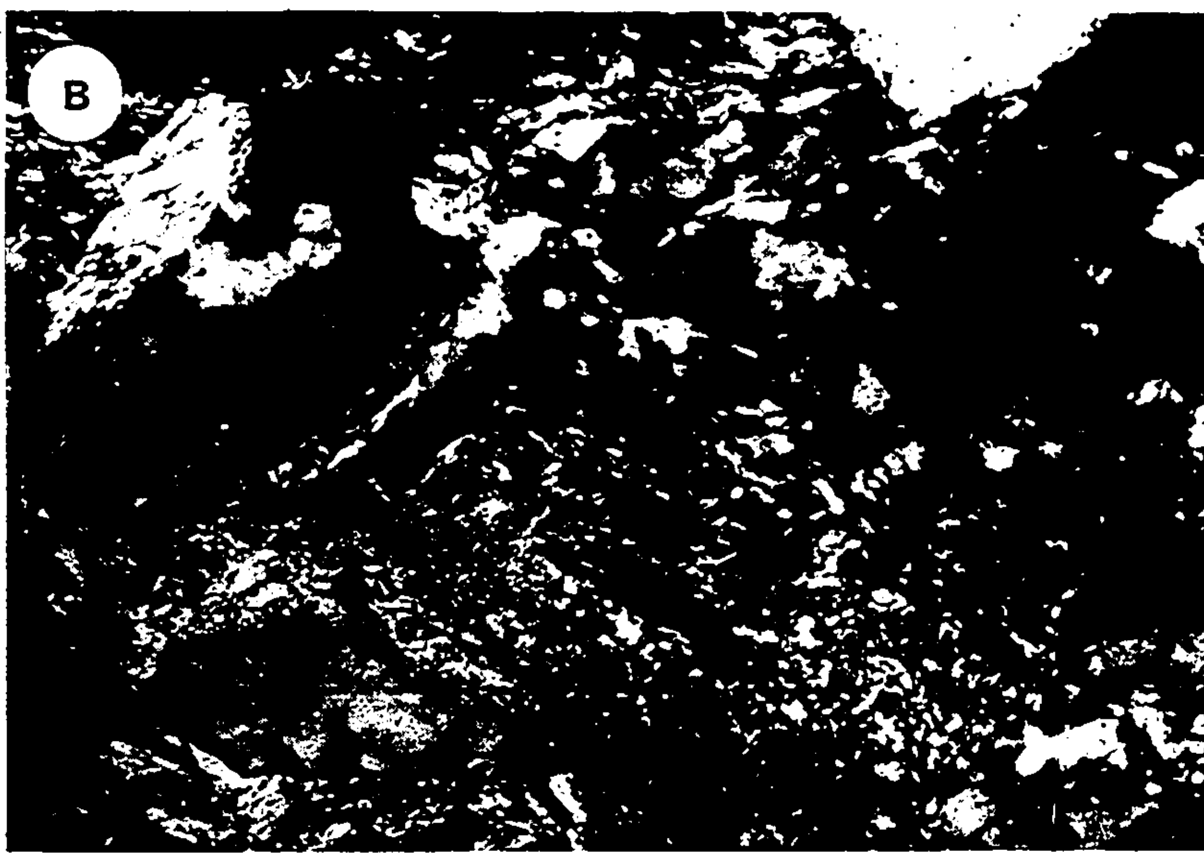

B

Plate 26

Sandstone diagenesis: silica cementation.

A) Dissolution at grain-to-grain contacts: tangential, long or straight and concavo-convex welded contacts are present.
   Location: medium-fine, micaceous, lithic sandstone at Morien North section 53 m. Scale: average quartz grain size 0.2-0.5 mm.

B) Authigenic (syntaxial) quartz overgrowth. The boundary between particle and overgrowth is outlined by the presence of clay minerals, iron oxides and/or inclusions rimming the particle as a dusty border. Quartz overgrowth characteristically develops around single quartz particles. Sample as in (A) but highly magnified. Scale: quartz grain in center of photo is 0.5 mm in diameter.


A

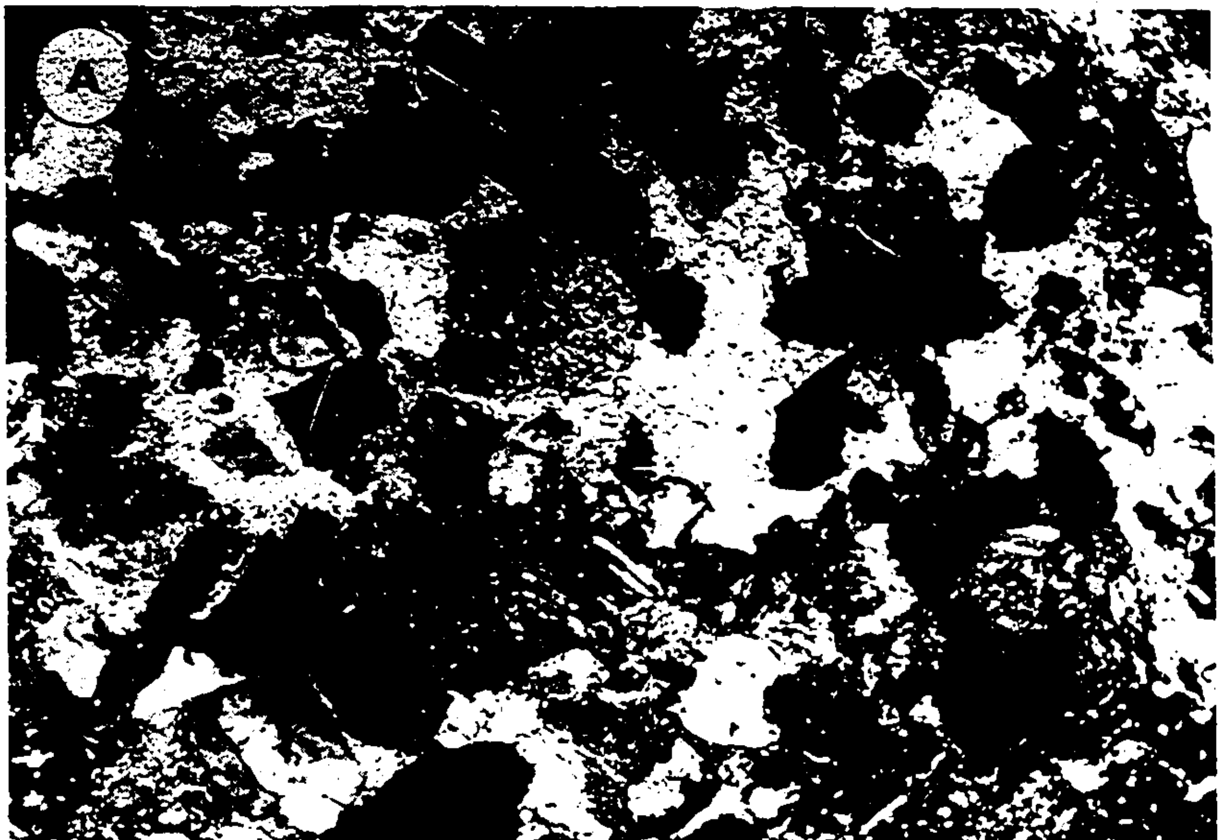

B

Plate 27

Sandstone diagenesis: calcite and hematitic/iron oxide cementation.

A) Calcite cementation as a crystalline pore-filling cement (poikilotopic calcite cement type). This sparitic cement encloses all grain types, exhibits expansion and pushing aside of framework matrix and individual grains and particles including quartz grains coalesced by pressure-solution contacts. Location: medium-coarse, salt and pepper calcareous cemented sandstone at the base of the trough cross-bedded strata, Donkin West section 58 m. Scale: average dimension of quartz grains is 0.4 mm.

B) Hematitic and iron-oxide cement occurring as a red to black pigment coating grains, in interparticle patches complexly mixed with primary clay matrix and as disseminated grains. Location: fine-medium, salt and pepper, micaceous, hematitic uppermost sandstone, Morien North section 30 m. Scale: average dimension of quartz grains is 0.25 mm.


A

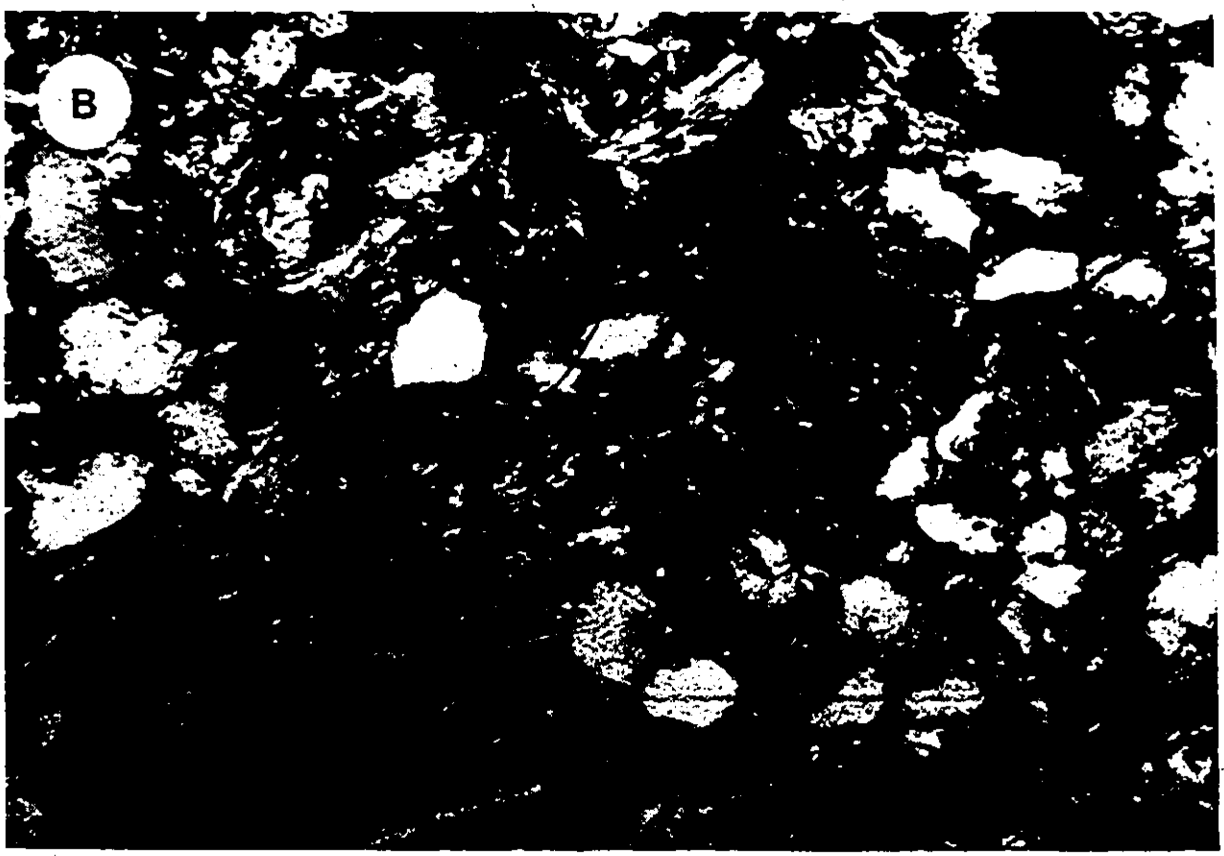

B

Plate 28

Channels overlying and underlying coal seam. Facies indicated are: Ch - channel, Fl - floodplain, and C - coal.

Location: New Waterford section, interval 55-70 m. Scale: cliff height approximately 18 m.

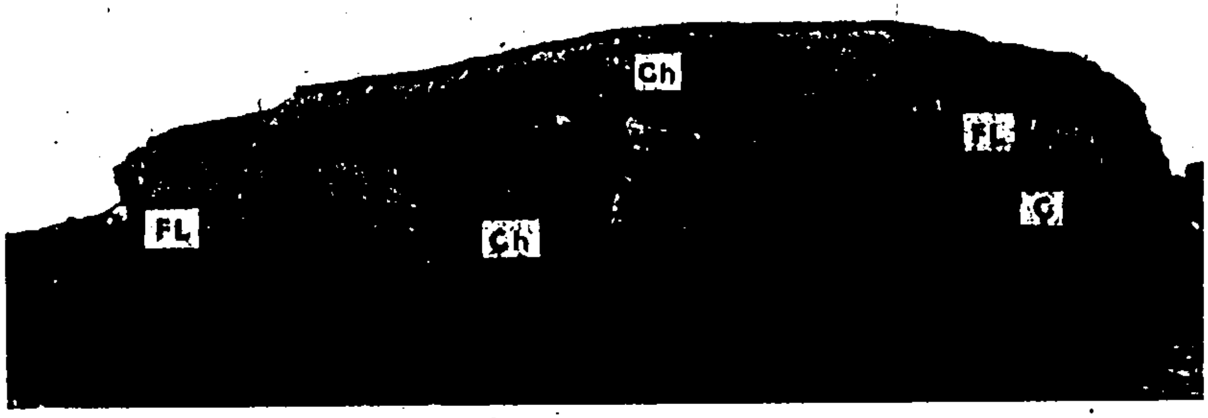

Ch
FL
FL
Ch
G

Plate 29

Example 1: Lacustrine deposit. Location: Victoria Mines section, interval 1-6 m.

A) Interstratified algally laminated, stromatolite and mudstone to packstone limestones enclosed in a marly claystone/mudstone package overlain by a minor coal seam. Scale: sequence approximately 6 m thick.

B) and C) Upward sequence within the main bodies: marly claystone (not shown) - stromatolite - mudstone packstone - algal laminite - carbonaceous shale. Scale: knife blade in (B) is 20 cm; pen in (C) is 15 cm.

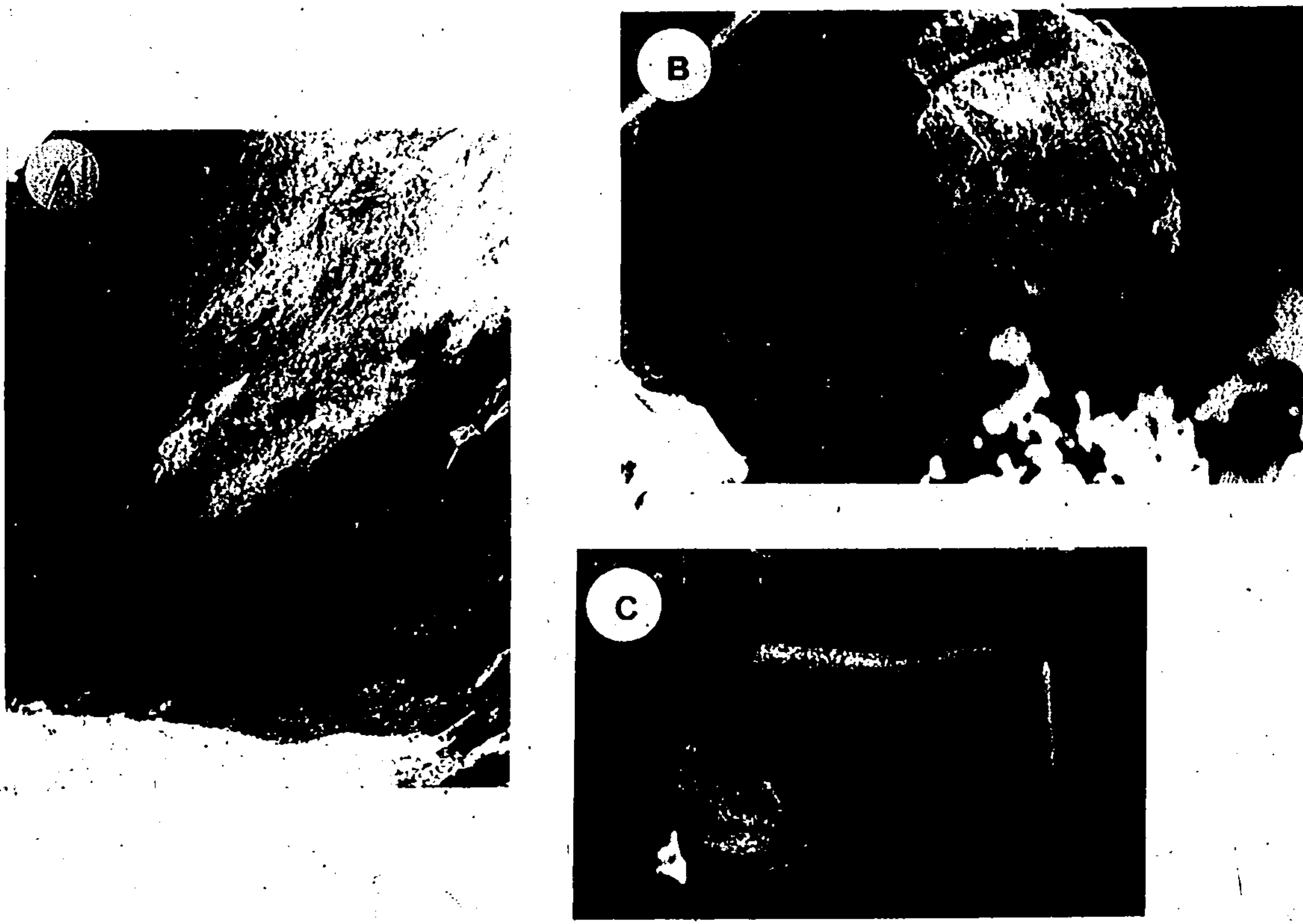
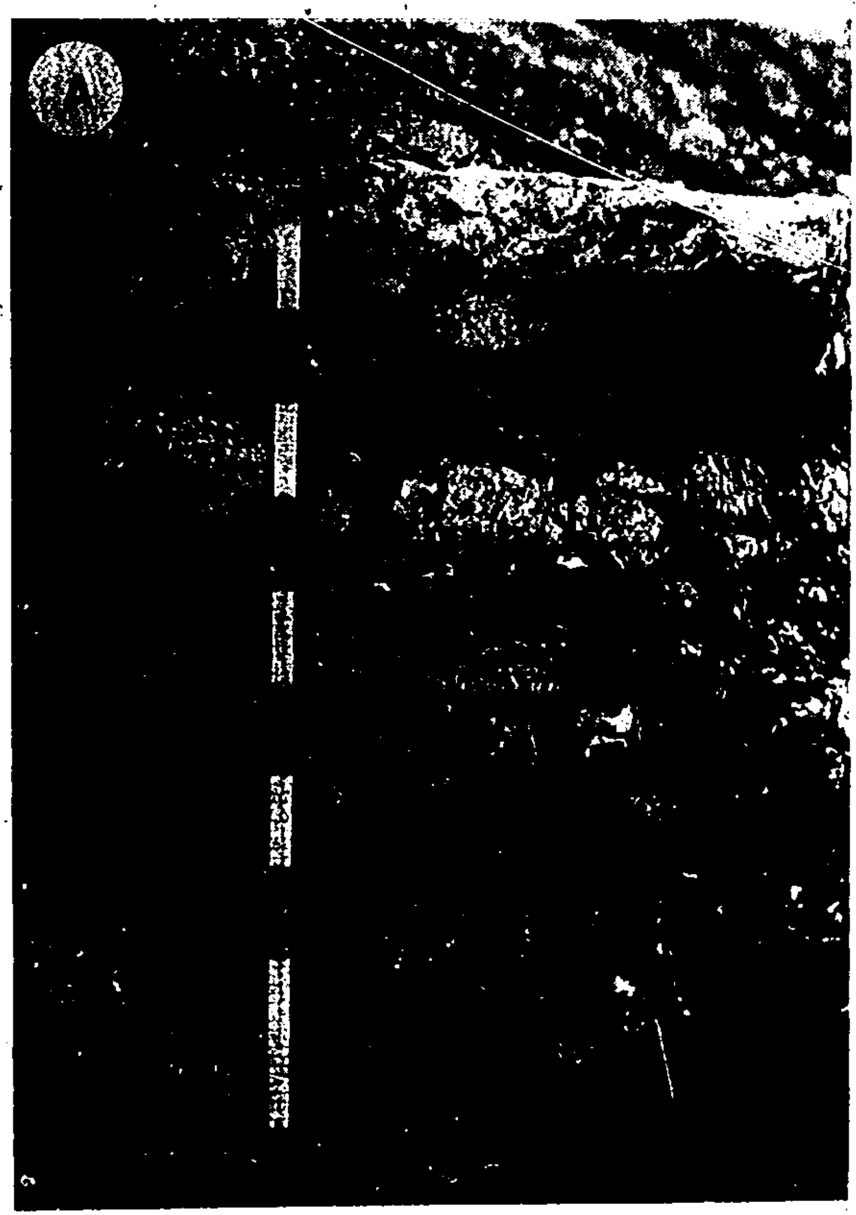

A
B
C

Plate 30

Examples 2 and 3: Lacustrine and marginal lacustrine deposits.

A) Example 2. Location: New Waterford section, interval 107–112 m (unit NW-17). Coarsening-upward 1.3 m thick lacustrine sequence of interstratified mudstone-packstone, algally laminated and horizontal stromatolite and marly claystone. Corresponding section is outlined in Fig. 22B. Scale is 1 m.

B) Example 3. Location: New Waterford section, interval 177–181 m. General coarsening-upward and thinning of beds in a marginal lacustrine sequence. Upward changes from predominantly horizontal stromatolitic beds (HS) to beds of domal stromatolite (DS) with increasing oncolite (O) content upward. Corresponding section is outlined in Fig. 22C. Scale is 1 m.



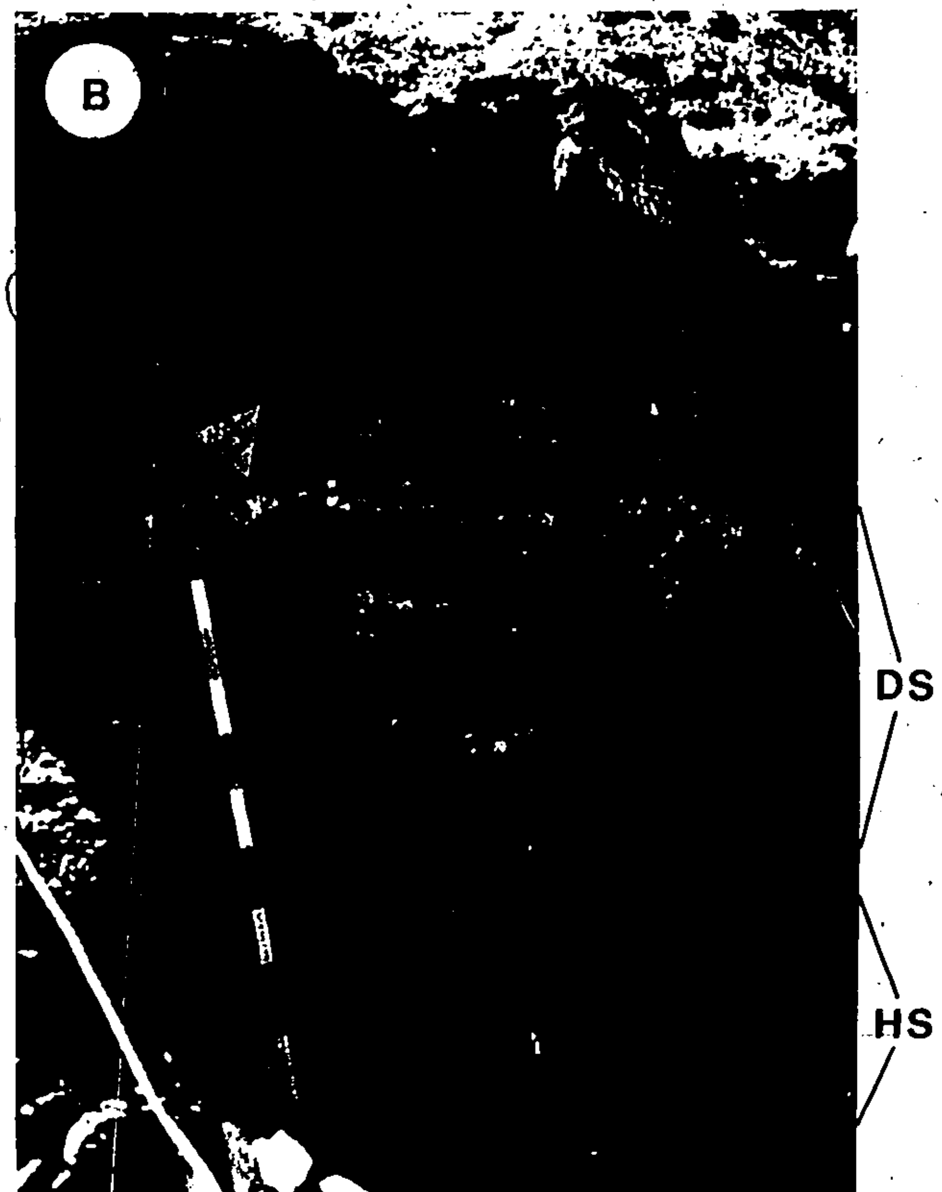

B
DS
HS

Plate 31.

Example 4: Lacustrine delta deposit. Location: New Waterford section, interval 185-191 m. Coarsening-upward sequence exhibiting transition from lacustrine sedimentation (A) upward into a small-scale lacustrine deltafill (B). Limestone bed in upper part of (A) is same bed as the one in lower part of (B). Scale in (A) and (B) is 1 m.


A

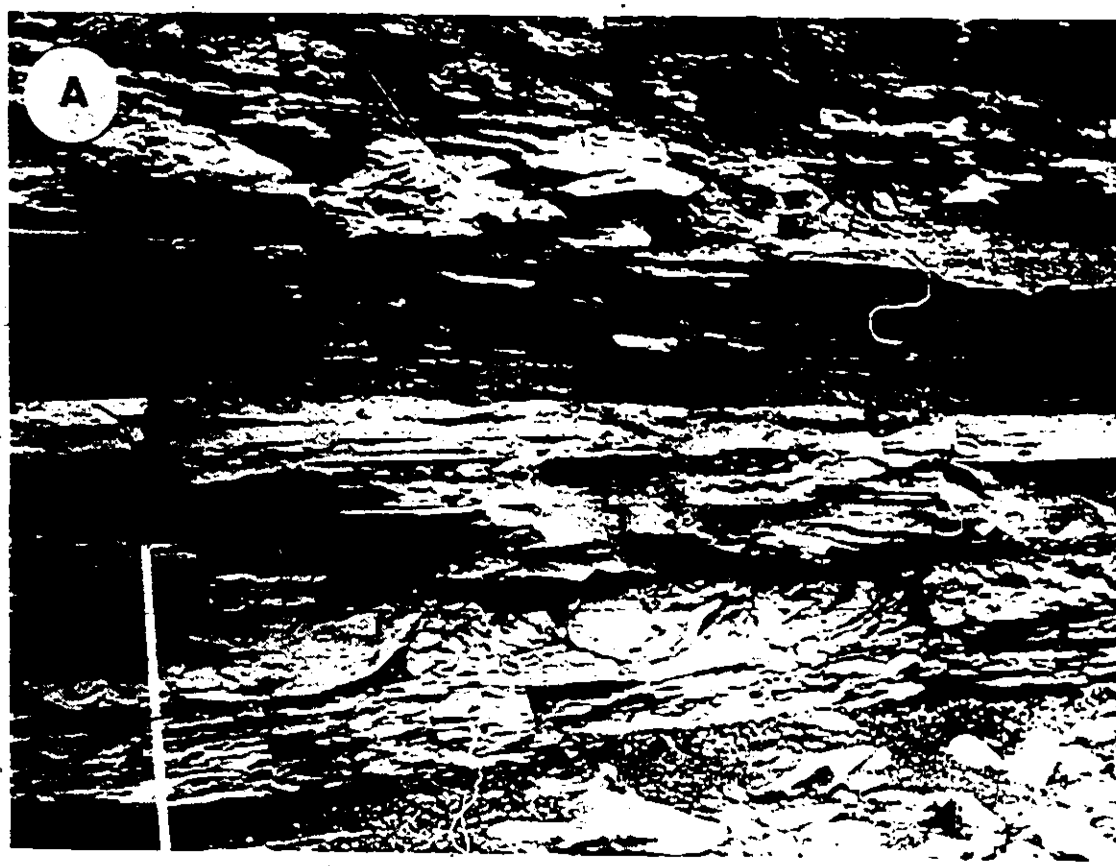

B

Plate 32

Example 5: Lacustrine splay deposit. Location: Glace Bay West section, interval 176-183 m.

A) Contorted bedding (ruler at 179 m) within interstratified lacustrine splay sequence. Scale 1 m.

B) Desiccation cracks laterally equivalent to the sequence in (A). Scale: 10 cm units.


A


B

Plate 33

Lacustrine floodplain and swamp deposits

A) Thin coarsening-upward limestone deposit overlying coal/carbonaceous shale unit. Location: Donkin East section, interval 123-125 m. Coal seam is located at 123.5 m. Scale is 1 m.

B) Close-up of the complex interlaminations of several lithofacies characteristic of these deposits. Location: Glace Bay West section, interval 66-68 m. Unit shown is located at 65 m. Scale in cm.

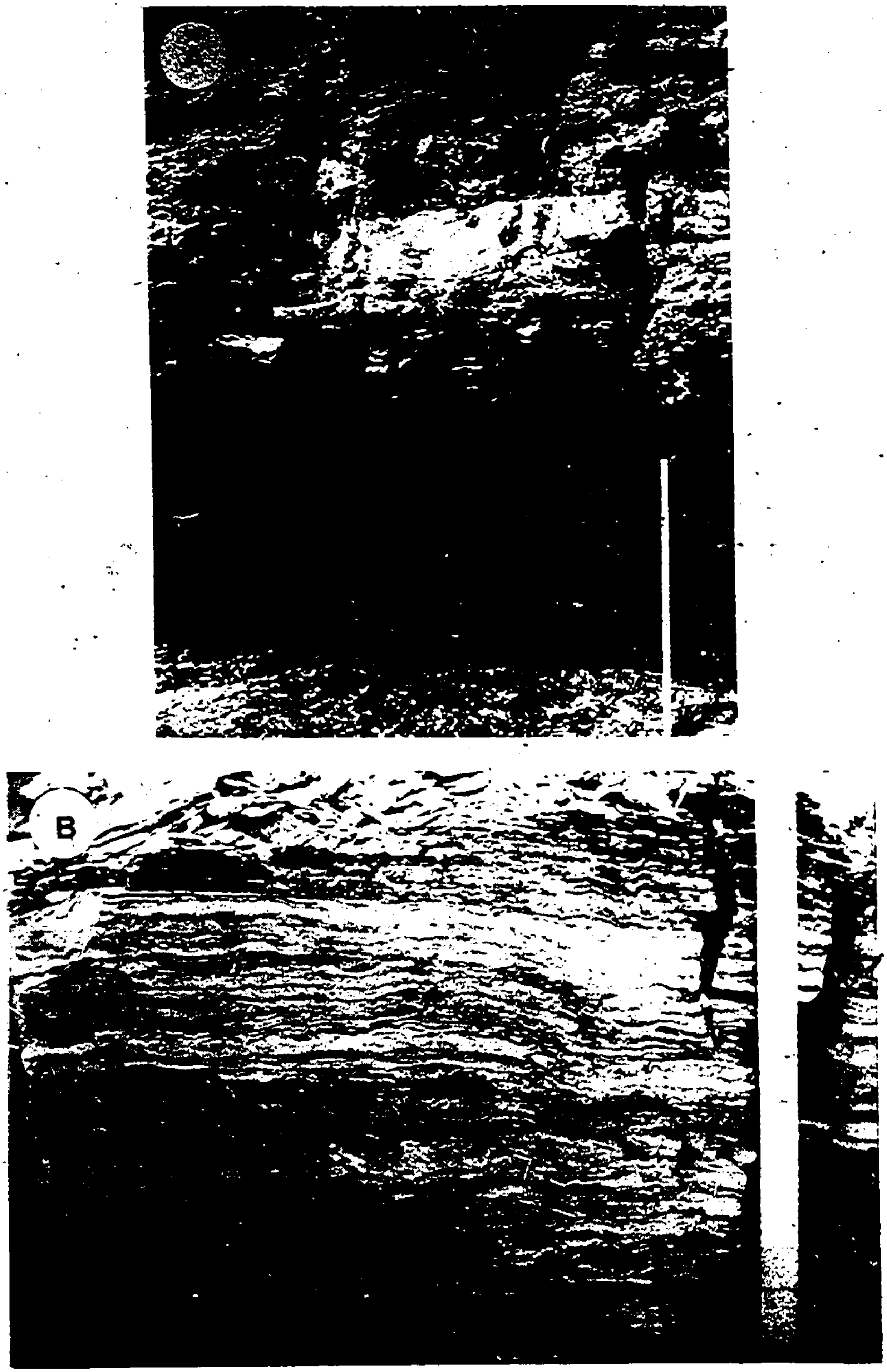

B

Plate 34

Carbonate diagenesis: horizontally algal-laminated and stromatolitic limestones

A) Distinctly banded, gently wavy laminated light layers composed of sparitized calcite separated by dark micritic filaments a few micrometers thick. Location: Victoria Mines section, interval 2-3 m. Scale: total thickness of the three light layers and filaments is 1.5 mm.

B) Distinctly banded, slightly curved horizontally laminated light layers composed of neomorphosed faint radial fibrous calcite separated by dark micritic filaments a few micrometers thick. Location: Victoria Mines section, interval 2-3 m. Scale: total thickness of the three light layers and filaments is 1.7 mm.

C) and D) Close-up of algal fragment of Garwoodia-Mitcheldeania complex at the base of a domal structure.
Location: New Waterford section, interval 174-183 m. Scale bar in (D) is 0.1 mm; different magnification for each microphotograph.

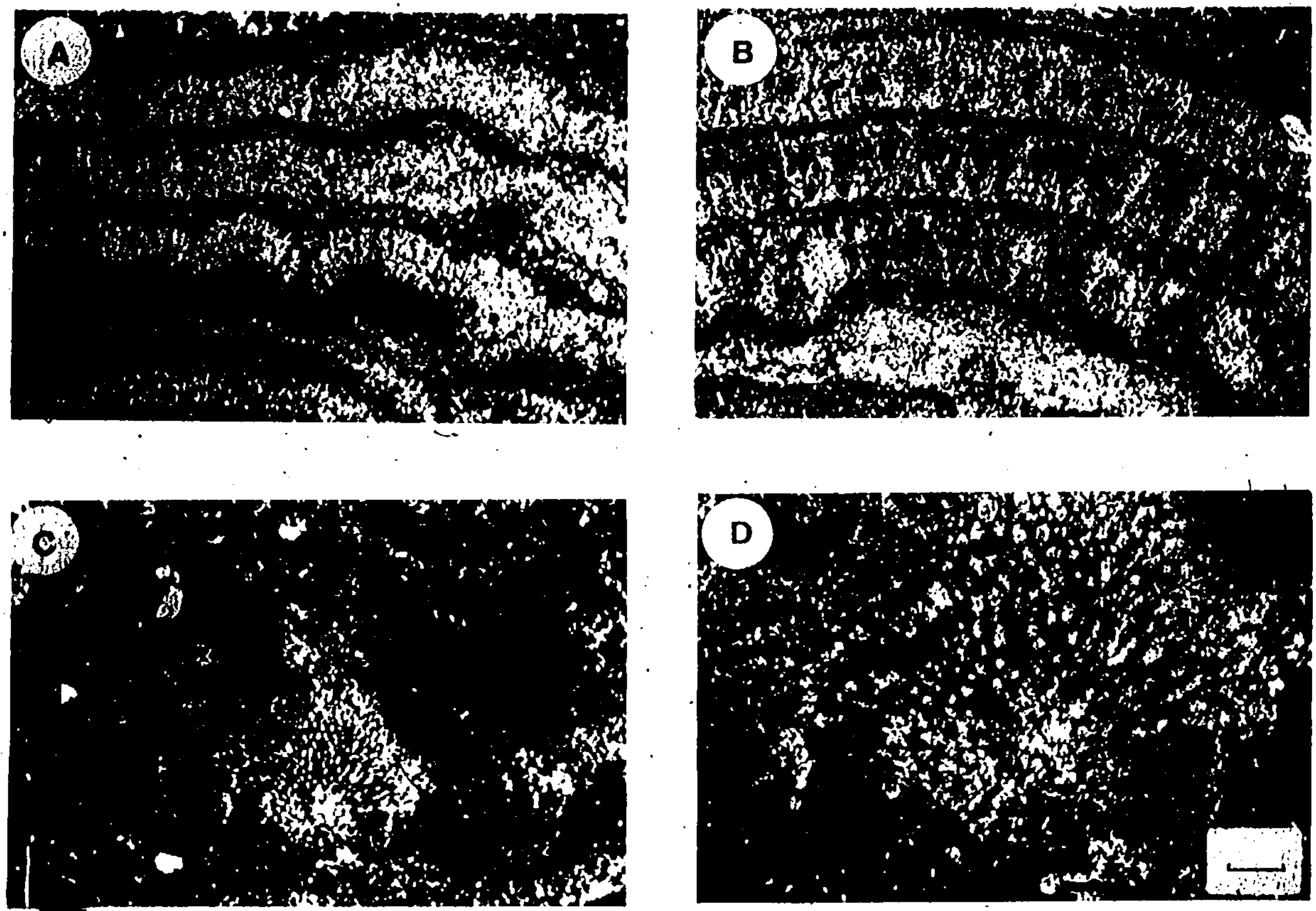

A
B
C
D

Plate 35

Carbonate diagenesis: domal stromatolites and oncolitic limestones.

Location: New Waterford section, interval 174-183 m.

A) Columnar internal structure of laminae in which the principal convexities are in the growth direction and exhibiting sparitization of laminae within the domes and of open-space structure at the base of the dome. Grains at the base of dome are pellets, pelloids and lithic fragments. Scale: total height of dome is 1.5 mm.

B) Closely spaced internal structure laterally linking the columnar structures. Scale: interdomal connection is 0.2 mm wide.

C) Sparry calcite cementation of interdomal cavity fill. Fragments are skeletal debris, pellets, pelloids and lithic grains. Scale: large skeletal fragment is 0.3 mm wide.

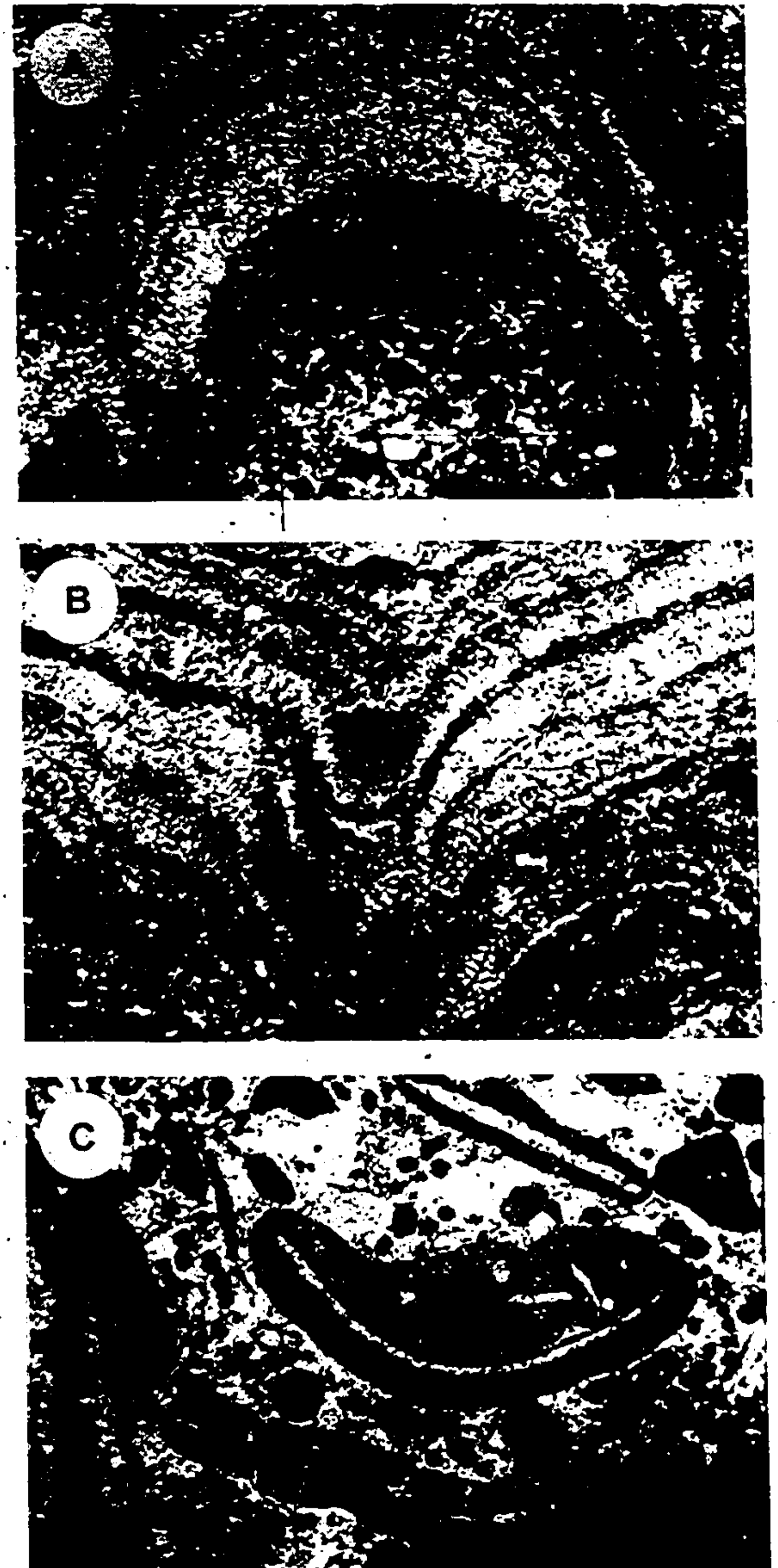

B
C

Plate 36

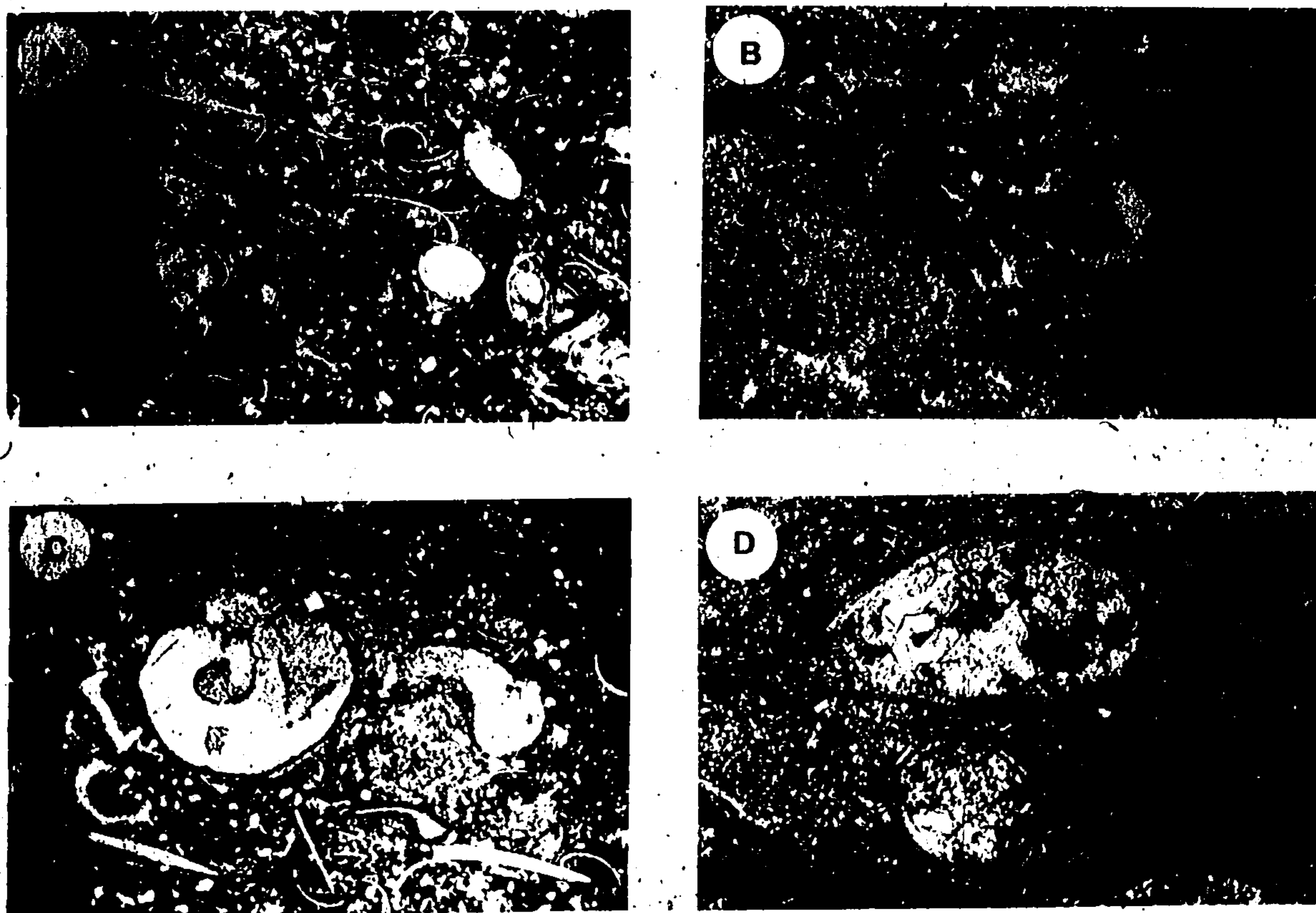
Carbonate diagenesis: mudstone to packstone subfacies. Location: New Waterford, interval 108-110 m.

A) Poorly defined laminae from mudstone-packstone subfacies. Scale: maximum dimension of cement-filled ostracod shell is 0.3 mm.

B) Bioturbated/pelleted mudstone with interparticle microcrystalline silica cement. Magnification as in (A).

C) Interlaminated skeletal wackestone (upper dark layer) to packstone (lower two-thirds of photo). Fossils present include broken ostracod, thin-shelled gastropod, Spirorbis tube and fish scale. Scale: largest fossil fragment is 0.4 mm wide.

D) Skeletal packstone ("ostracodite") exhibiting compaction and deformation of shells and XF-F granular calcite intraskeletal cement. Organic debris and hematitic staining of partially recrystallised micrite is present. Scale: horizontal width of largest ostracod shell is 0.6 mm.


B
D

APPENDIX A

Detailed stratigraphic columns from measured sections

LEGEND - APPENDICES A & B

LITHOLOGY

- Minor Coal
- Calcareous or Calcareous cemented
- Algal Laminite / Stromatolite
- Main Coal Seams

GRAIN SIZE SCALE

- C.S - Clay and Silt
- VF - Very Fine
- F - Fine SS
- M - Medium SS
- C - Coarse SS
- VC - Very Coarse SS
- G - Granular / Pebbly

SEAMS CODE

(Stratigraphic order)

E - Emery (btm)	Bo - Bouthillier
Ph - Phalen	Hbr - Harbour
Ba - Backpit	H - Hub (top)

BODIES

- Channel Abandonment
- R - Reddish
- Pedogenic Unit
- FU - Fining - Upward Sequence
- CU - Coarsening - Upward Sequence
- Extent of FU/CU

SECTIONS CODE

- VM - Victoria Mines
- NW - New Waterford
- GBW - Glace Bay West
- GBE - Glace Bay East
- DW - Donkin West
- DE - Donkin East
- SH - Schooner Head
- MS - Morien South
- MN - Morien North

SEDIMENTARY STRUCTURES

- Ripples
- Climbing Ripples
- Planar Bedding / Epsilon X-Beds
- Trough X-Strat.
- Horizontal Stratification
- Deformed Bedding / Soft-Sediment Deformation
- Burrows / Bioturbation
- Desiccation Cracks
- Roots
- Upright Tree
- Logs / Tree Trunks

CORRELATIONS

Degrees of Confidence

- — — — Proven, walked out.
- — · — · — Likely, good match.
- · · · · · Inferred, presumed.

ACCESSORIES

- Coal Clast
- Lithic Clast
- Calcareous Clast
- Pedogenic Nodule
- Oncolites
- C - Shells / Clams
- F - Fish Fossils

OTHERS

- Paleocurrent Direction (ripples, troughs, channels)
- Primary Current Lineation (PCL)
- Covered Section

APP A FIG 1 VICTORIA MINES 120m

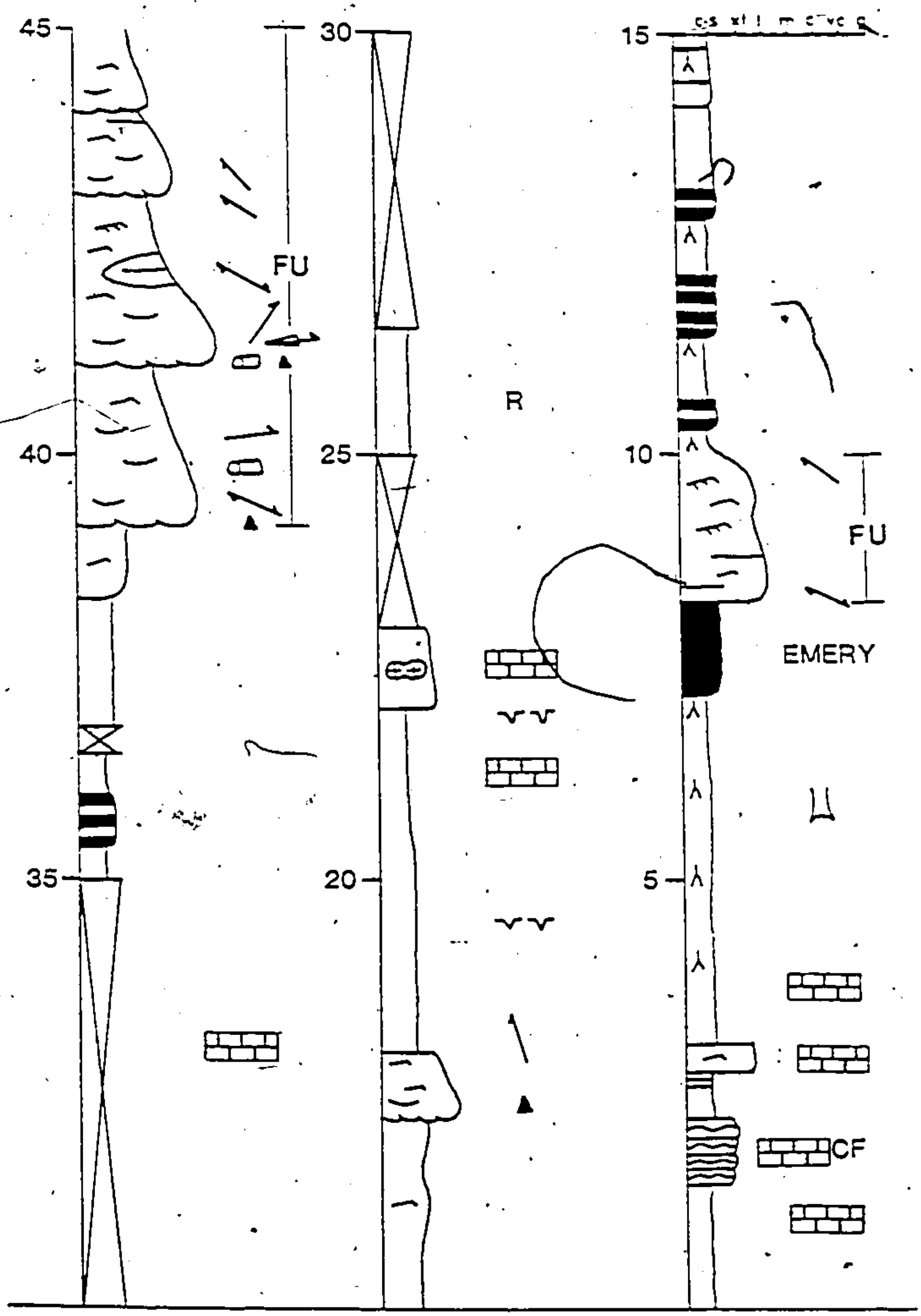


Fig 1

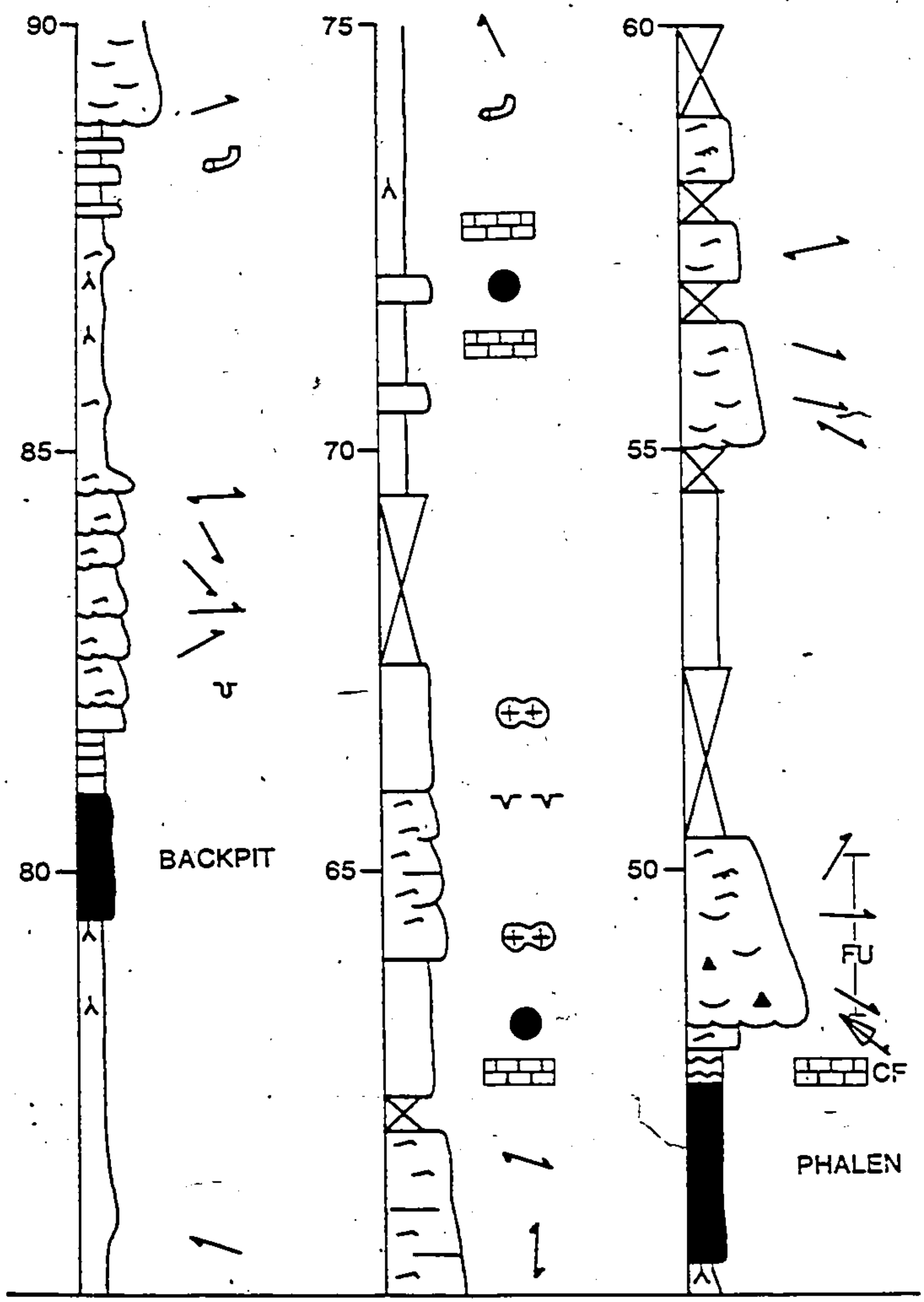
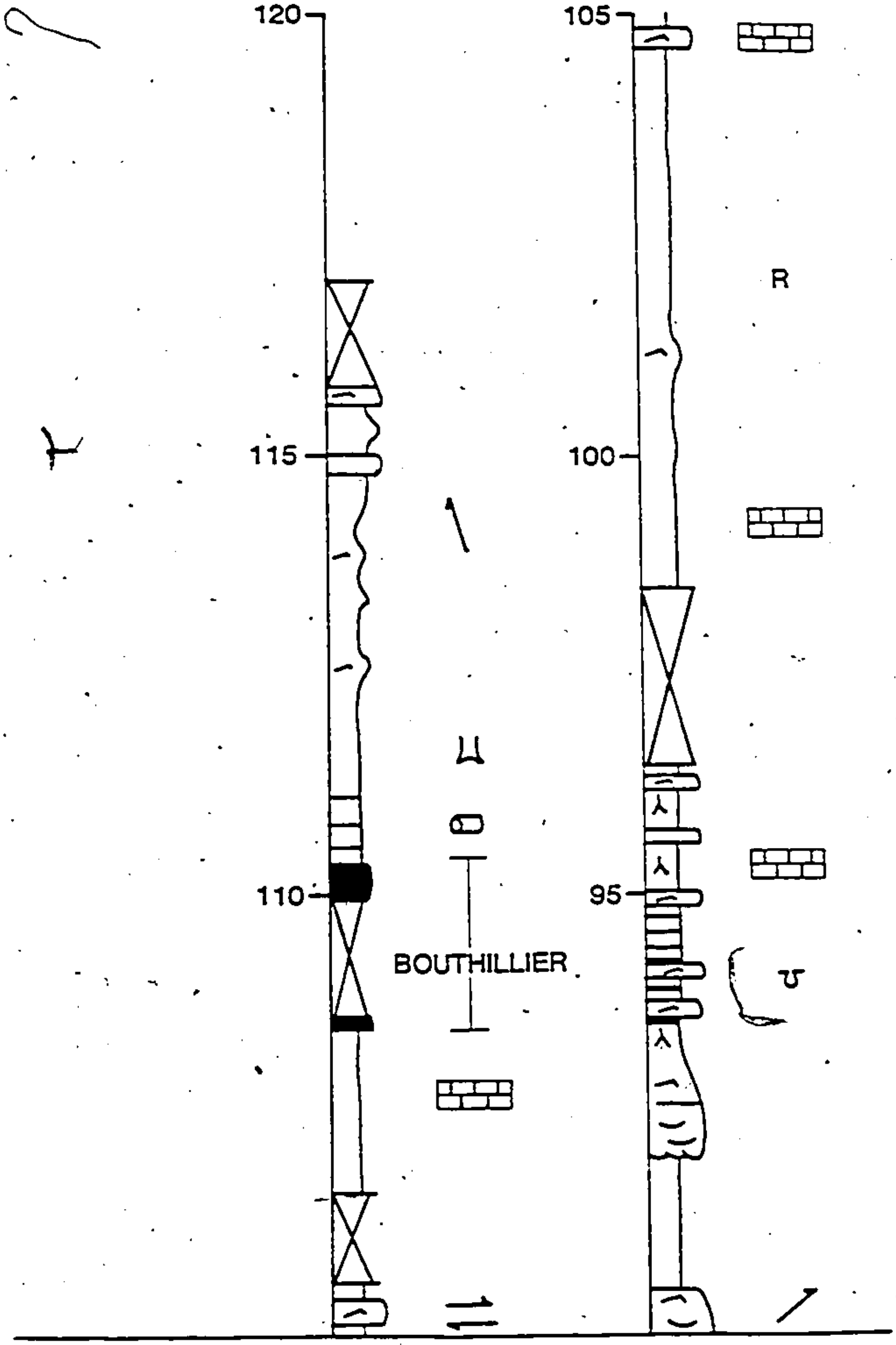


Fig 1



APP A Fig 2 NEW WATERFORD 285m

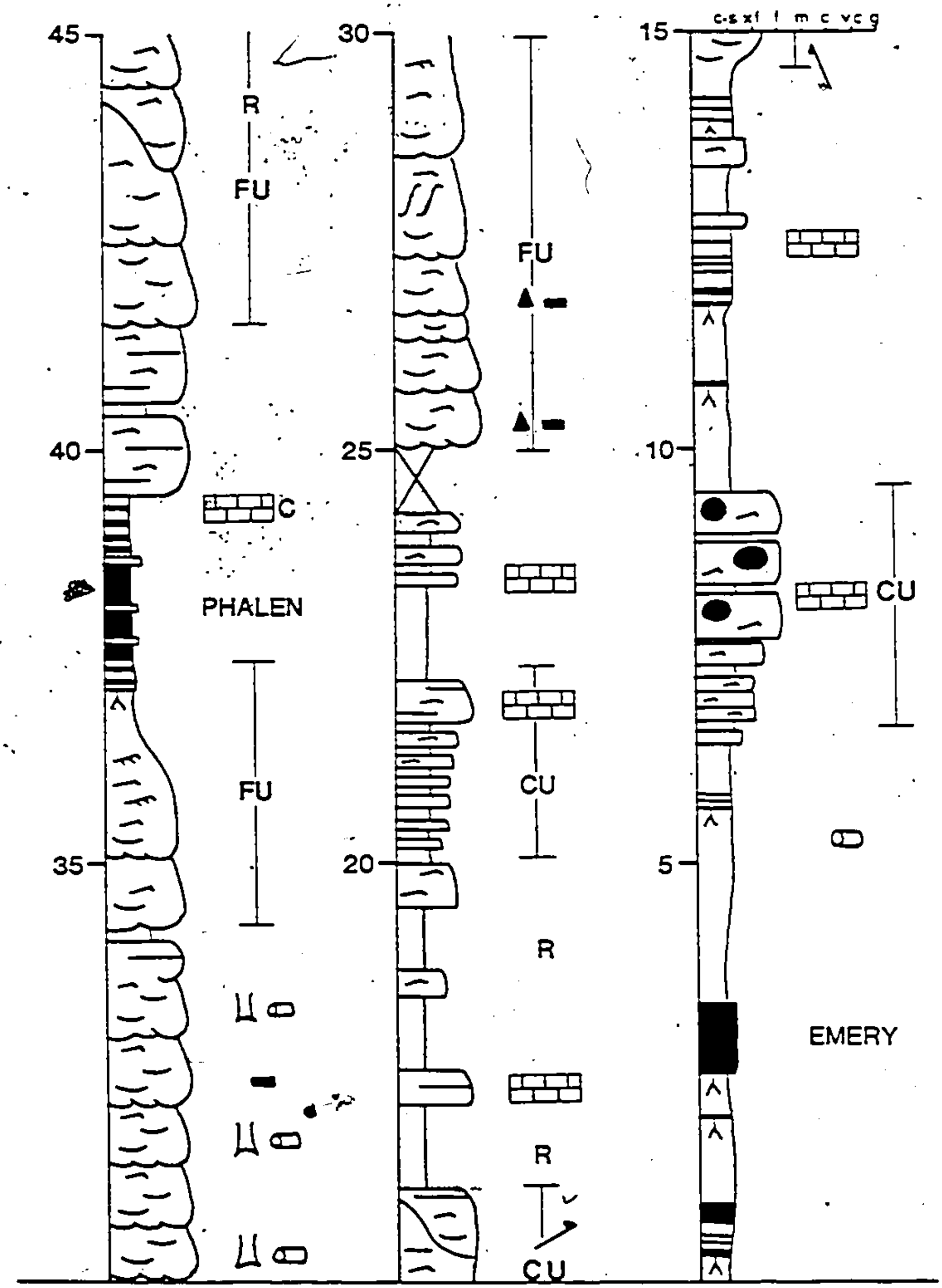


Fig 2

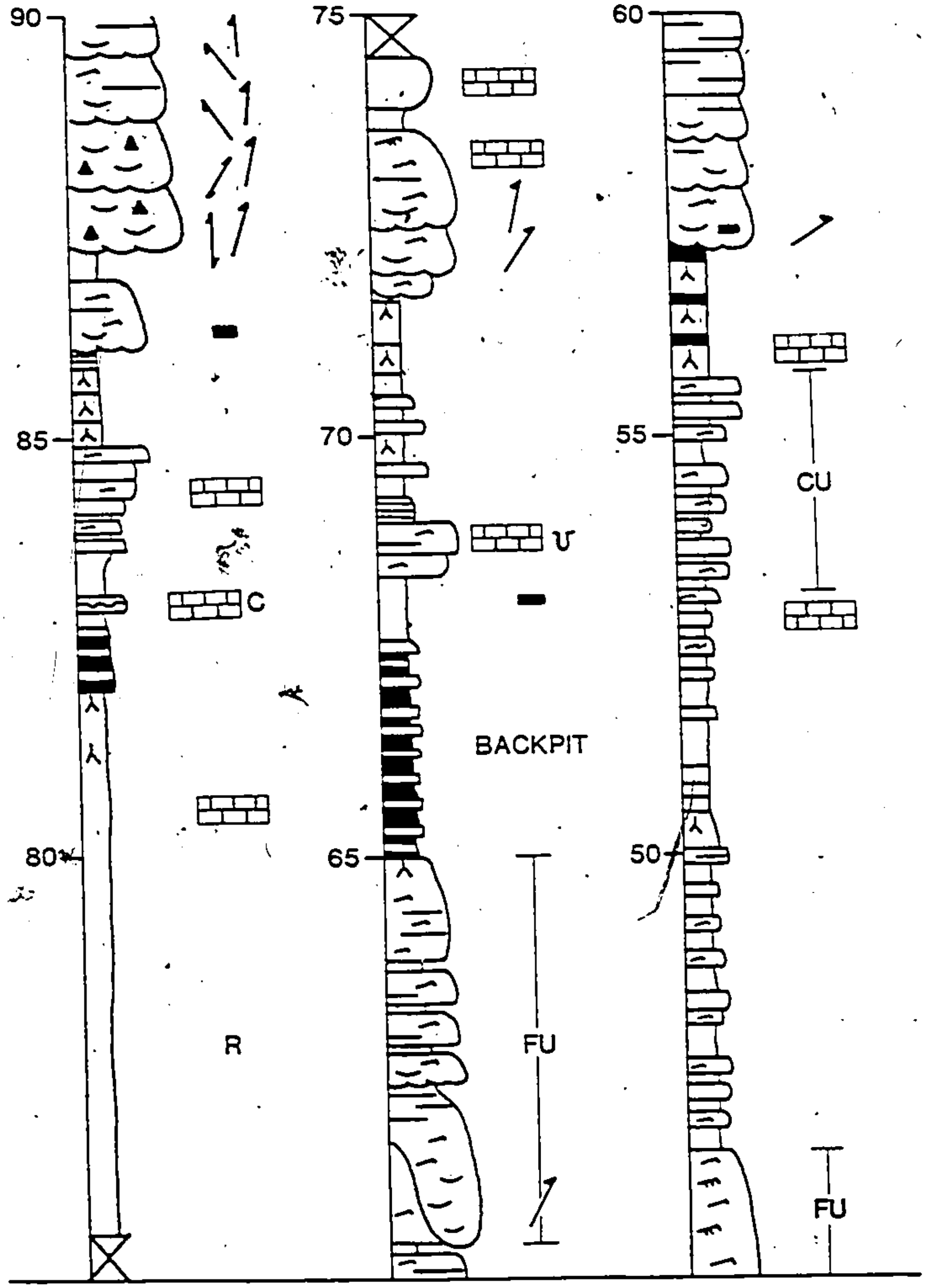


Fig 2

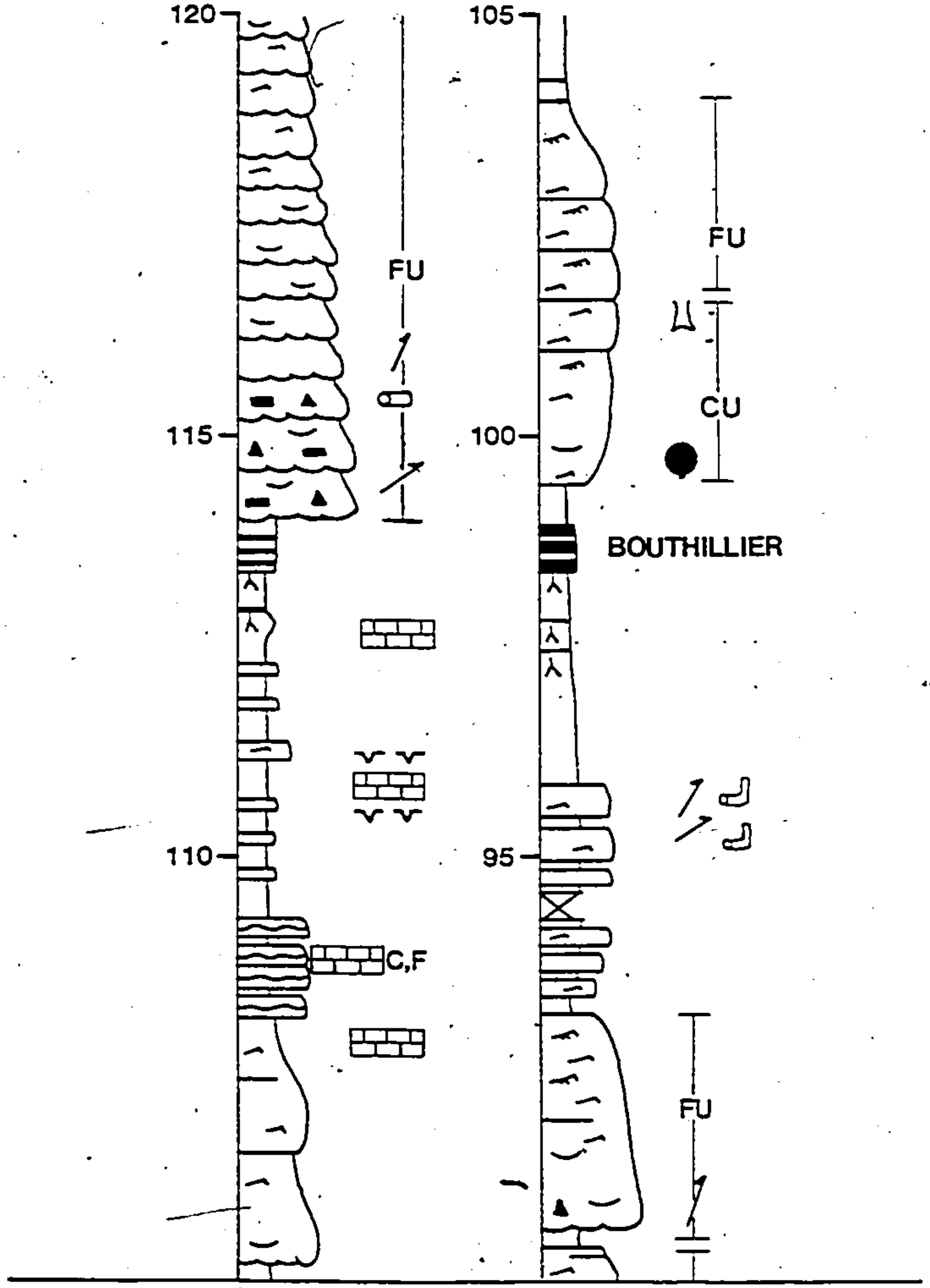


Fig 2

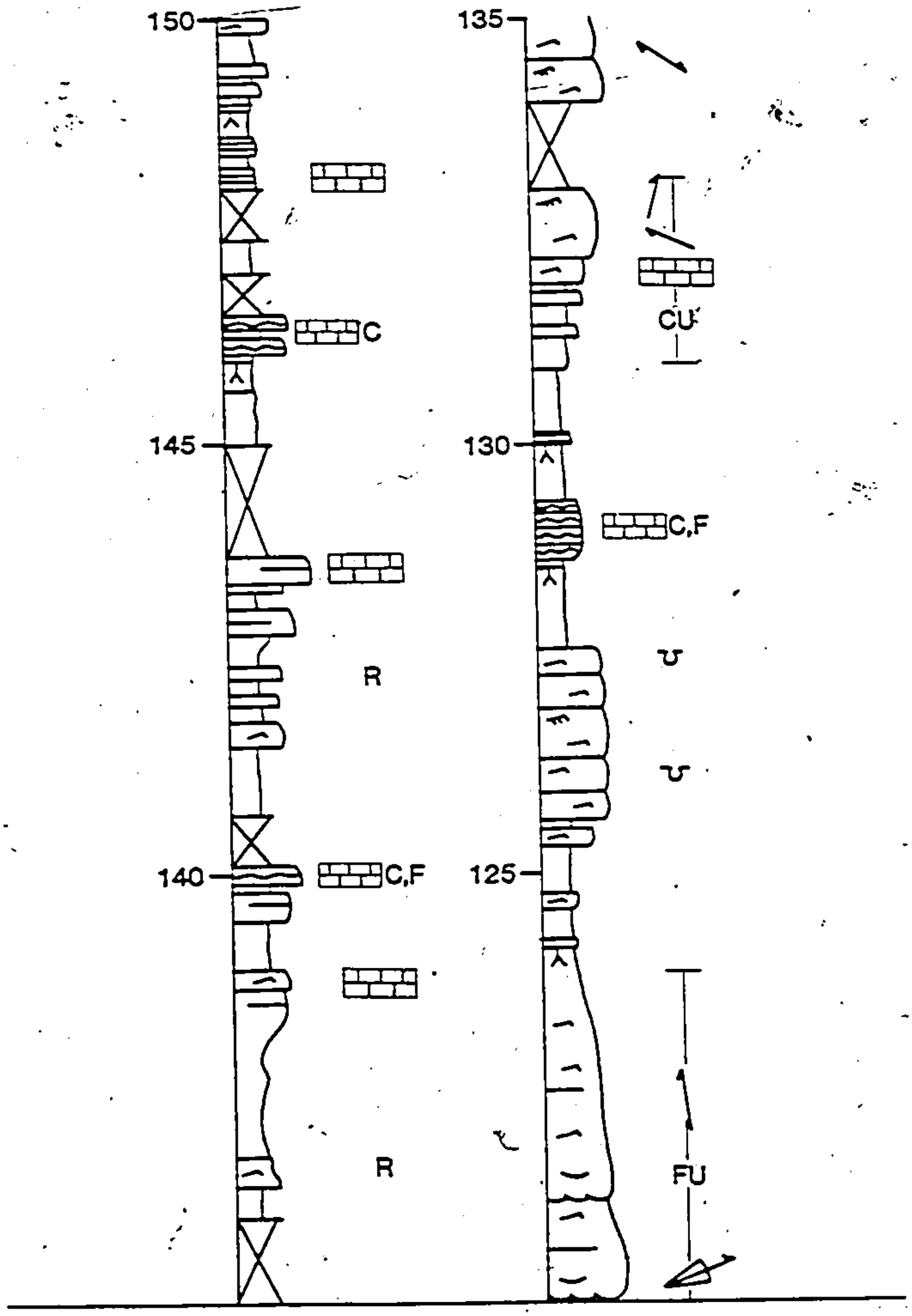


Fig 2

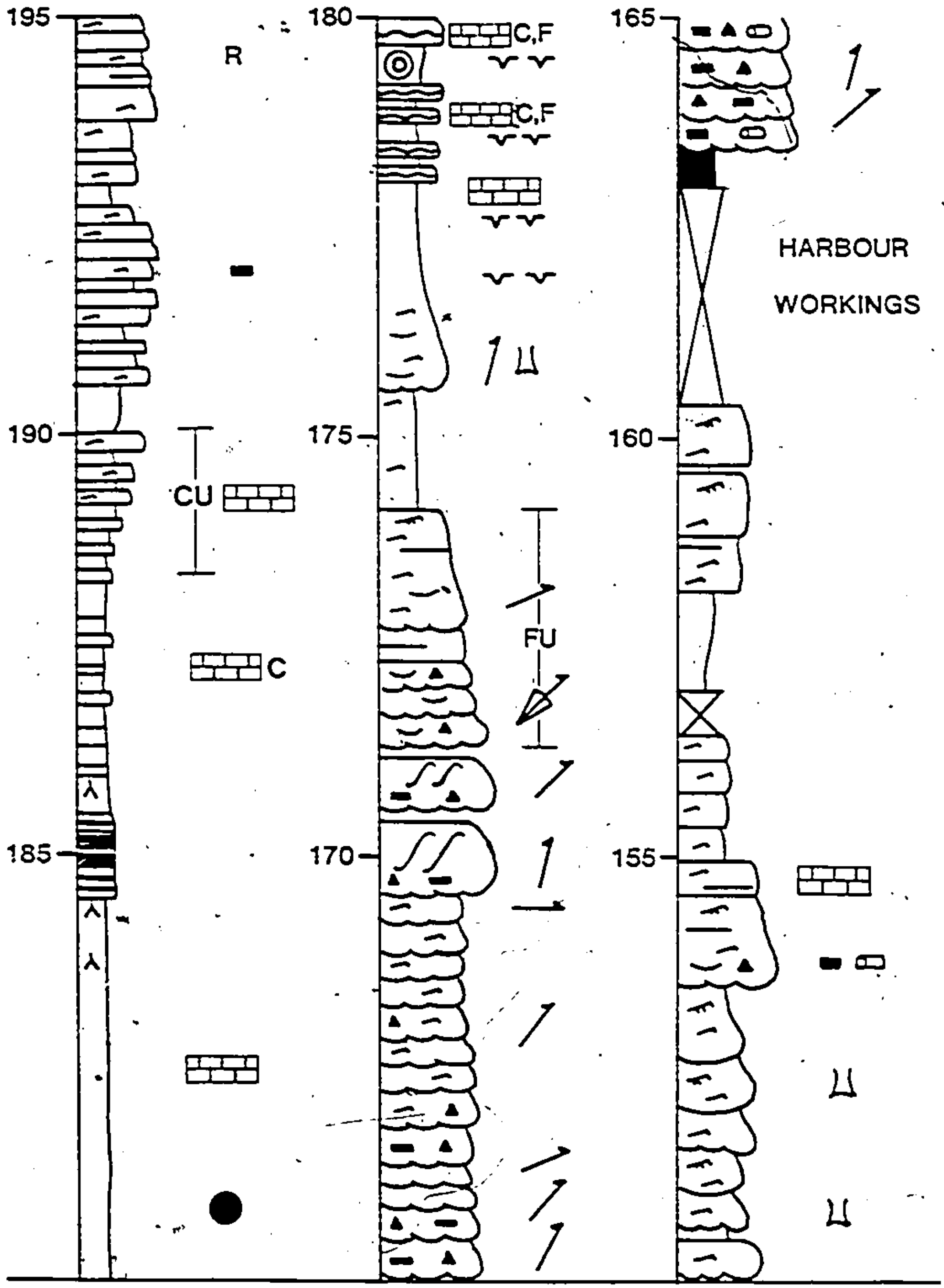

195
190
185
R
CU
C
180
175
170
C,F
C,F
FU
165
160
155
HARBOUR
WORKINGS

Fig 2

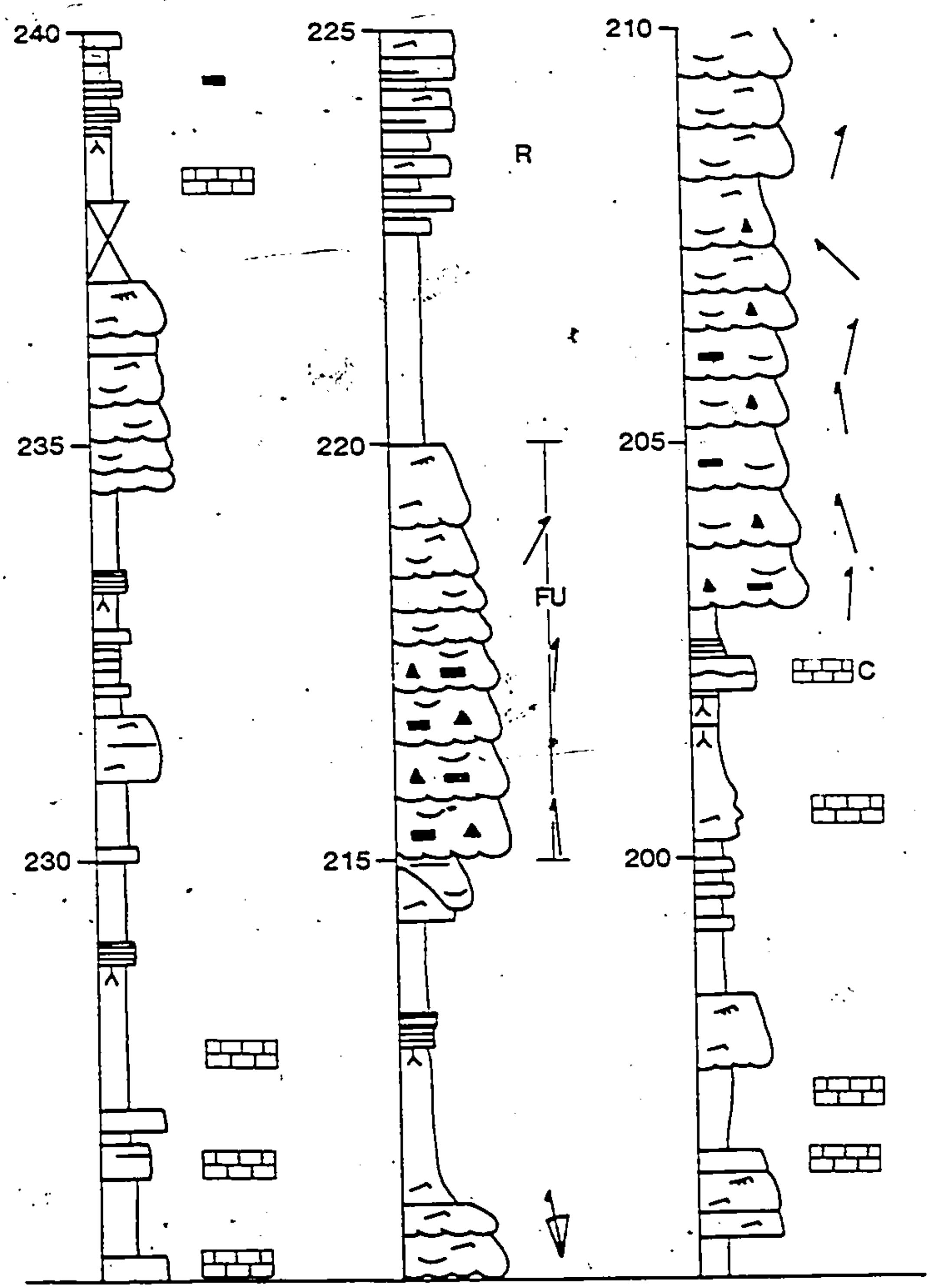
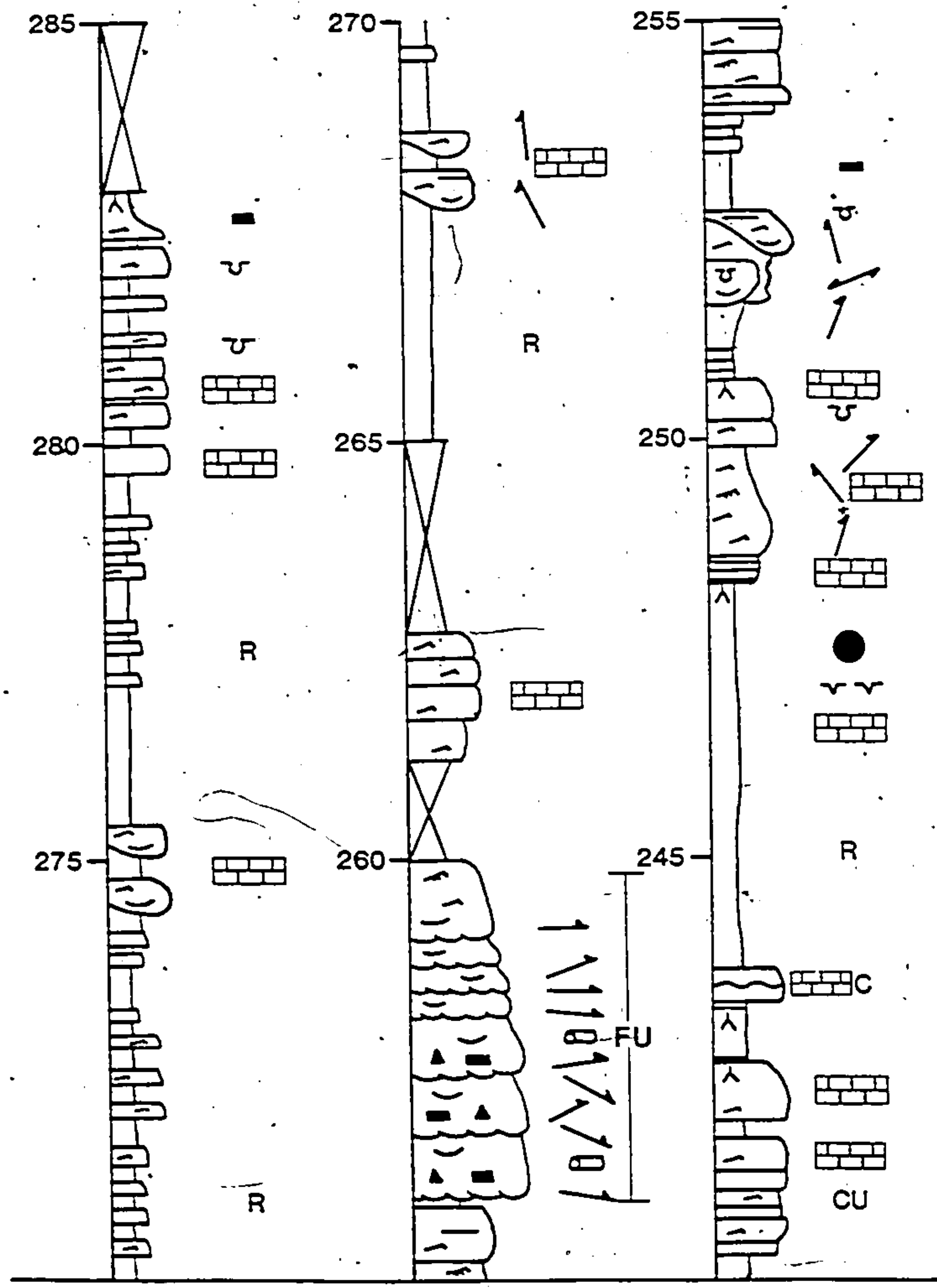


Fig 2



APP A FIG-3 GLACE BAY WEST 280m

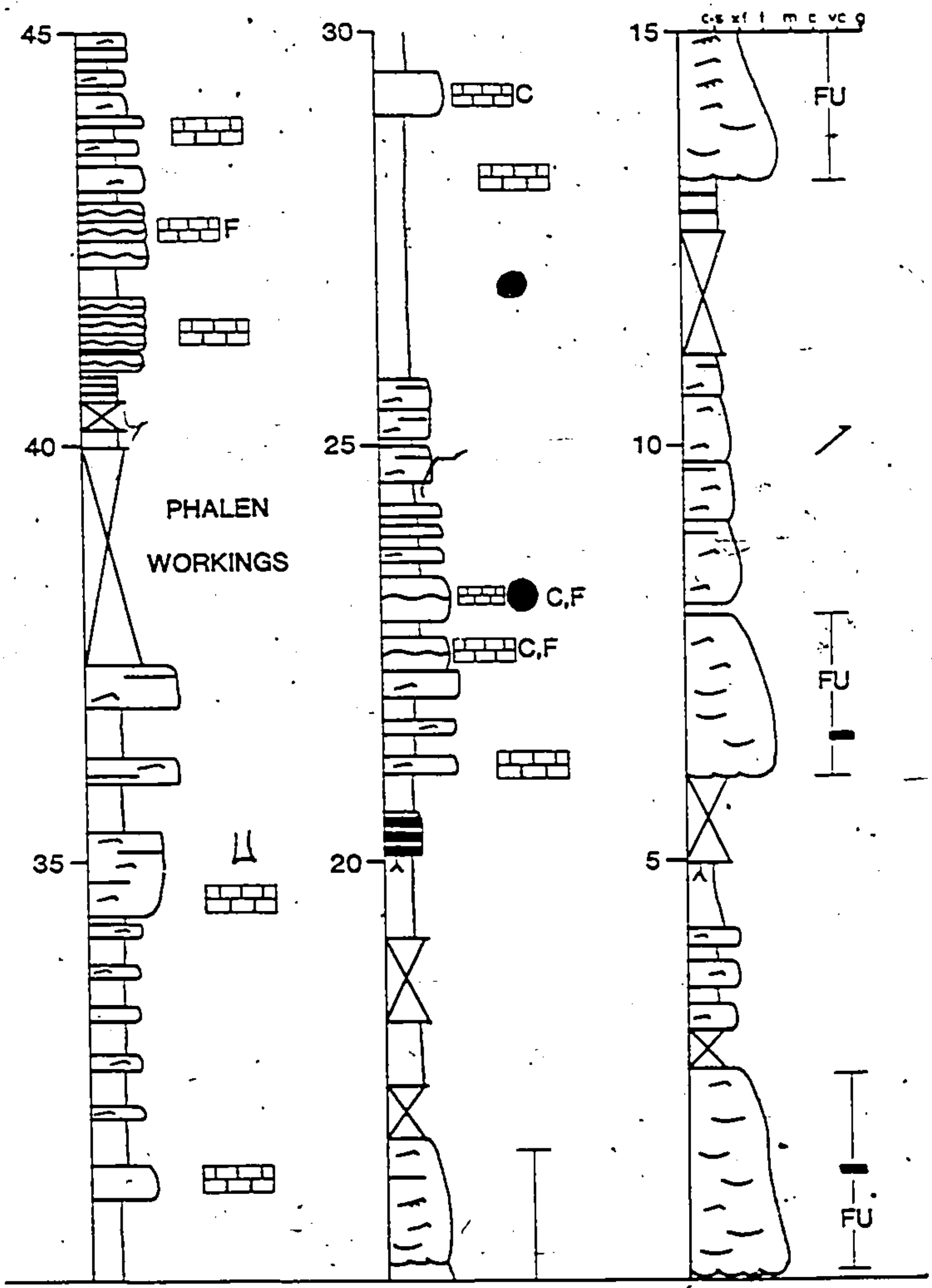


Fig 3

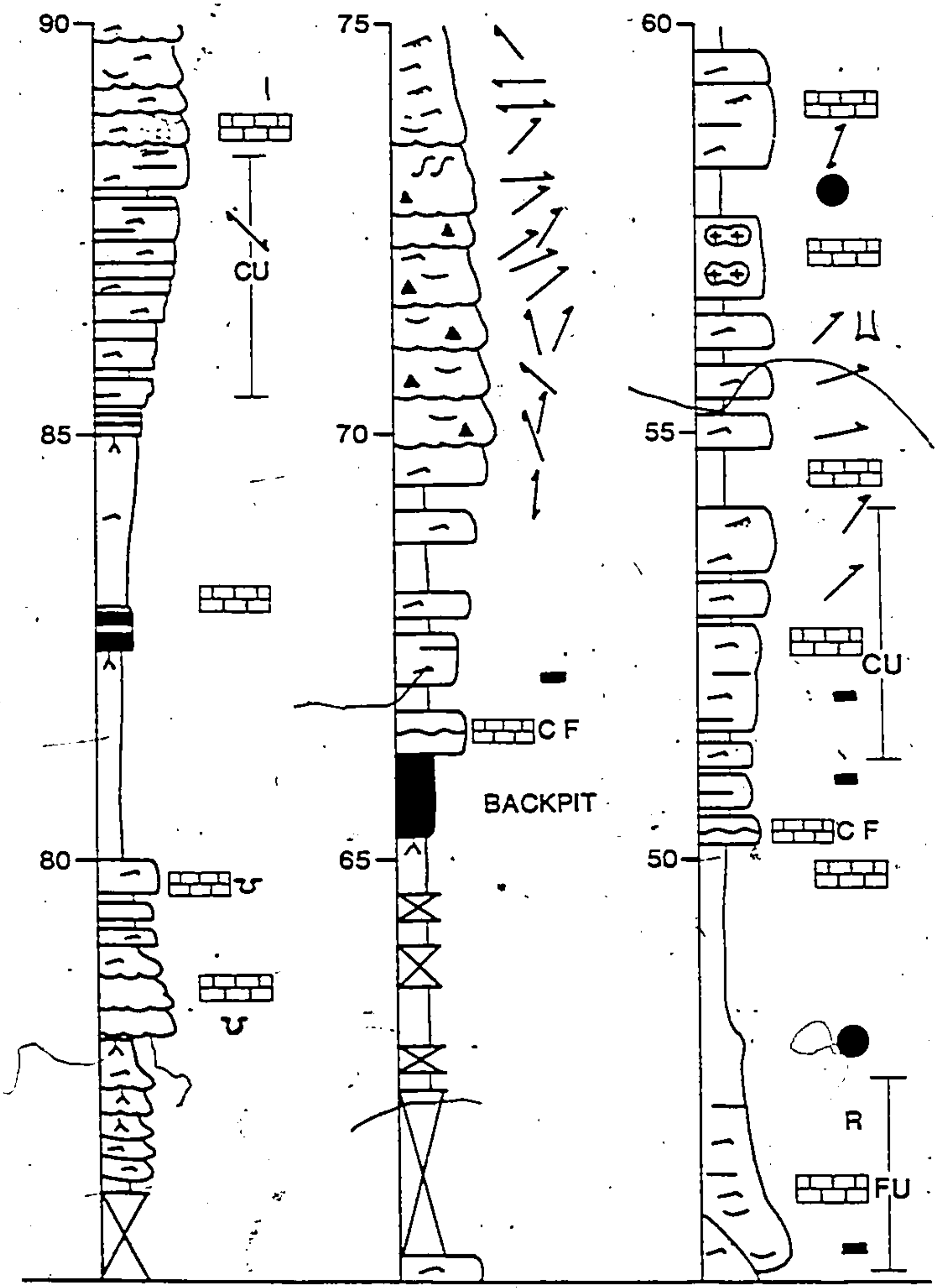


Fig 3

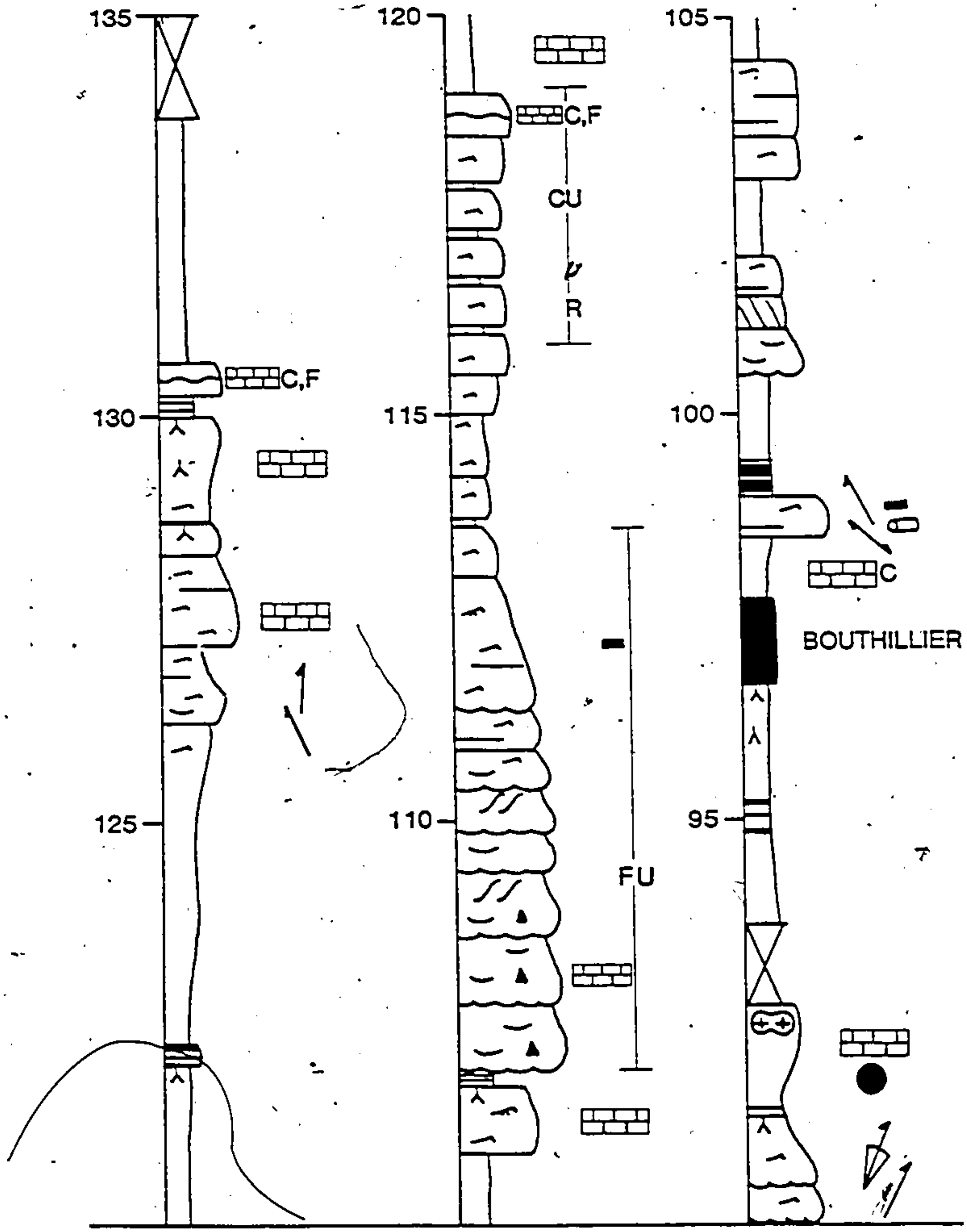


Fig 3

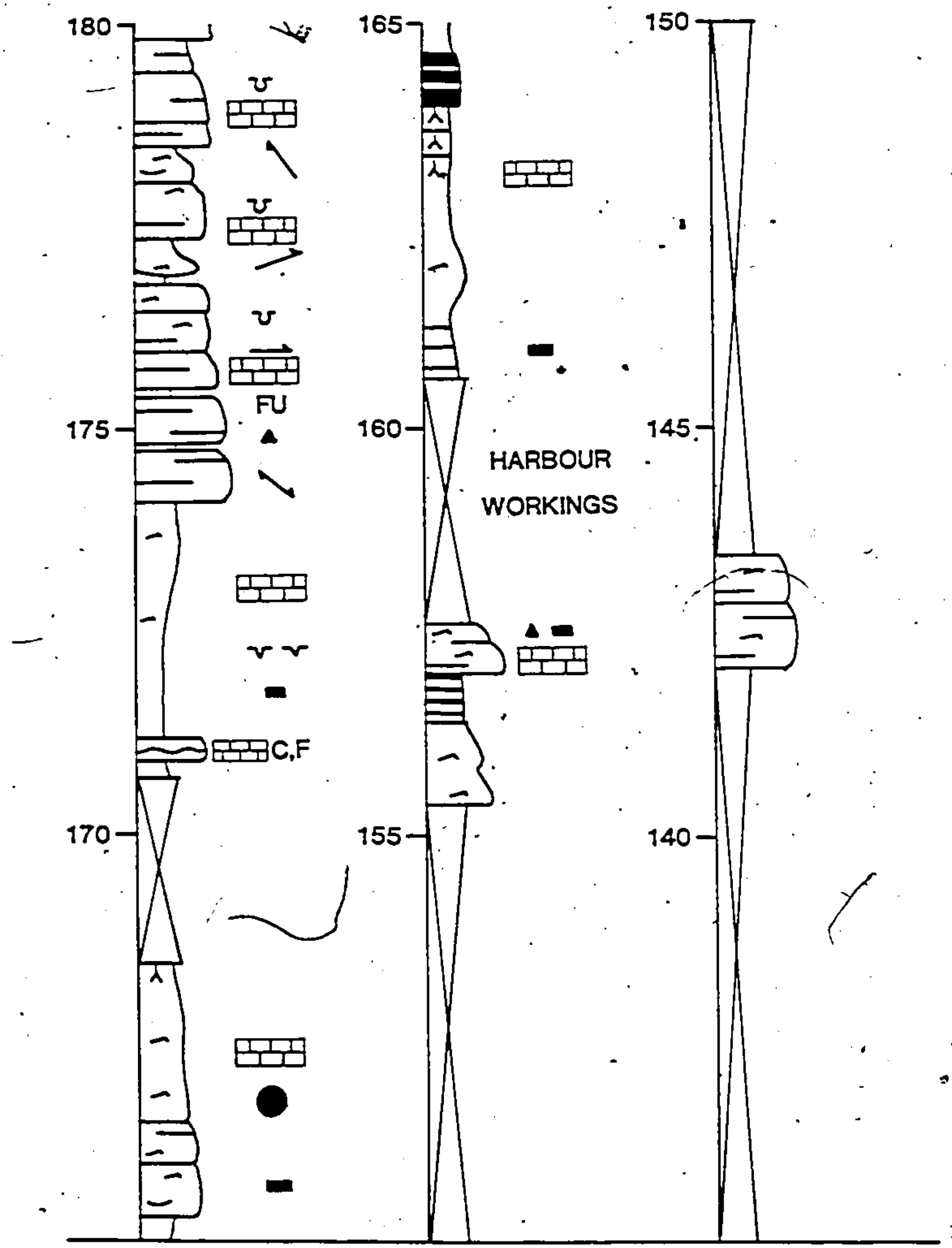


Fig 3

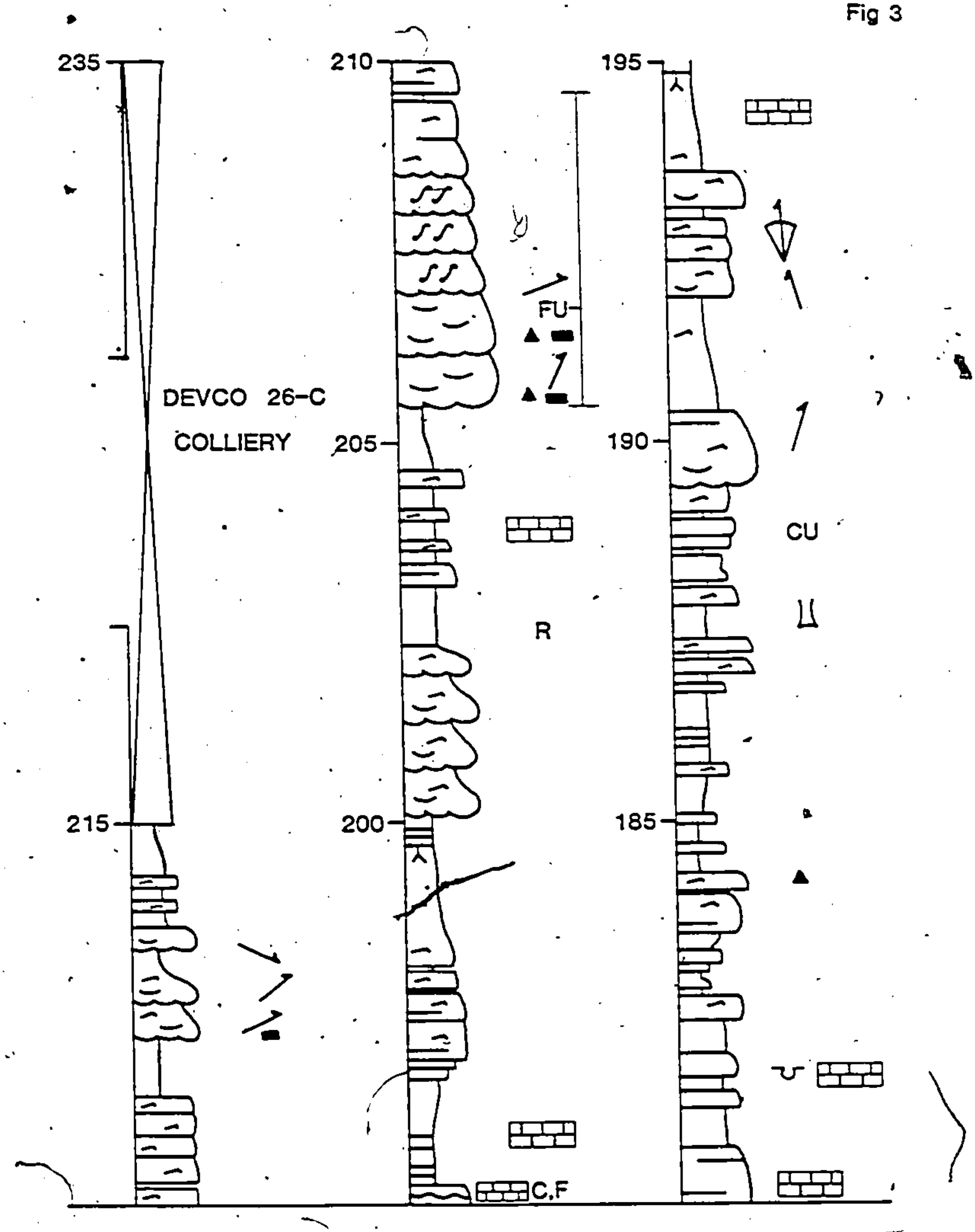
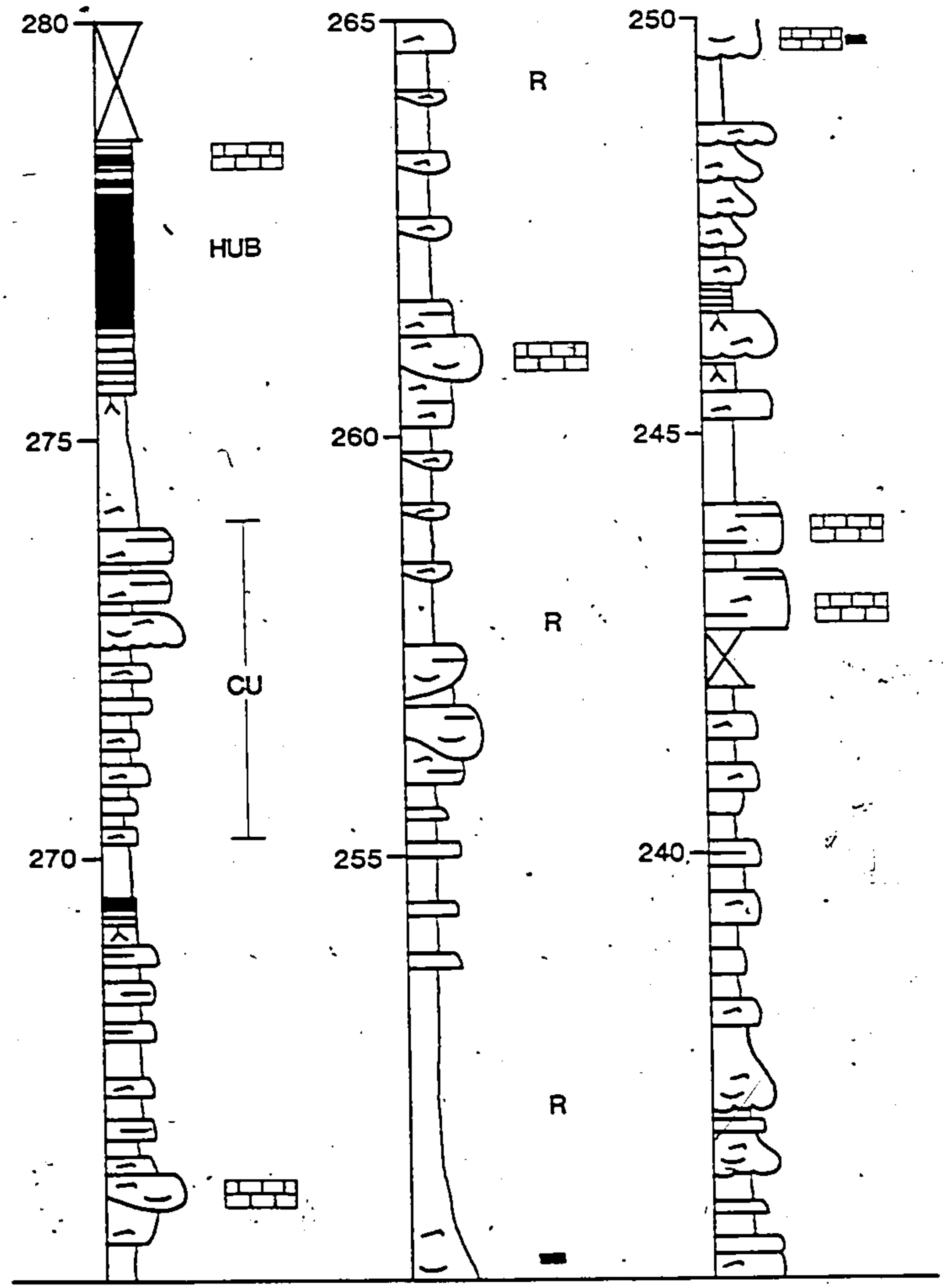


Fig 3



APP A FIG 4 GLACE BAY EAST 210m

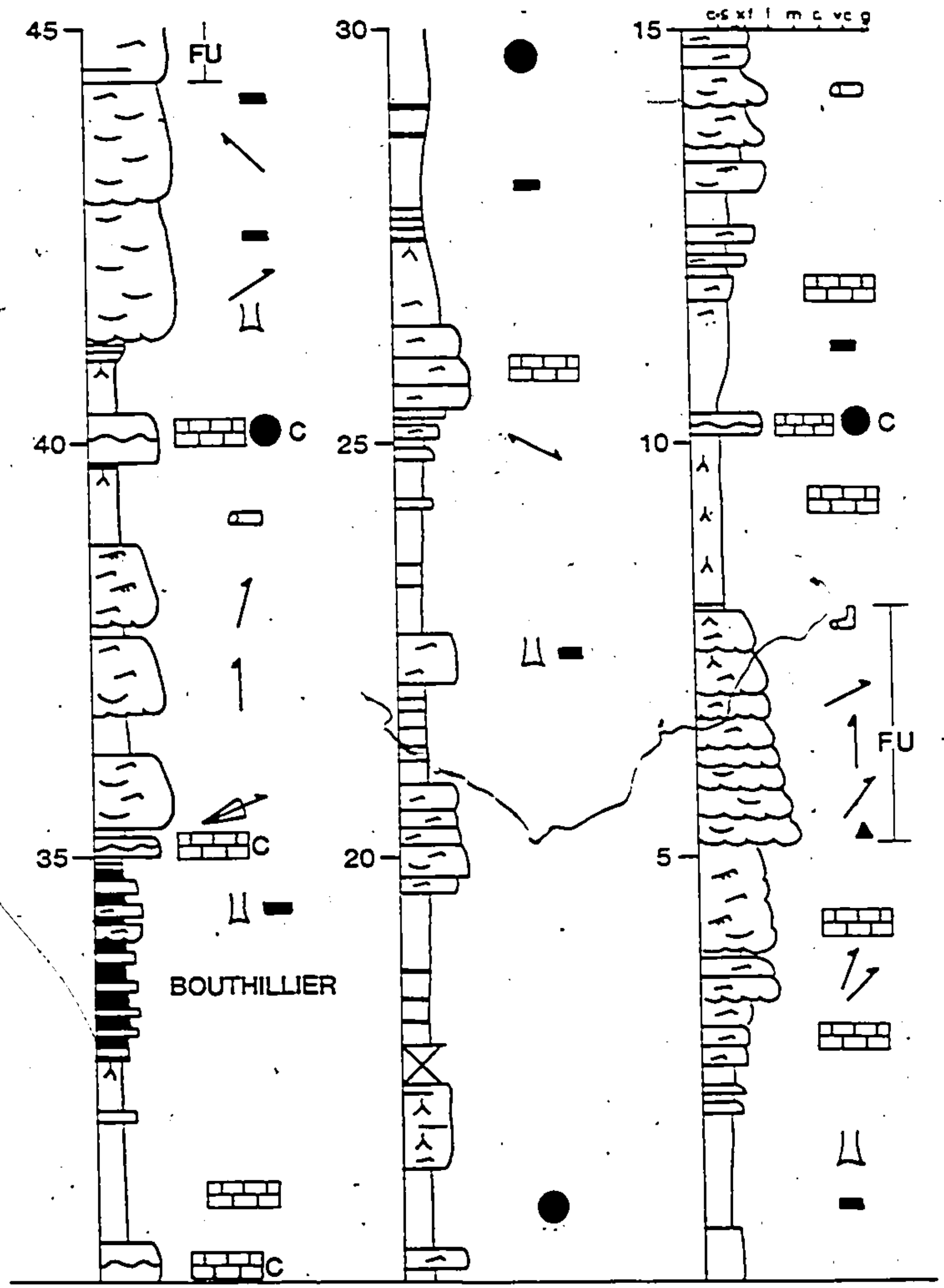


Fig 4

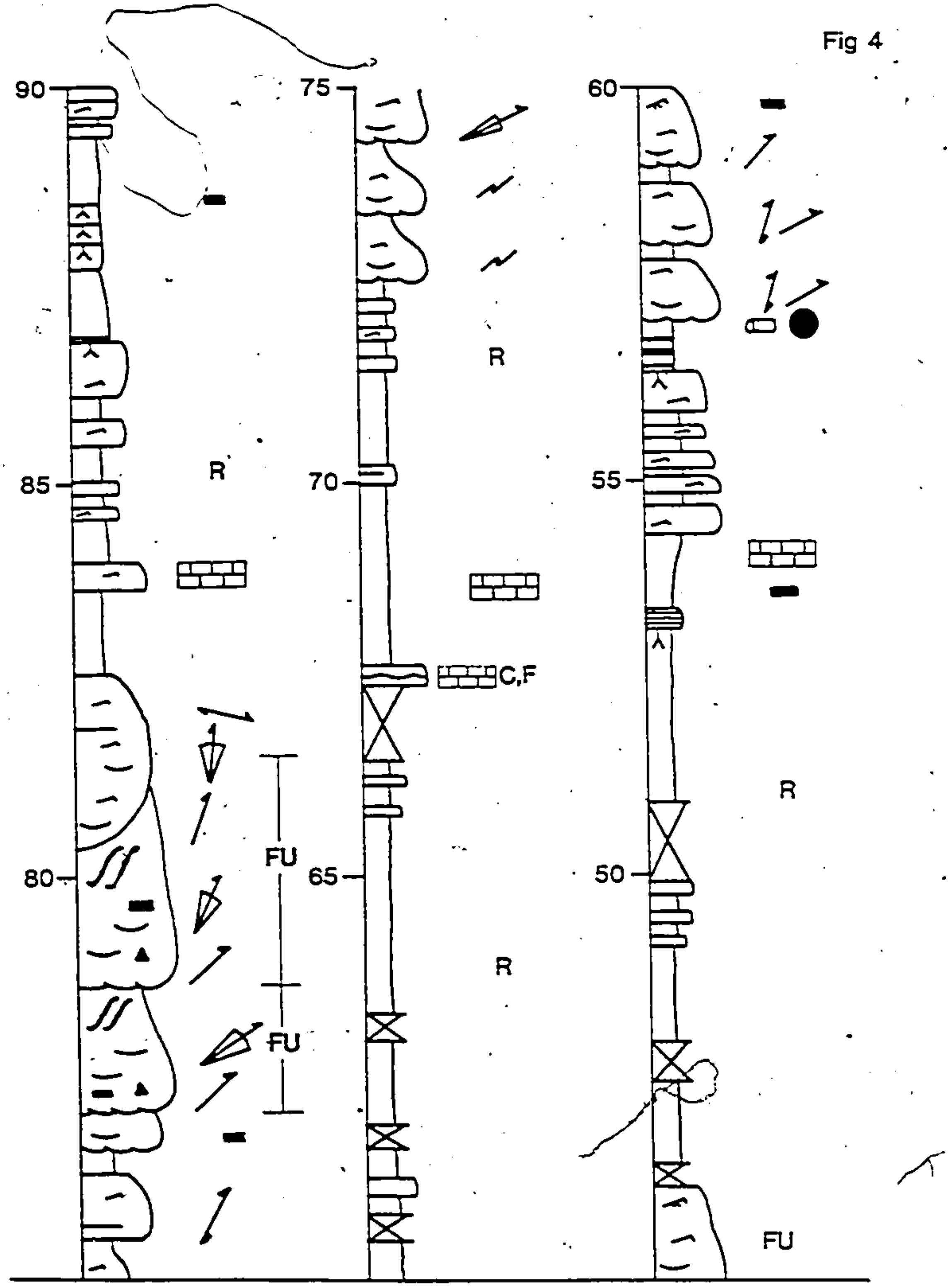


Fig 4

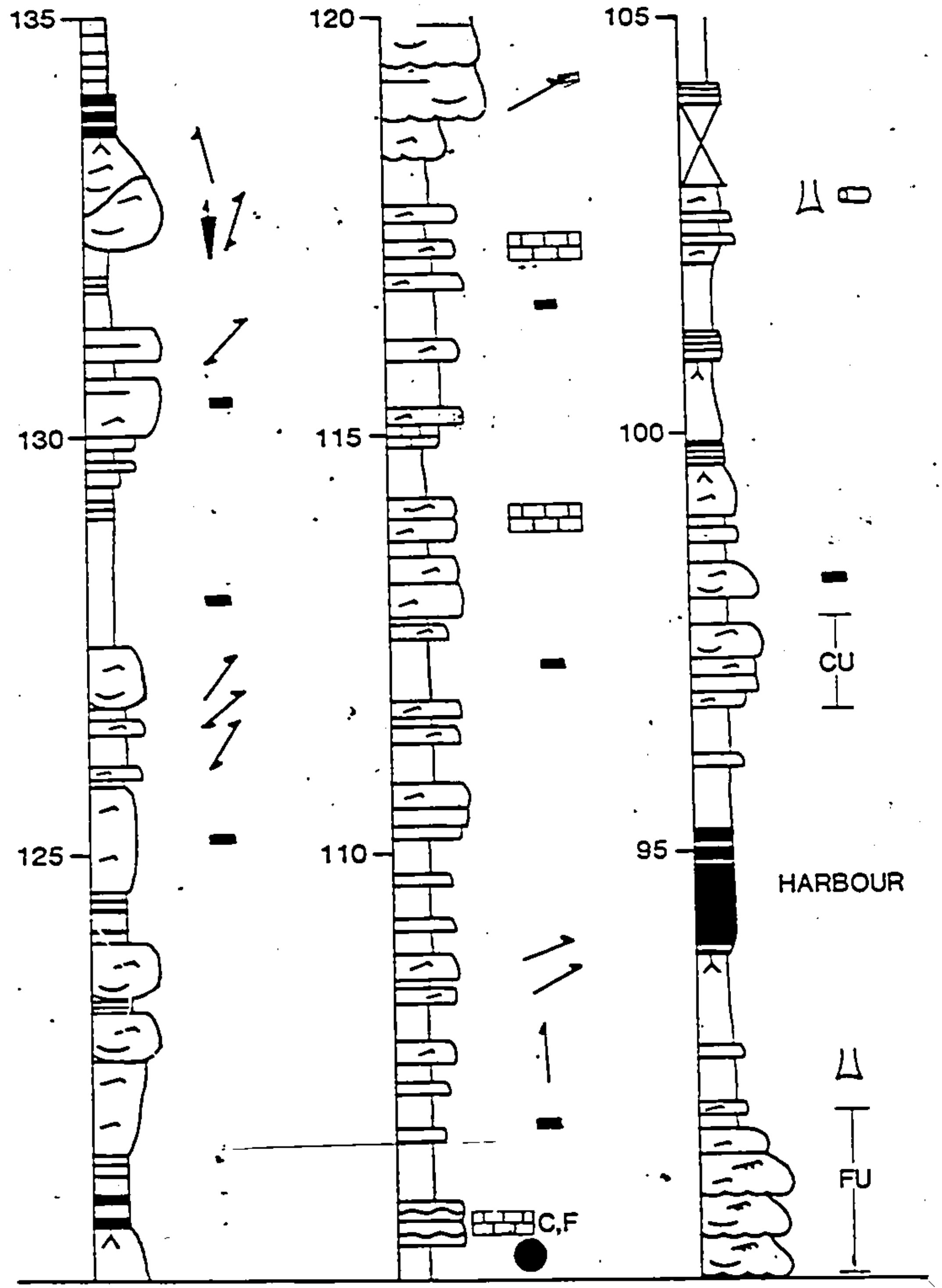


Fig 4

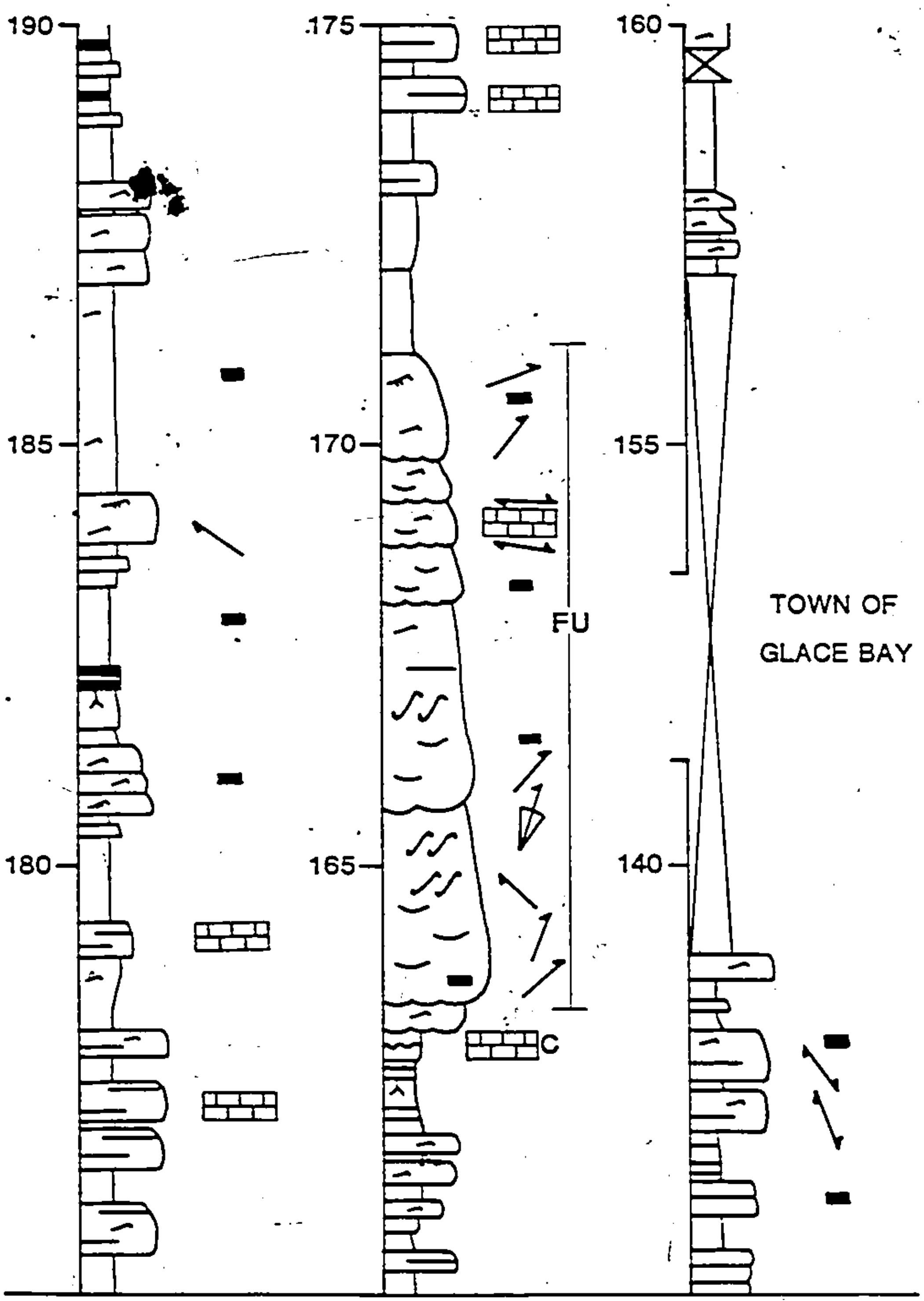
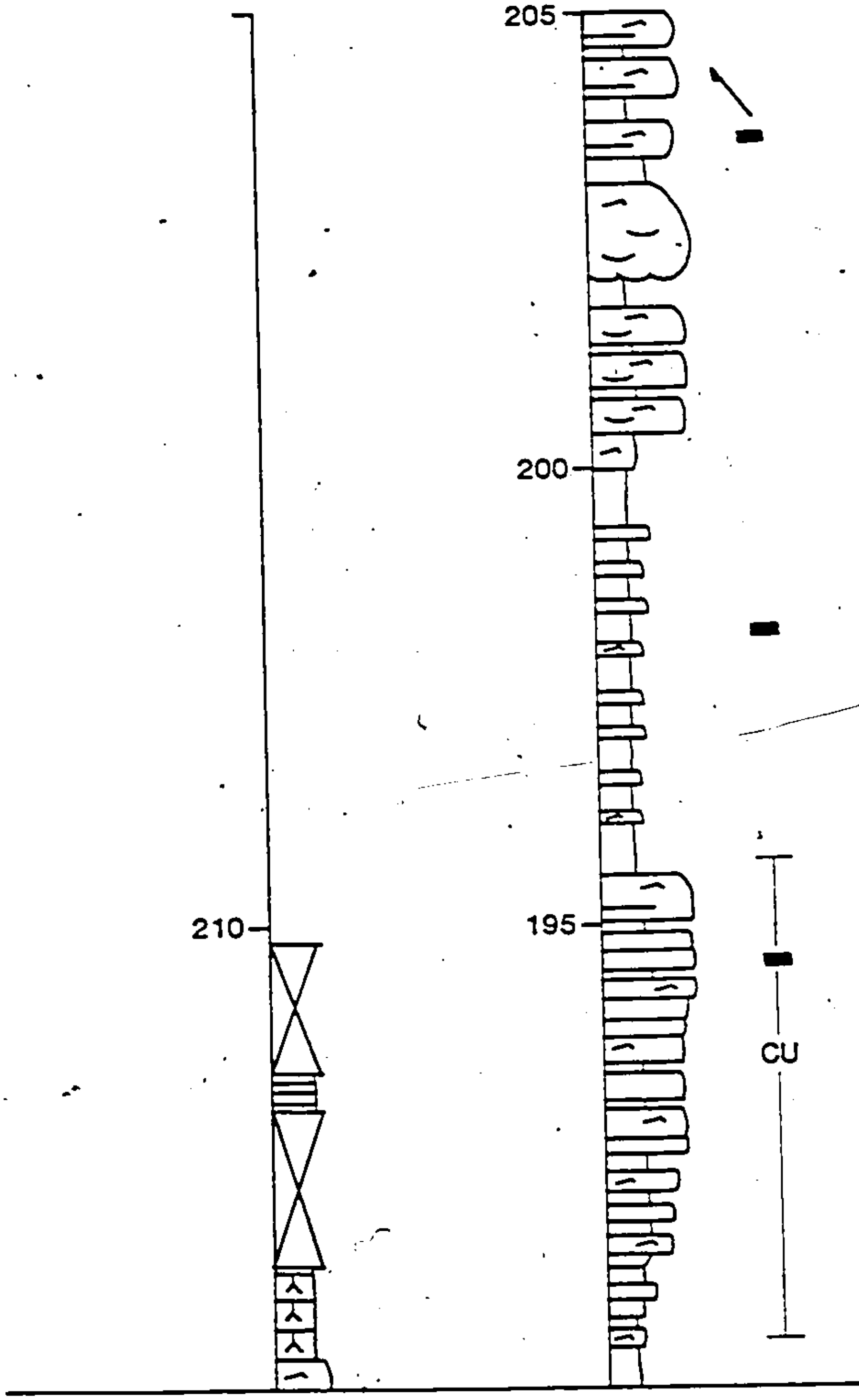


Fig 4



APP A FIG 5 DONKIN WEST 135m

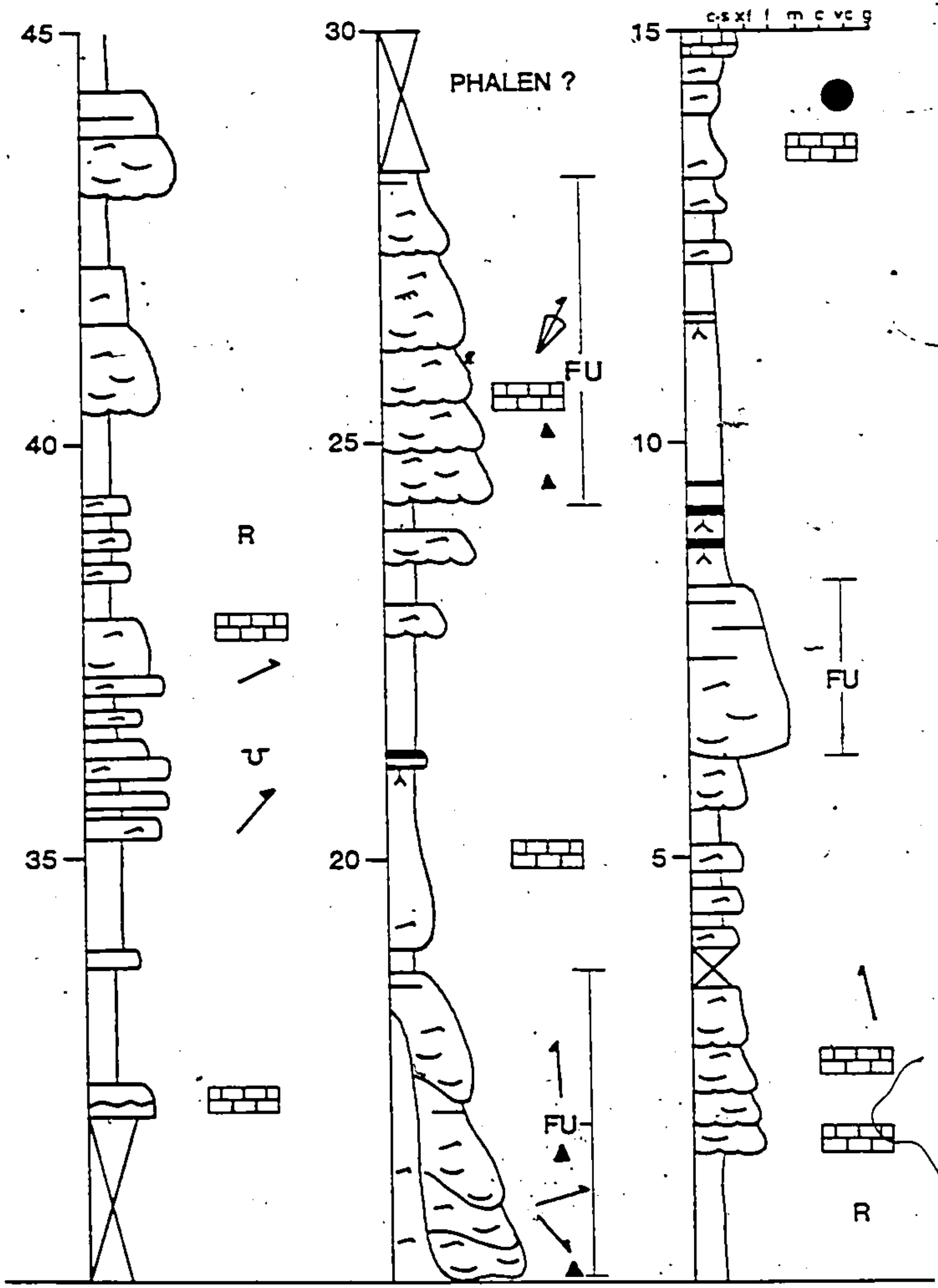


Fig 5

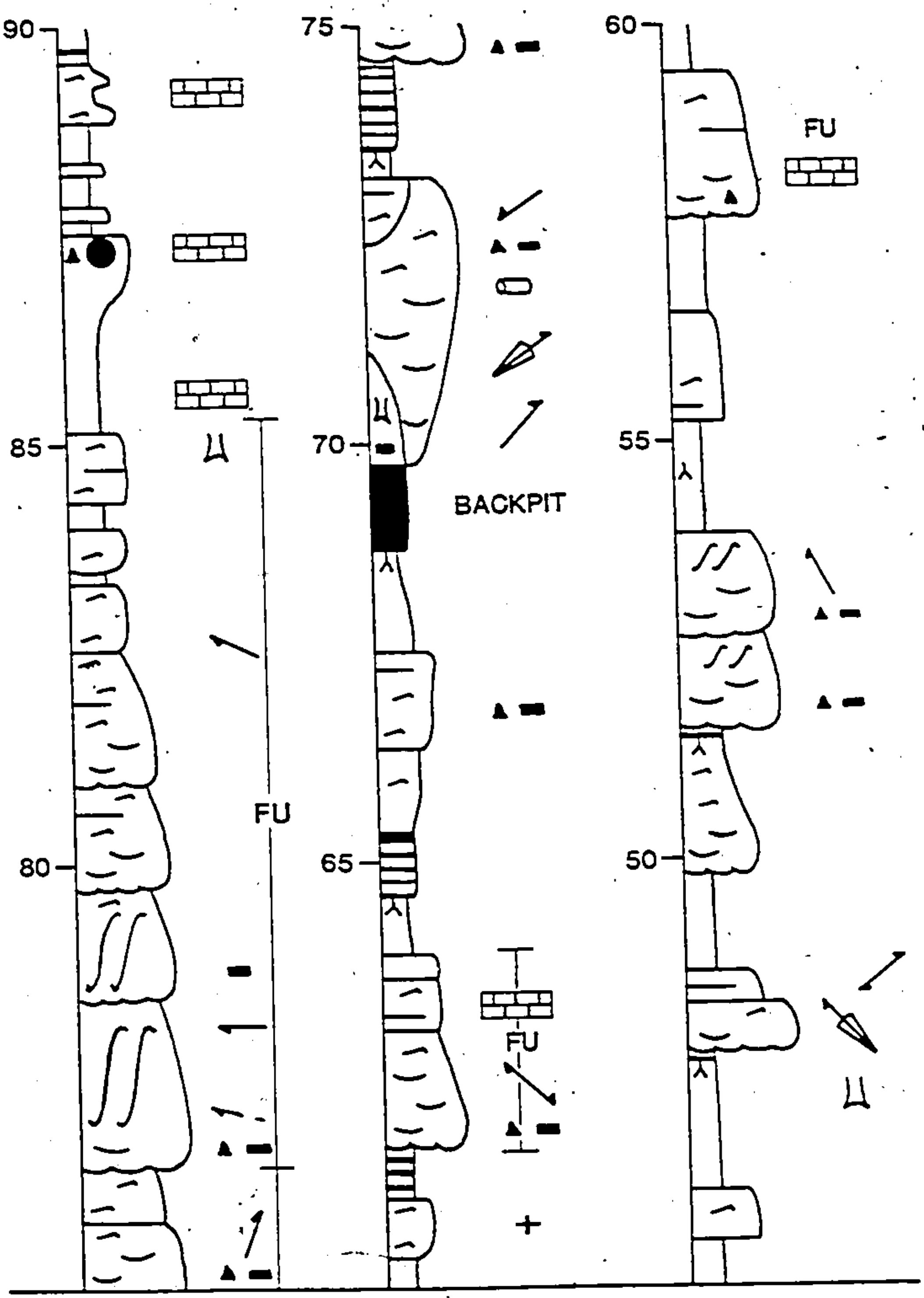
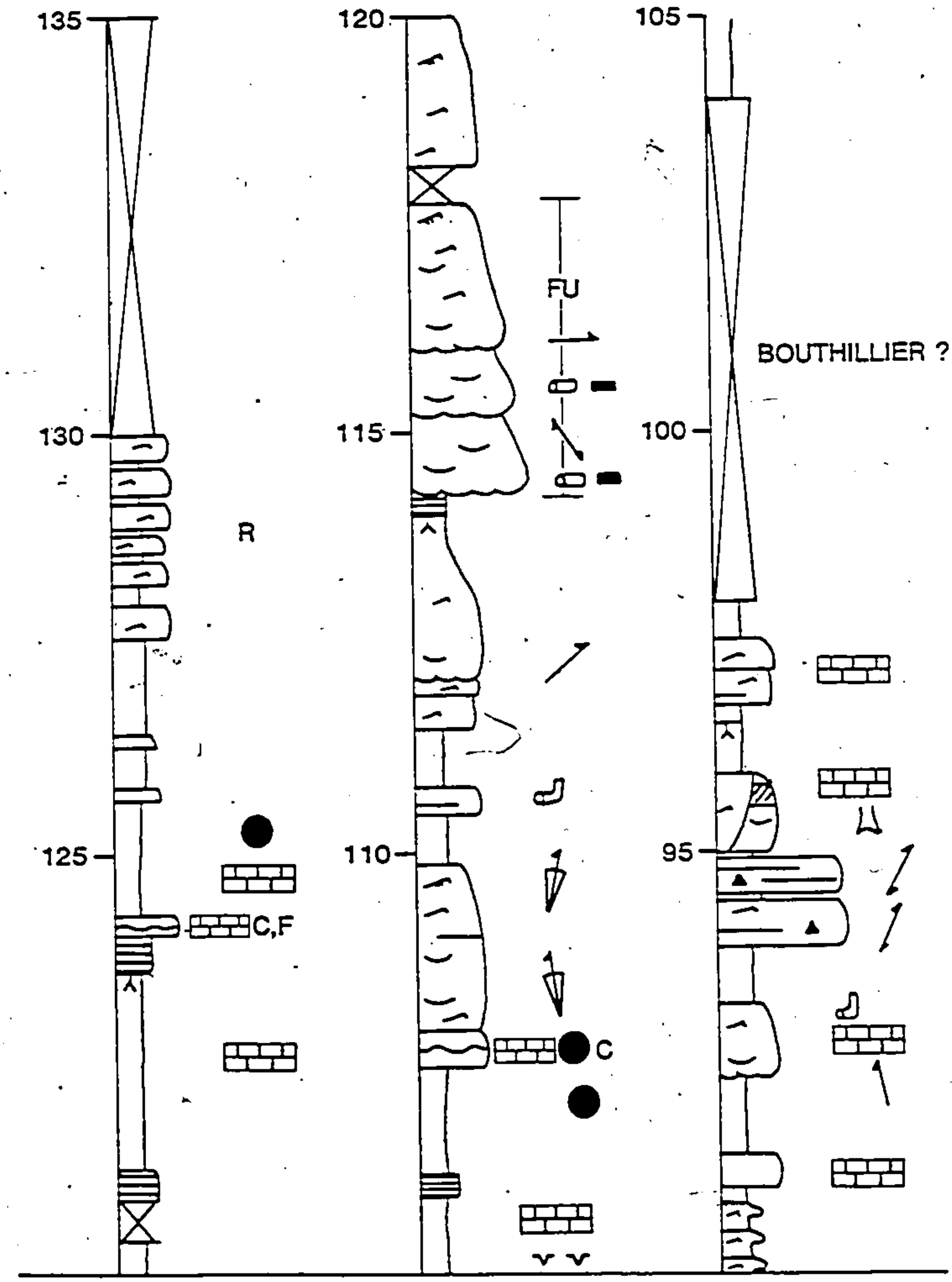


Fig 5



APP A FIG 6 DONKIN EAST 135m

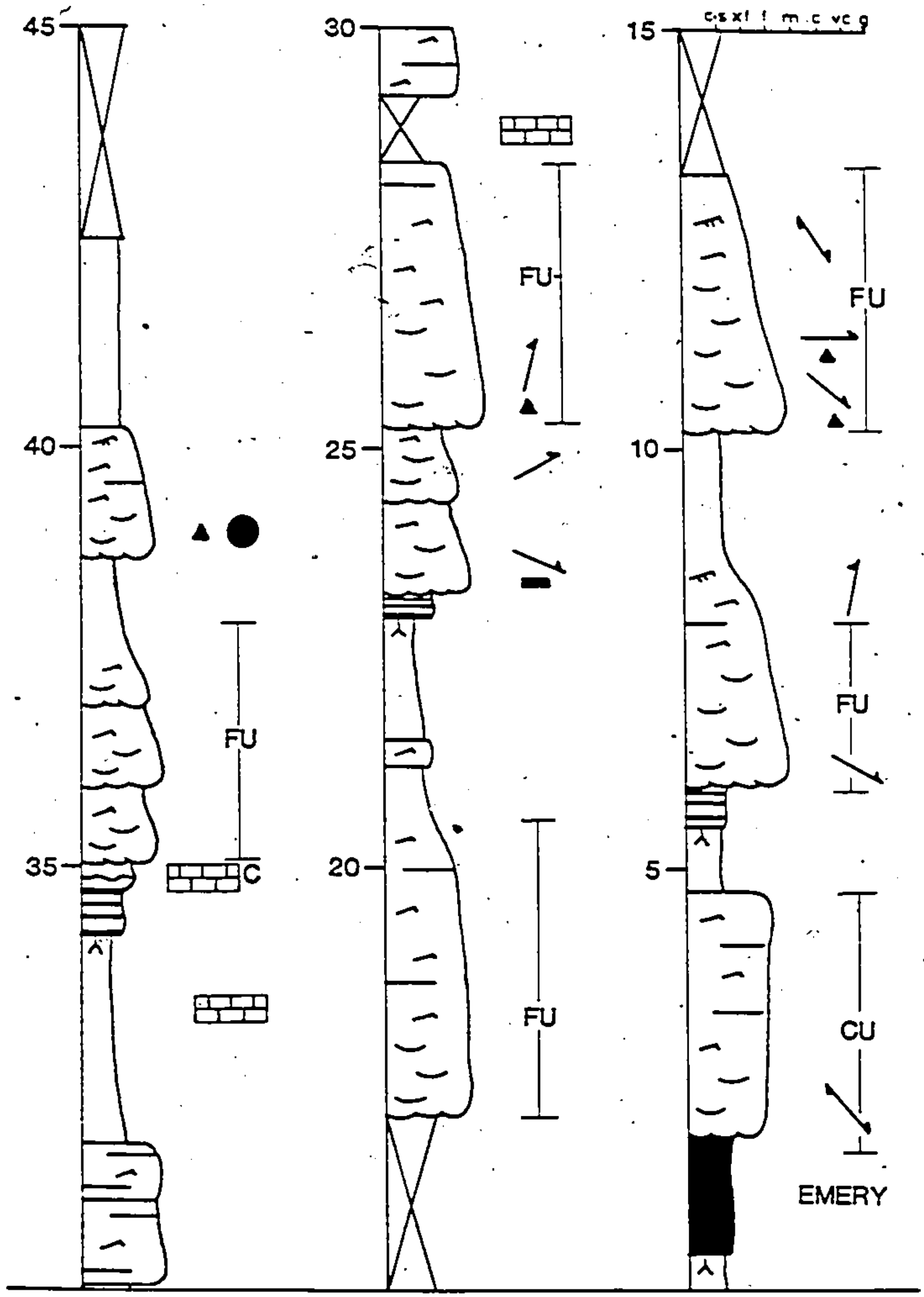


Fig 6

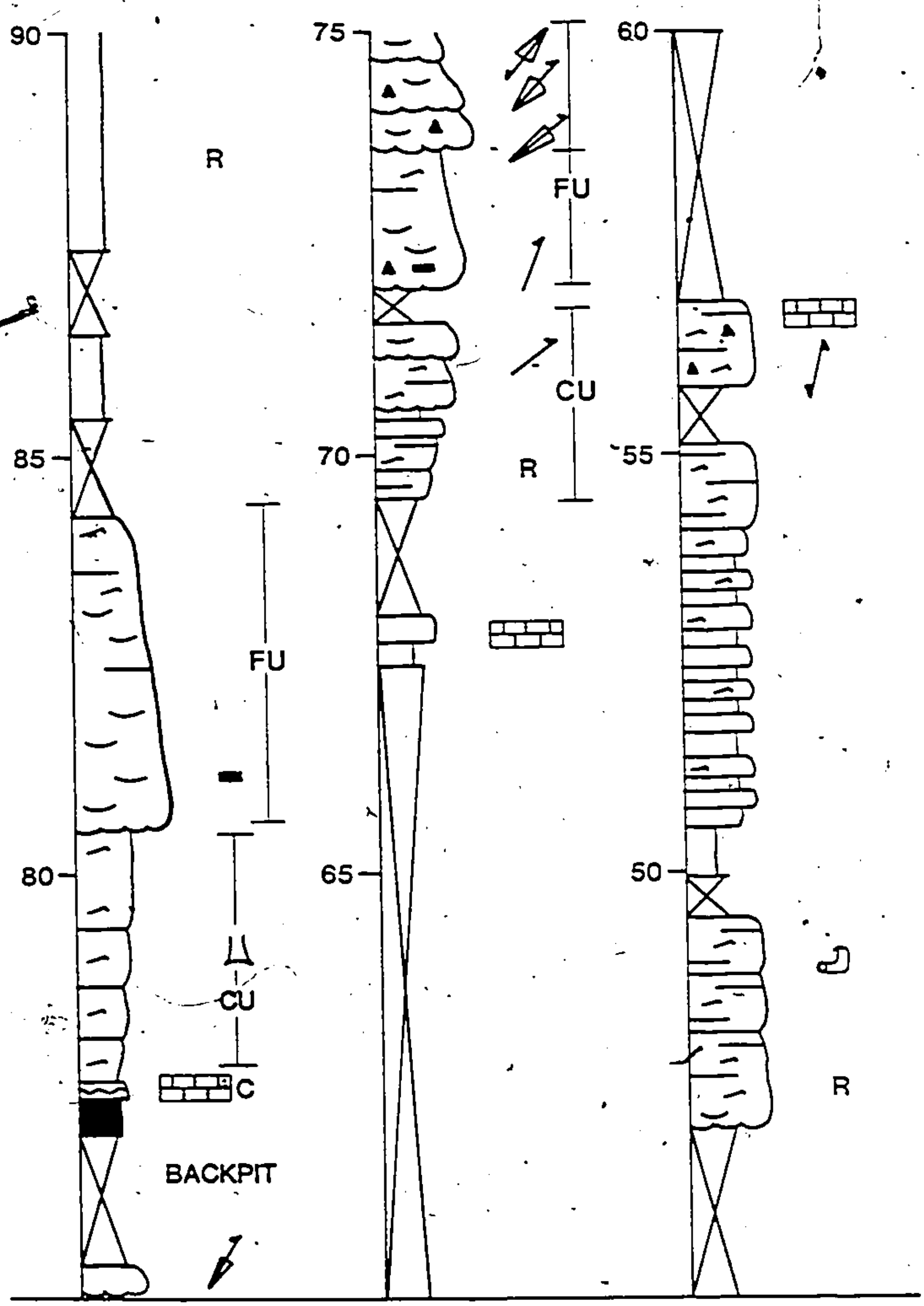
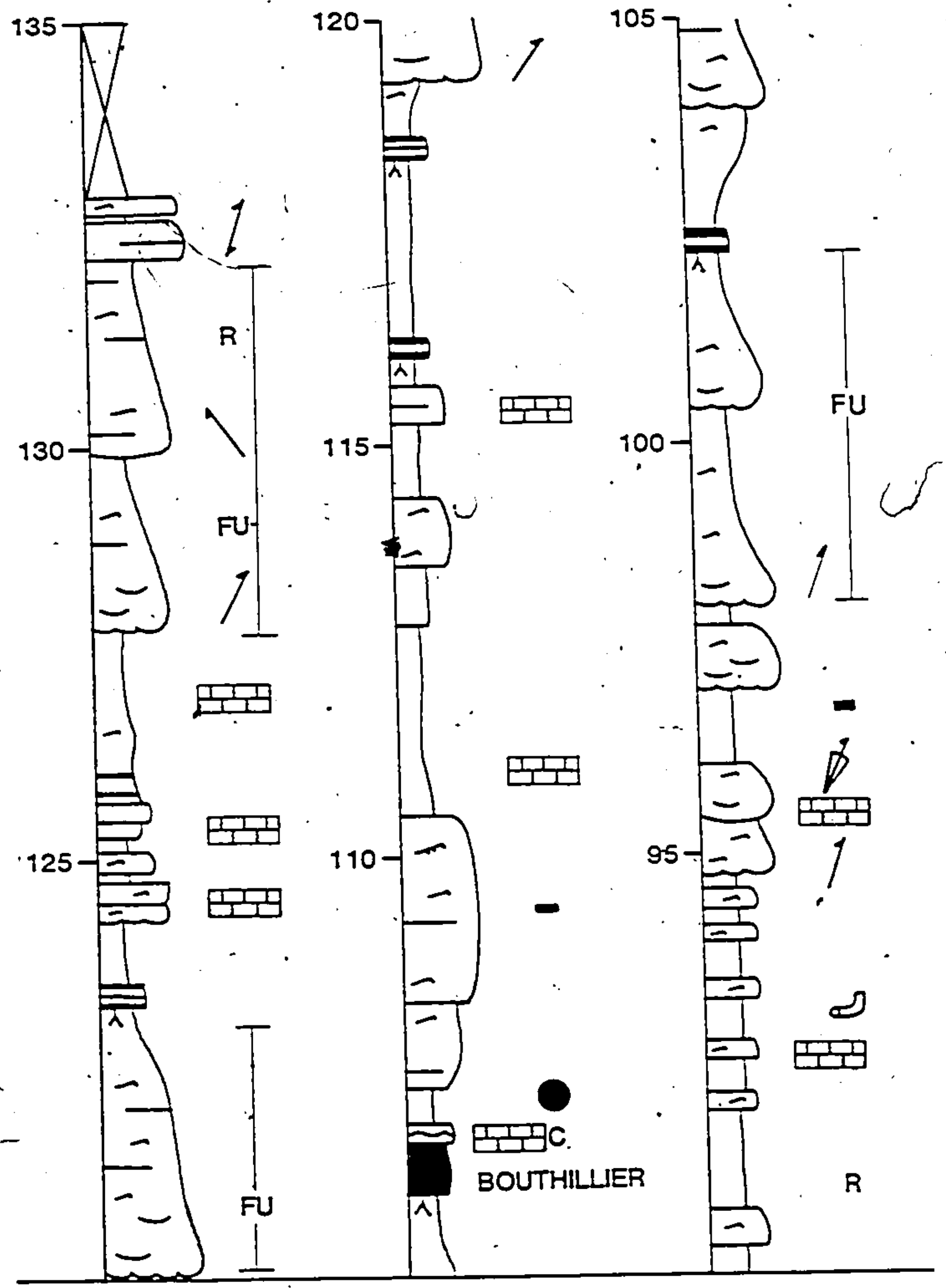


Fig 6



APP A FIG 7 SCHOONER HEAD 60m

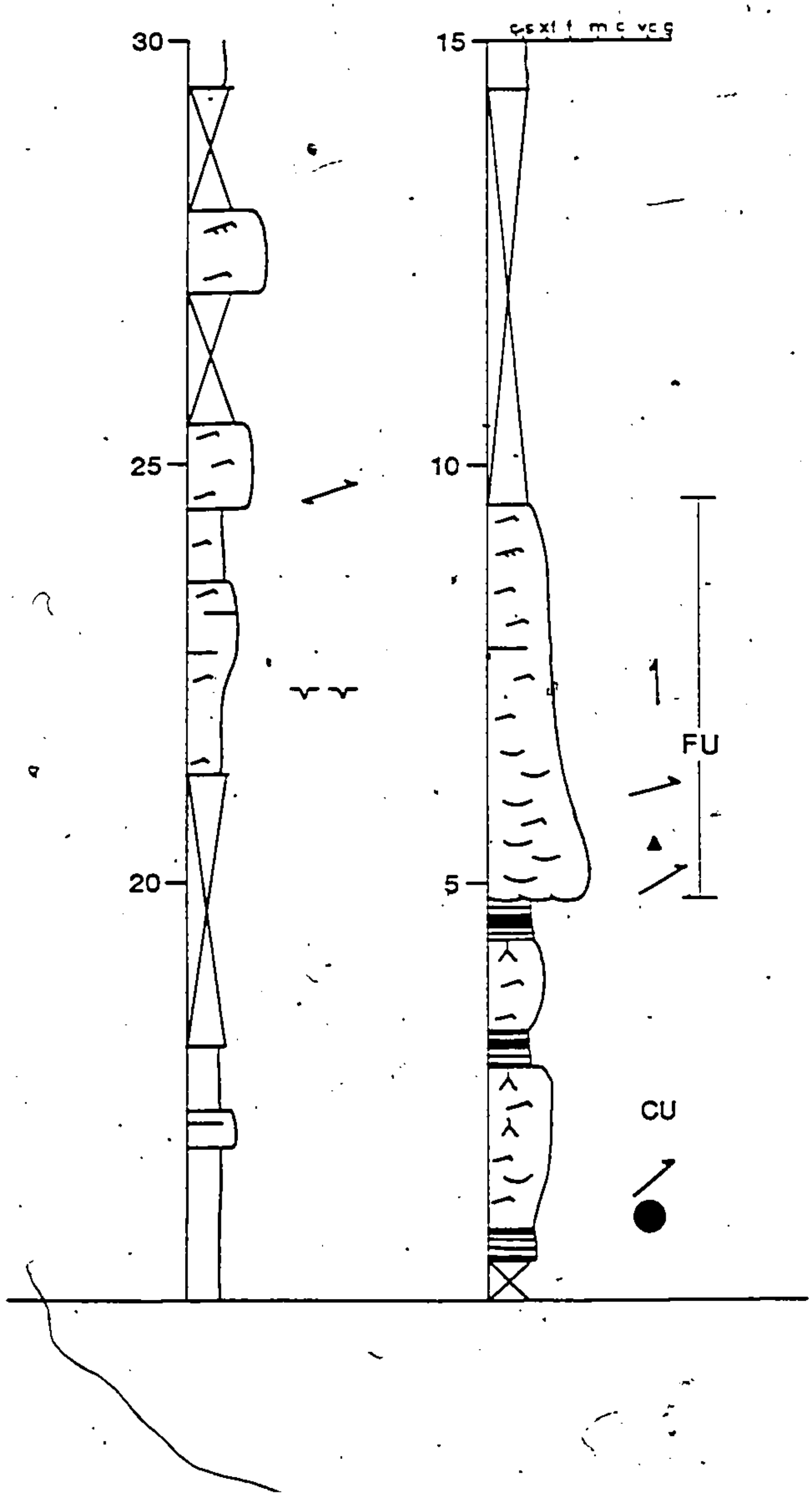
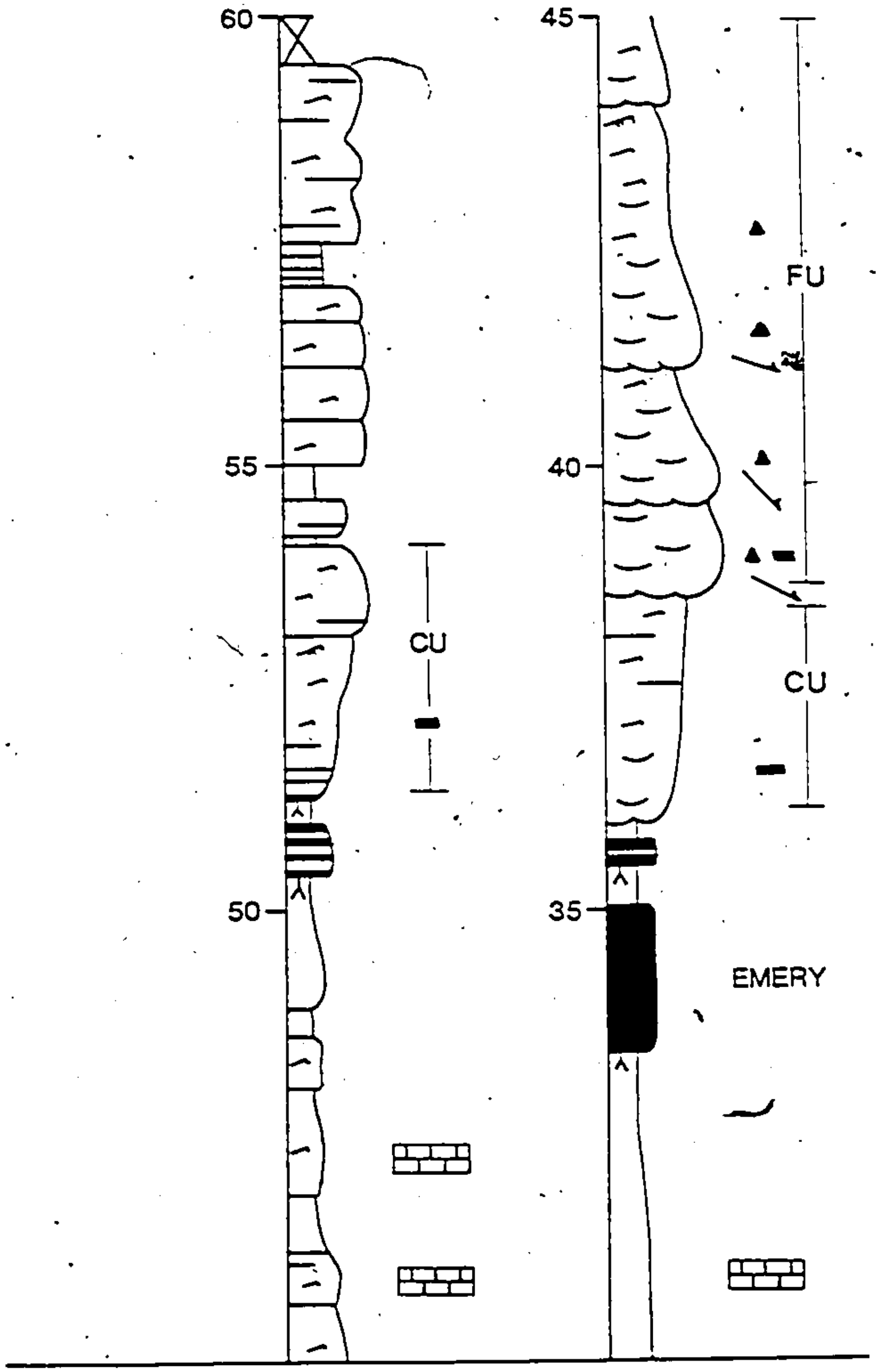


Fig 7



APP A FIG 8A MORIEN SOUTH 105m

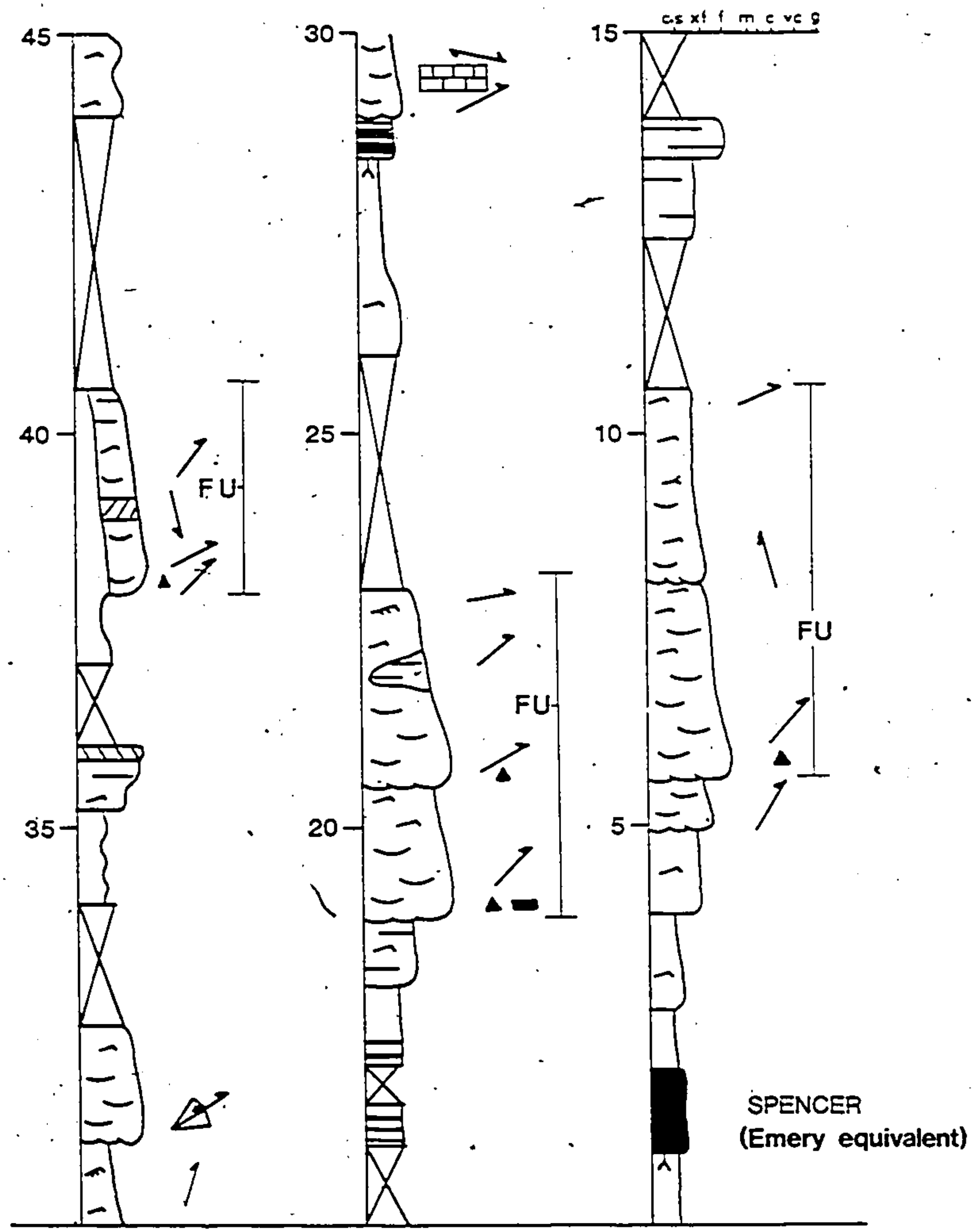


Fig 8A

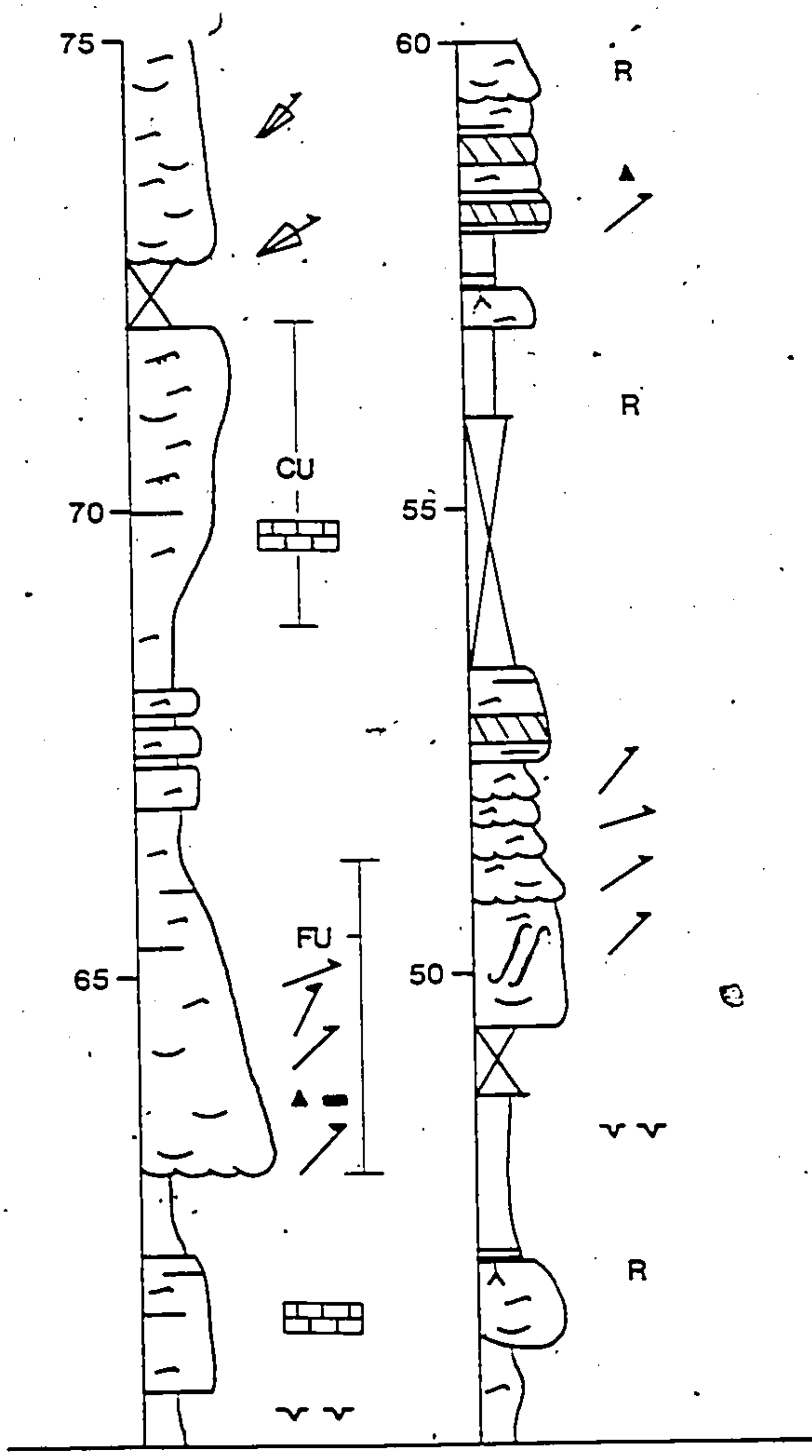
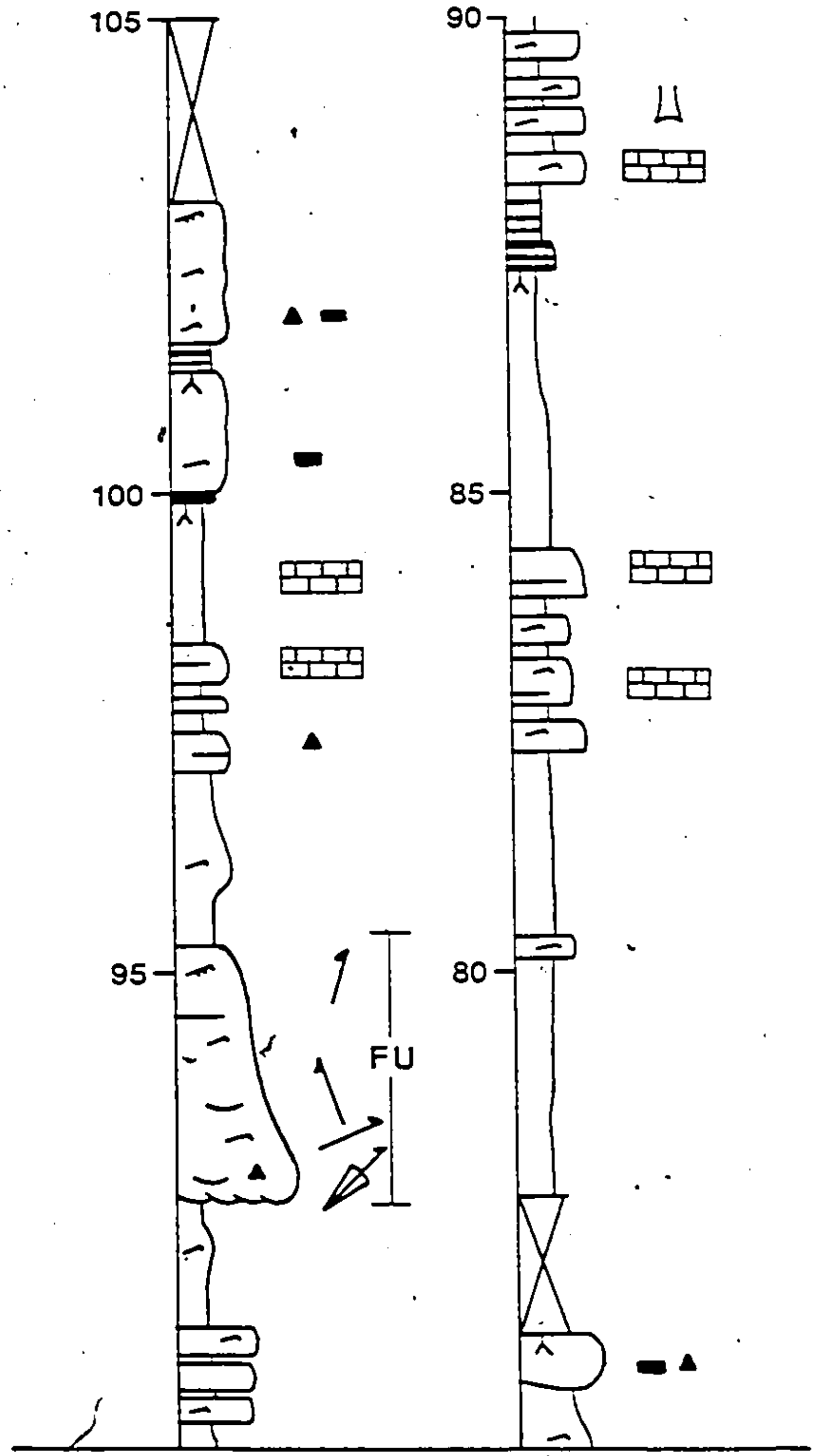


Fig 8A



APP A FIG 8B MORIEN NORTH 115m

Fig 8B

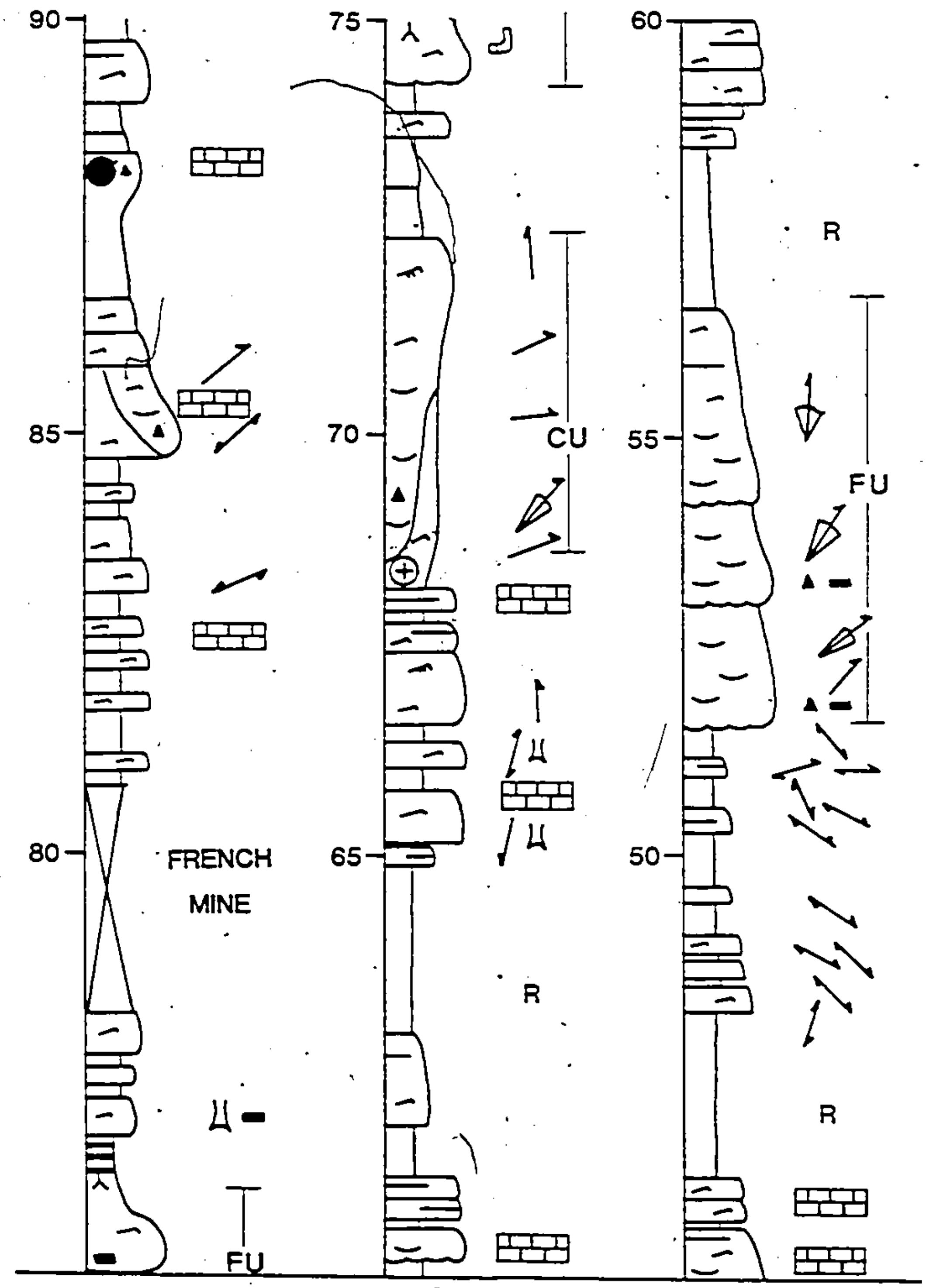
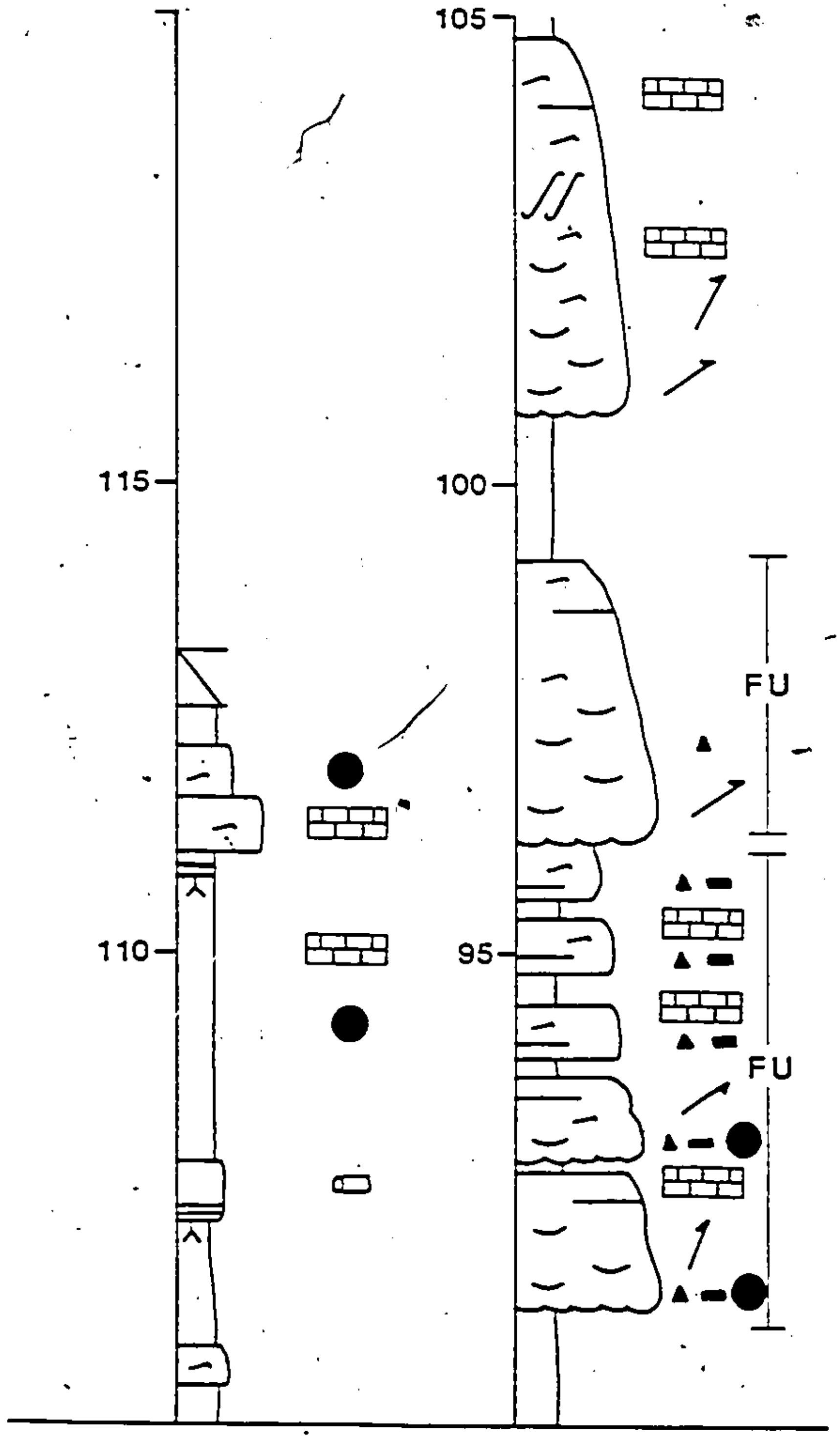


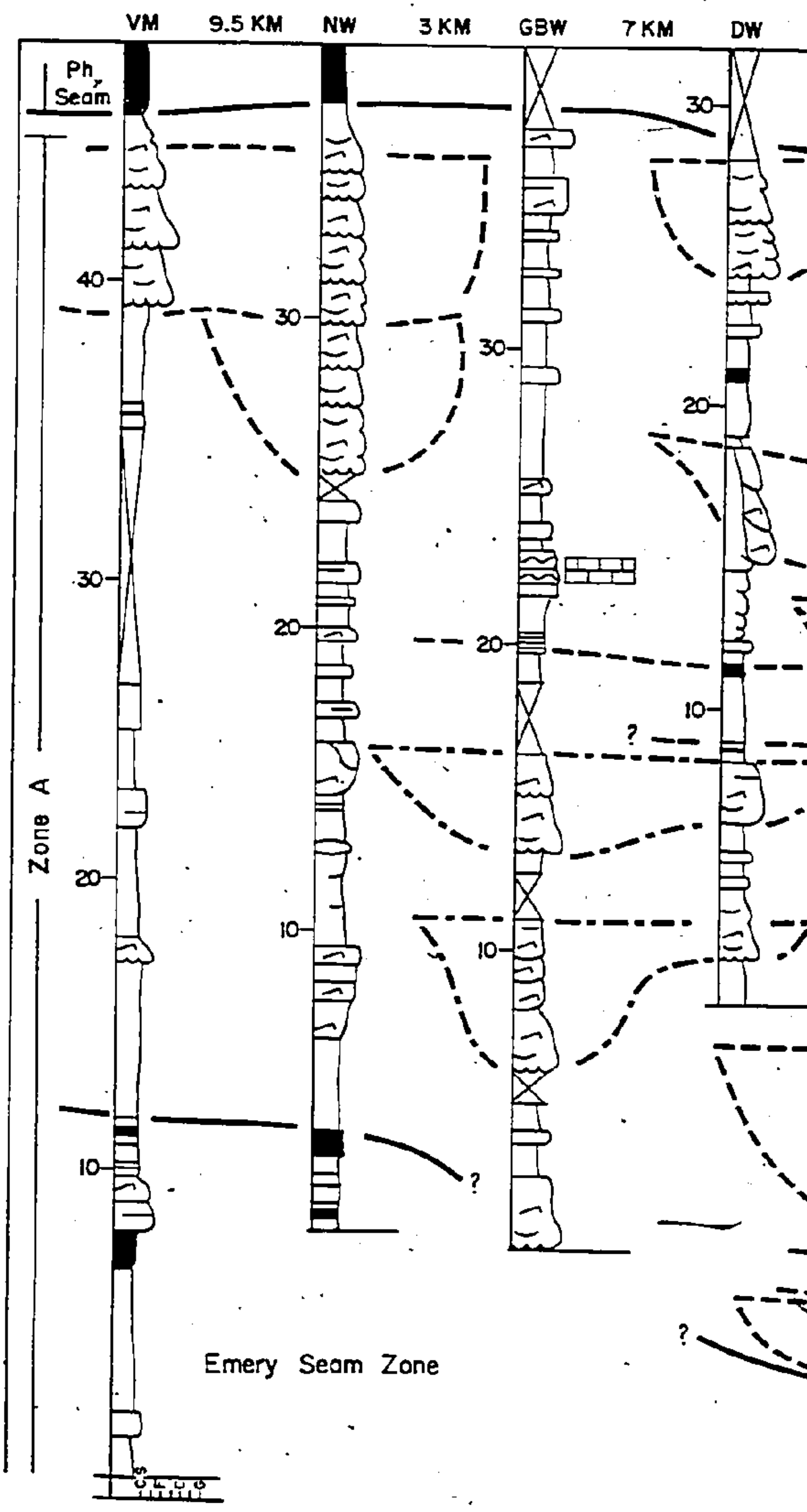
Fig 8B



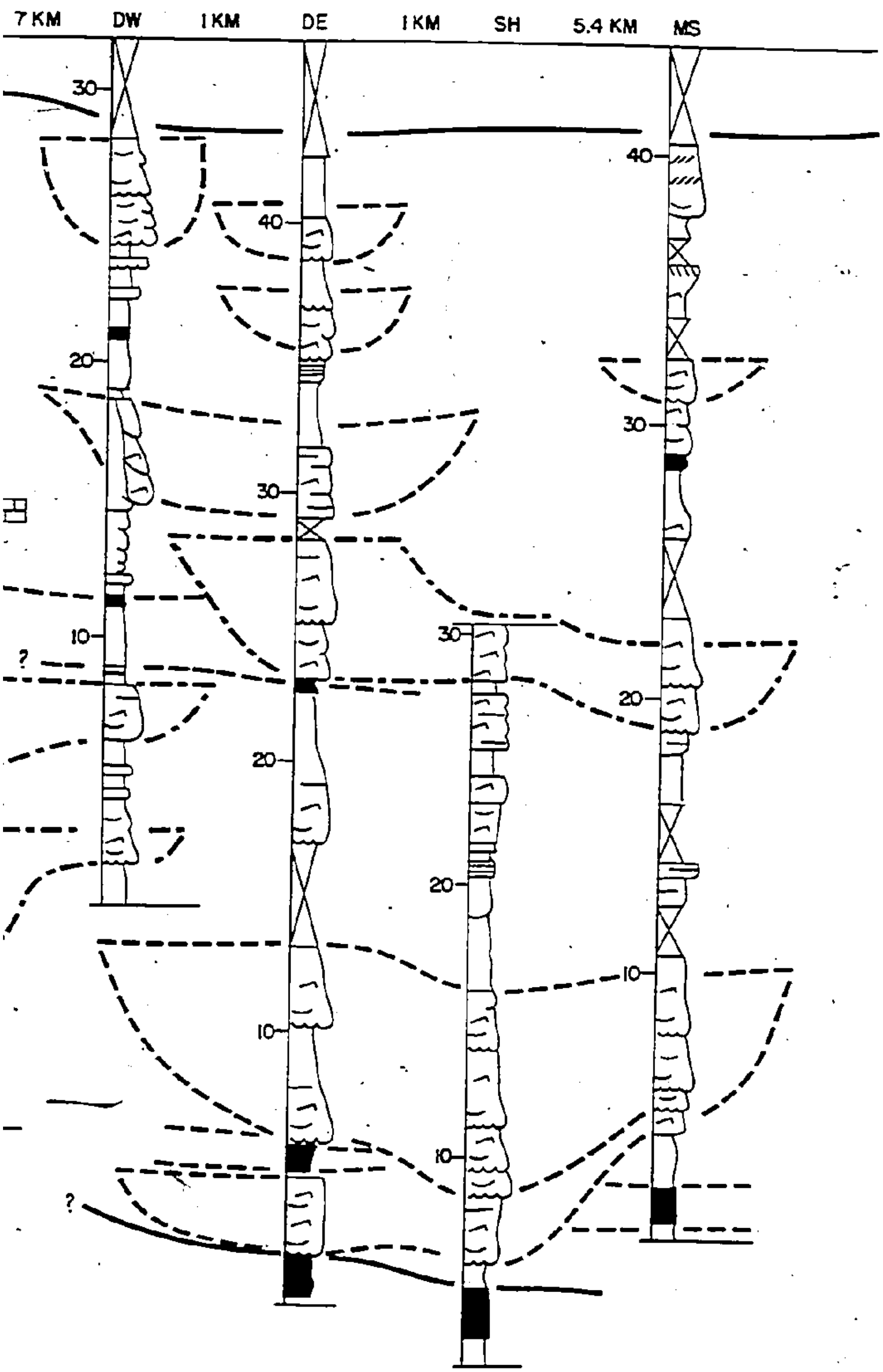
APPENDIX B

Correlations from detailed stratigraphic sections
and the extent of lithostratigraphic zones
(for explanation of symbols see Appendix A)

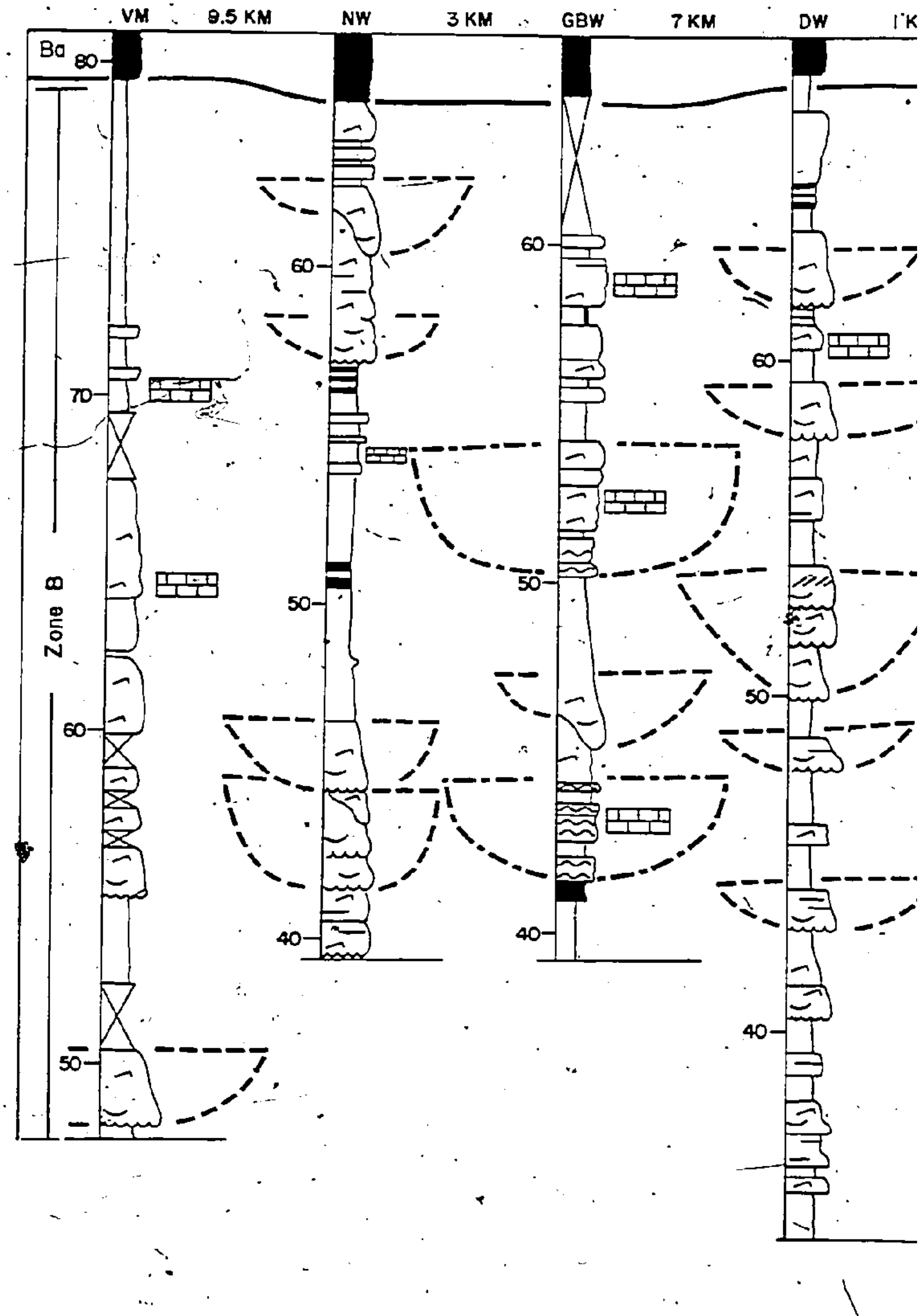
Appendix B - Figure I Columnar-secti

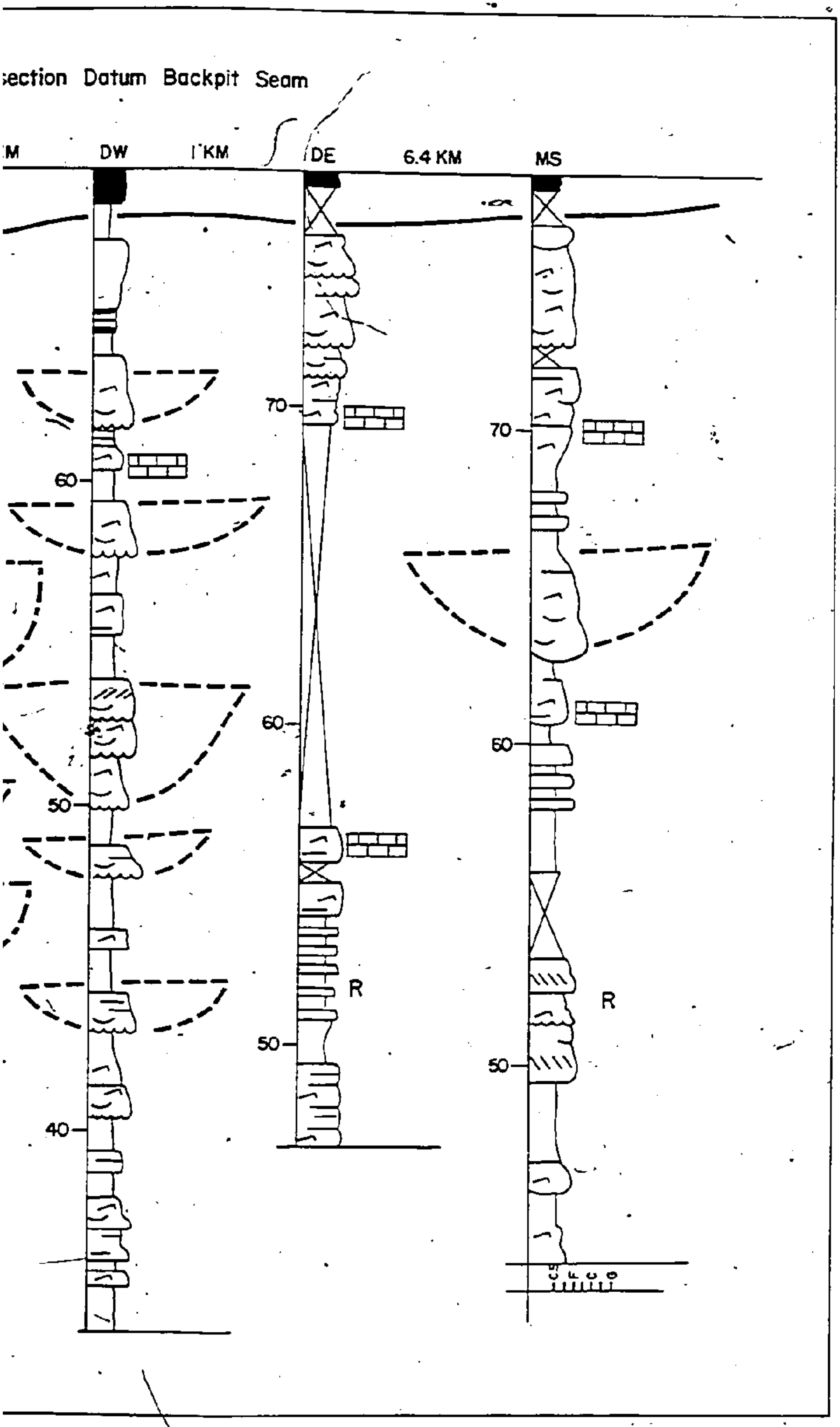


I Columnar-section Datum Phalen Seam



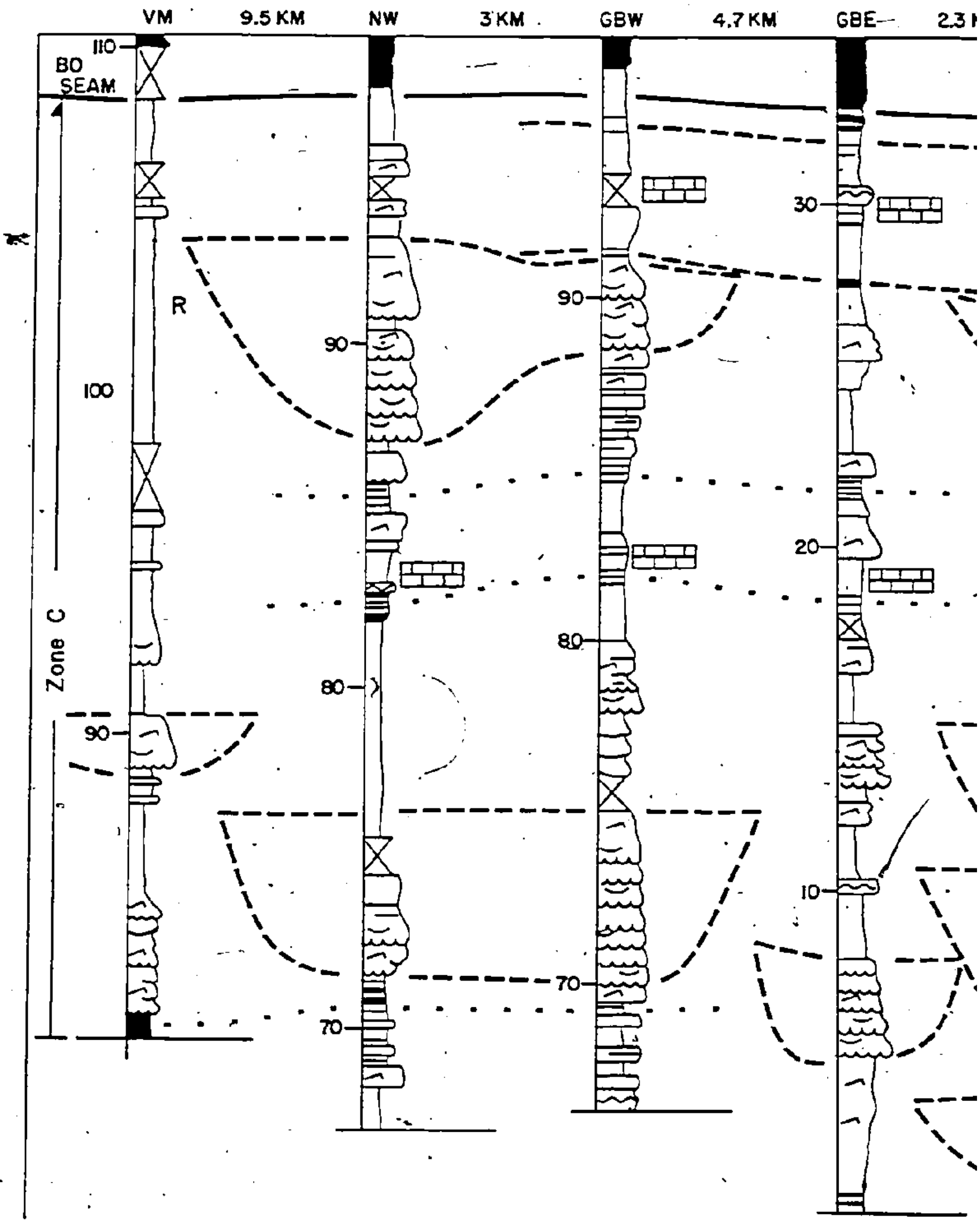
Appendix B – Figure 2 Columnar-section Datum Back



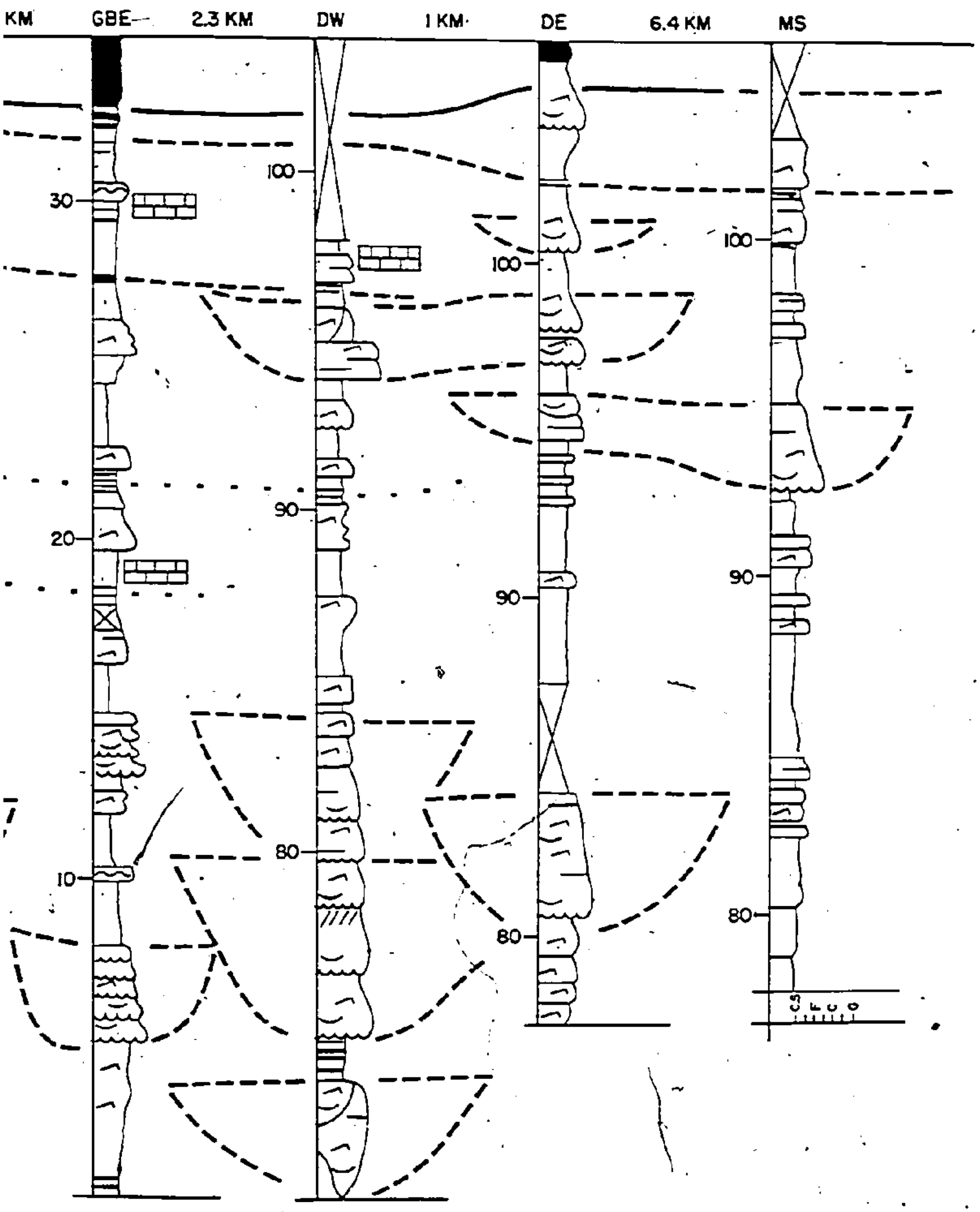


ection Datum Backpit Seam
M
DW
1 KM
DE
6.4 KM
MS
70
60
50
40
70
60
50
70
60
50
R
R

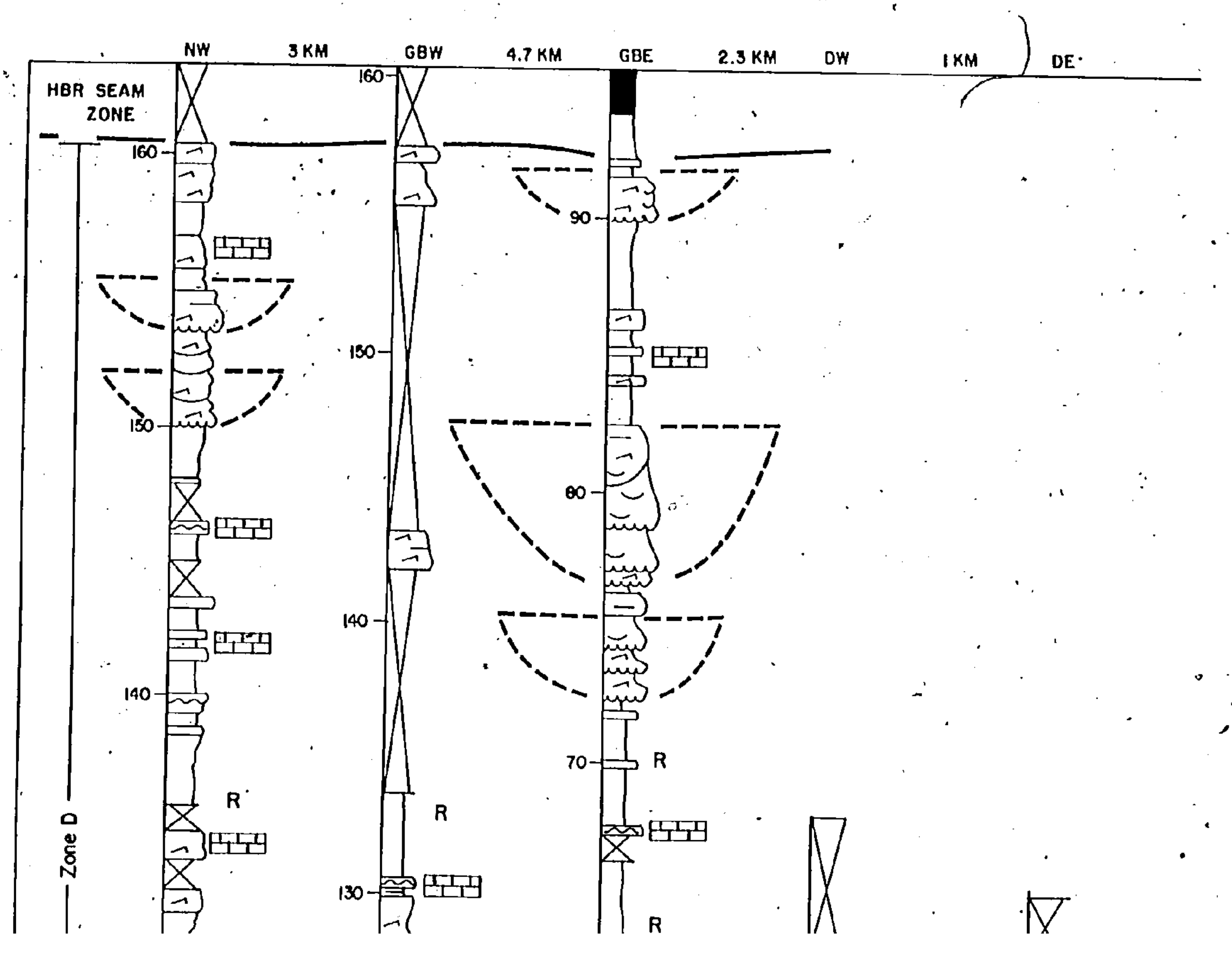
Appendix B Figure 3 Columnar-section Datum Bou

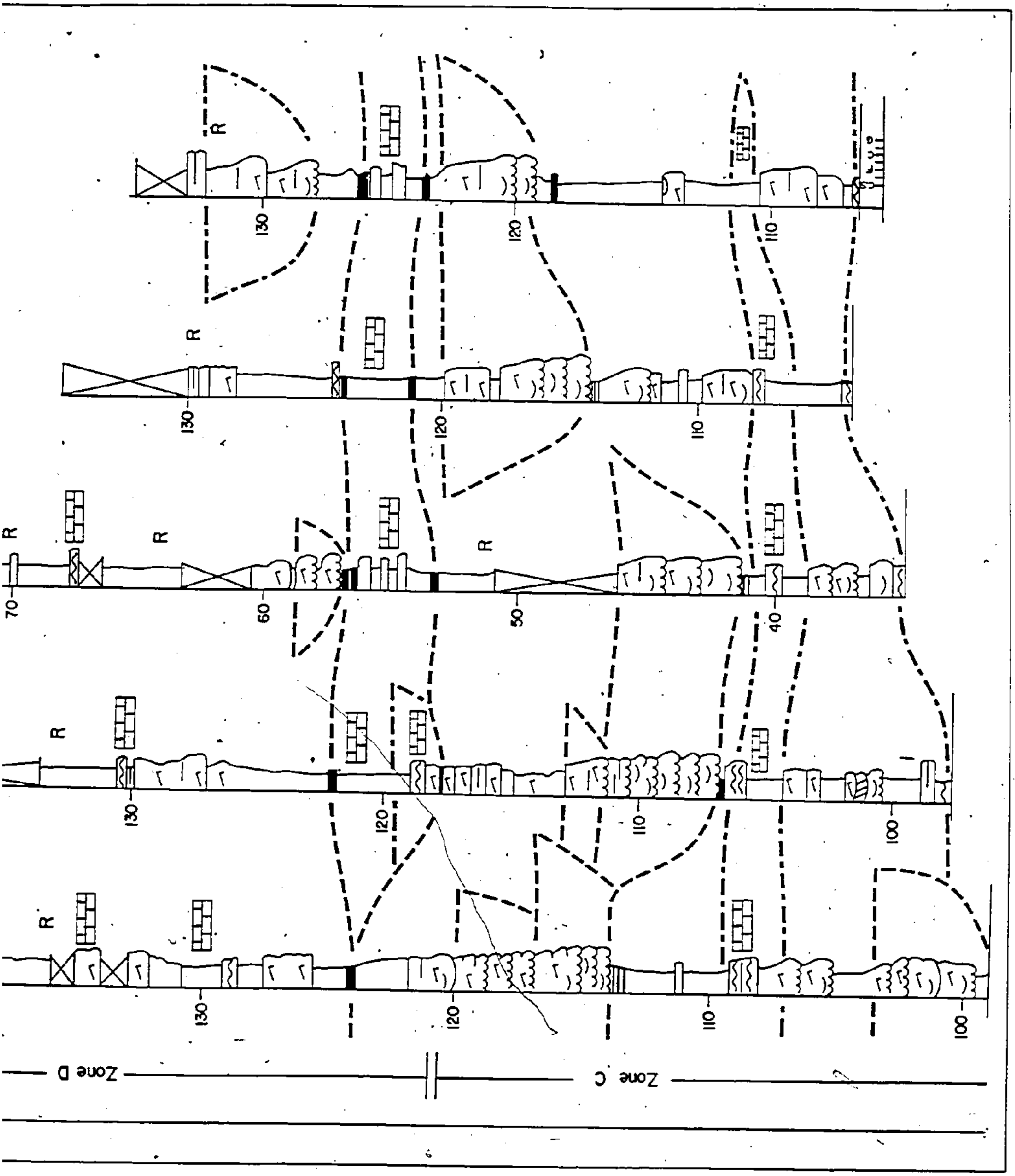


section Datum Bouthillier Seam



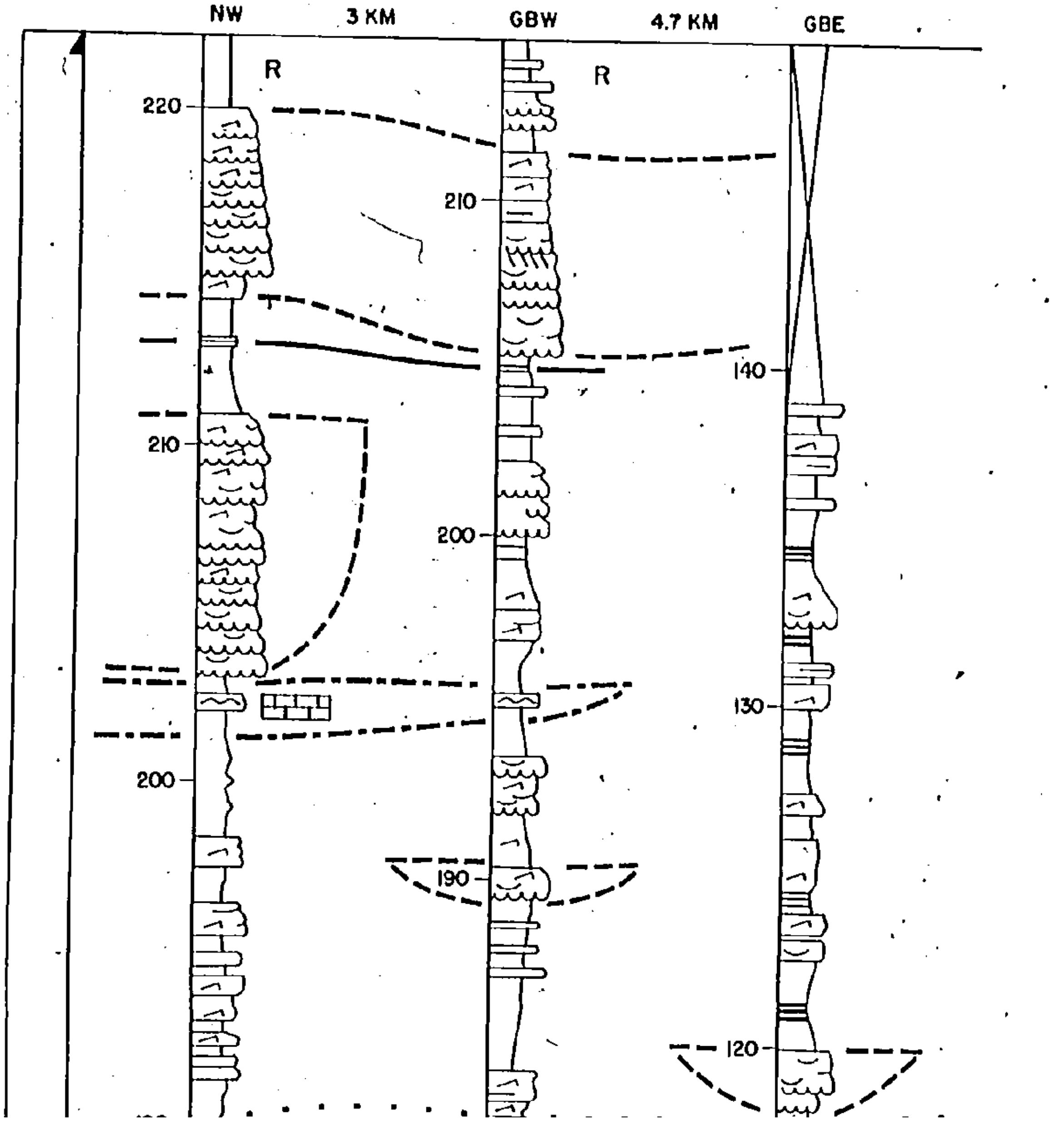
Appendix B - Figure 4 Columnar-section Datum Harbour Seam

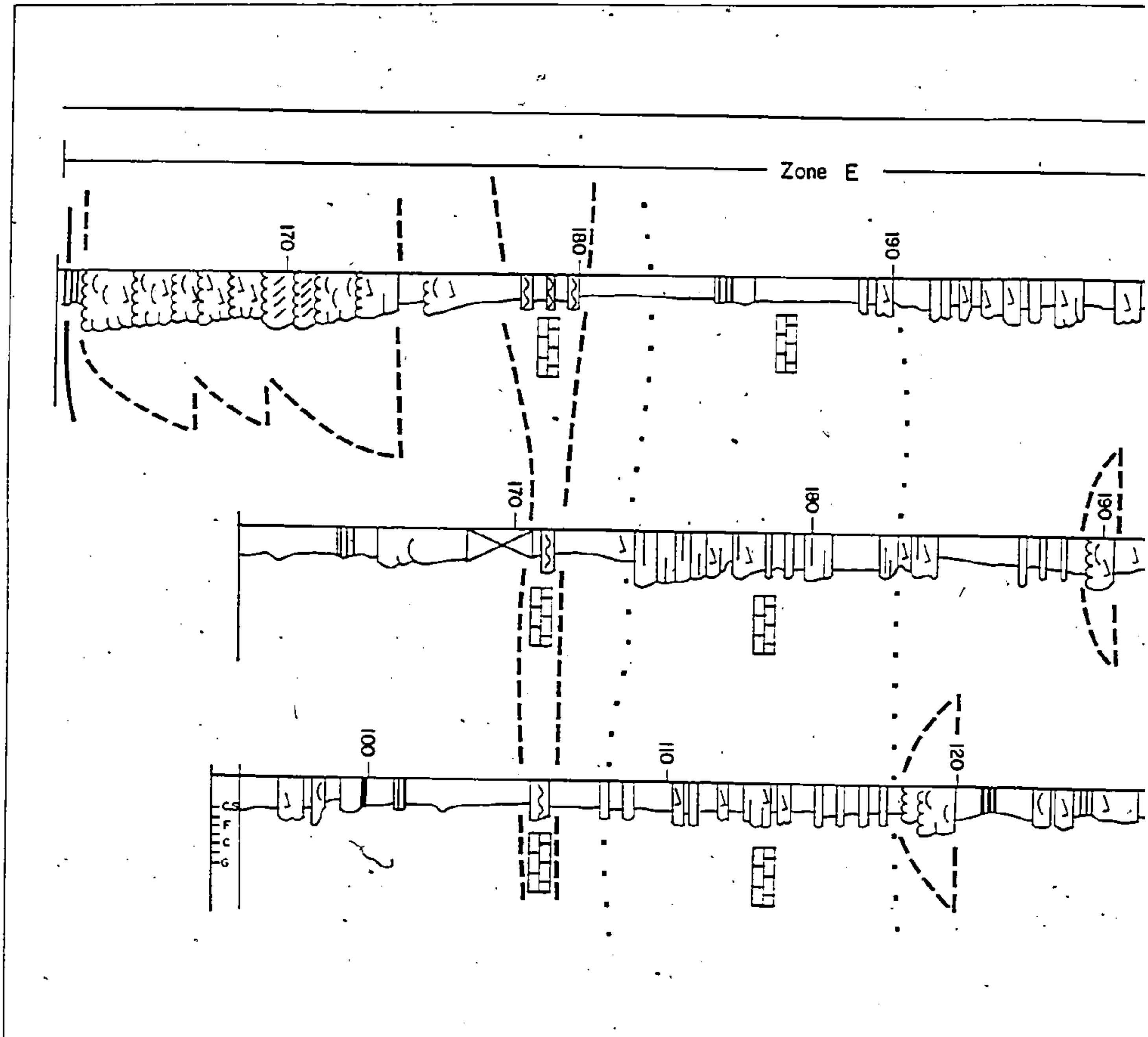




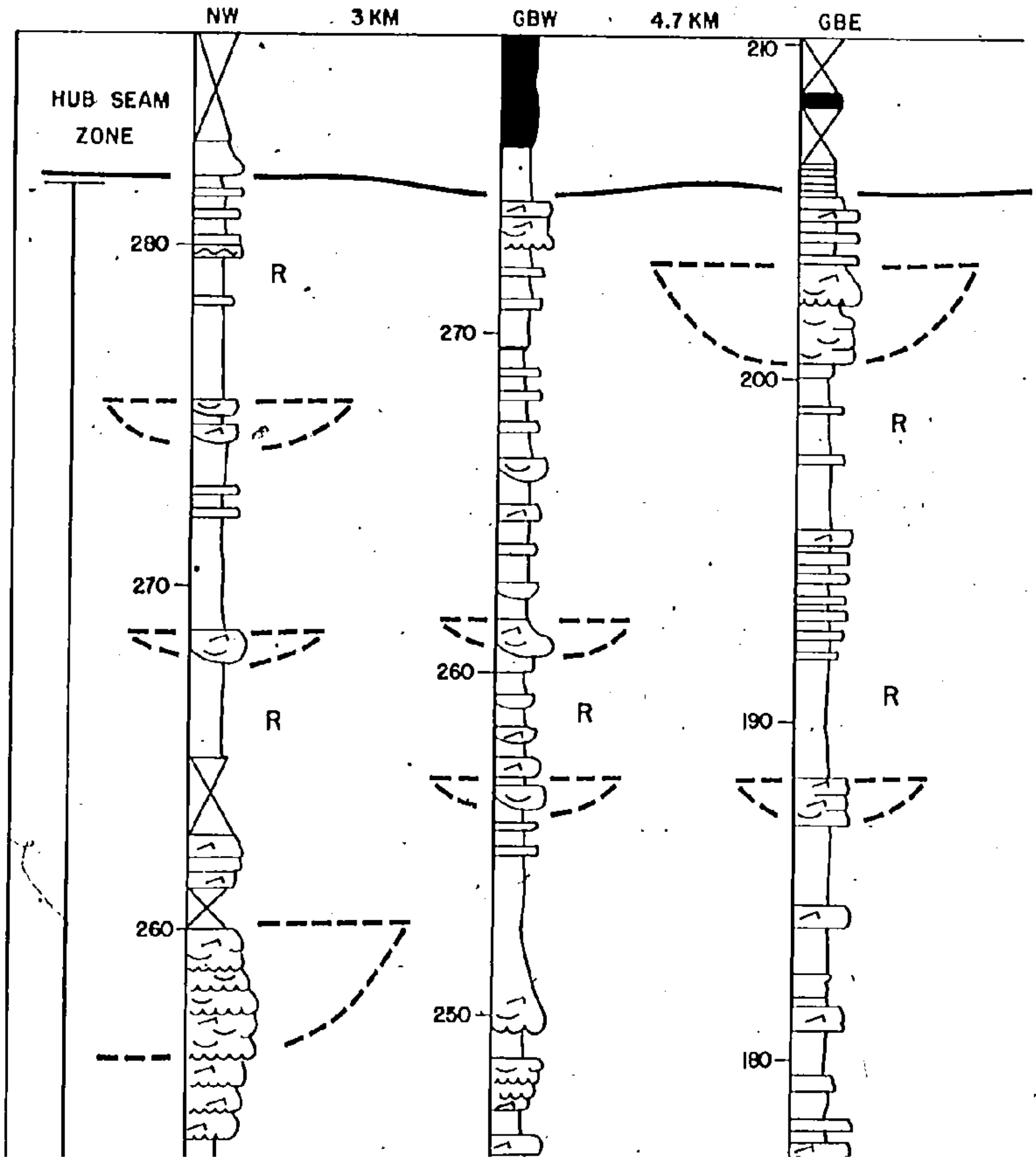
Zone C
Zone D
R

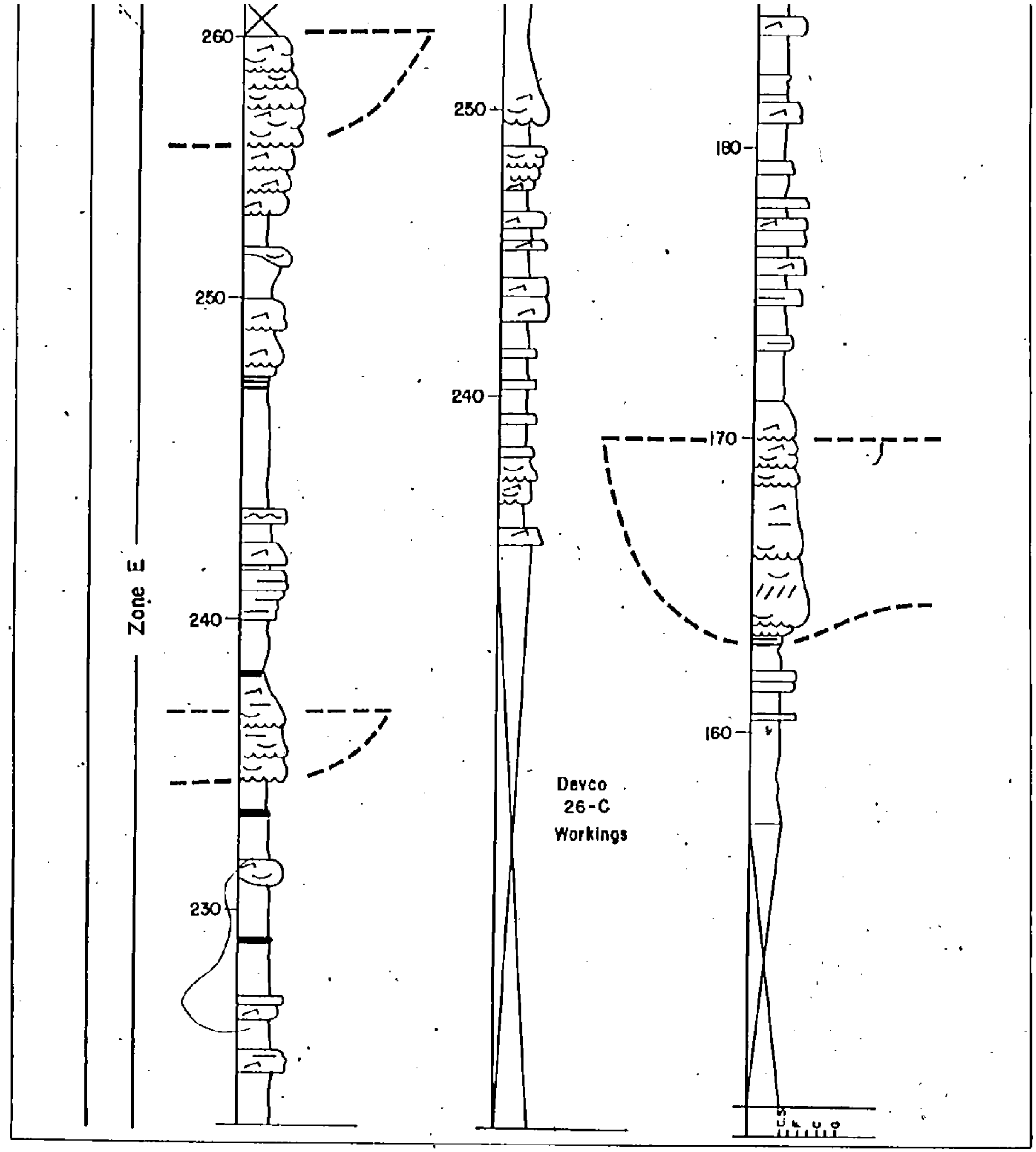
Appendix B - Figure 5 Columnar-section Datum Hub Seam
(lower half of interval)




Zone E
170
180
190
170
180
190
100
110
120
C S
F
C
G

Appendix B   Figure 6 Columnar-section Hub Seam
(upper half of interval)





Zone E
260
250
240
230
250
240
Devco
26-C
Workings
180
170
160