Sedimentology of the Carboniferous Canso Group at Broad Cove, Nova Scotia

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Submitted in partial fulfillment of the degree of Bachelor of Science with Honours in Geology, Dalhousie University.

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I certify that I have approved corrections and that the thesis is complete.

(Supervisor)
26 March/86.

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Abstract

Carboniferous Canso Group strata are well exposed on the west coast of Cape Breton Island at Broad Cove, 5 km northeast of Inverness. The study area is a coastal section extending from the mouth of Smith's Brook, which drains into Broad Cove, south to Plaster Rocks Cove.

The Canso Group was deposited in a fault-bound basin, part of a series of interconnected basins and surrounding uplifted blocks and stable platforms collectively known as the Fundy Basin.

Three facies assemblages are recognized in the Canso strata at Broad Cove. The carbonate facies assemblage includes calcareous shale, dolostone, calcareous mud, stromatolitic limestone, and oolitic limestone. The siliciclastic facies assemblage comprises sandstone and mudstone. The mixed facies assemblage comprises carbonate and siliciclastic units interbedded on a fine scale.

Evidence indicates that the depositional setting was a shallow saline lake on an alluvial plain. Deposition was under conditions of climatic aridity. Abundant carbonate minerals precipitated in a saline lake during periods of evaporation and low clastic influx. Flood waters from storms inundated the plain and clastic sediments were deposited in the lake. The clastic sediments were transported from surrounding uplands by the flood waters and surface runoff during storm events.

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Chapter 1 Introduction

1.1 Purpose

Canso Group strata are well exposed at Broad Cove on Cape Breton Island. The strata have not previously been studied in detail and have some interesting small-scale features. The present detailed sedimentological study of the facies, facies assemblages, and cyclicity of deposition of the units is followed by an interpretation and evaluation of the depositional environment.

1.2 Location, Access, Exposure

Broad Cove is on the west coast of Cape Breton Island, Nova Scotia, 5 km northeast of Inverness (Figure 1). Smith's Brook drains into the cove and this report concerns the strata exposed along the coast south of the brook. The study area extends to Plaster Rocks Cove where Windsor Group gypsum crops out (Figure 2). The younger rocks to the north of the brook have been studied by James Waterfield (B.Sc. thesis, 1986).

Broad Cove is surrounded by rolling hills and the rocks are well exposed in cliff faces 4 to 8 m high along the shoreline. A gravel and sand beach along the section averages 4 to 6 m in width.

The study area is easily accessible from Highway 19 by taking the road to Broad Cove Chapel and crossing the bridge over Smith's Brook. On the north side of the brook a gravel

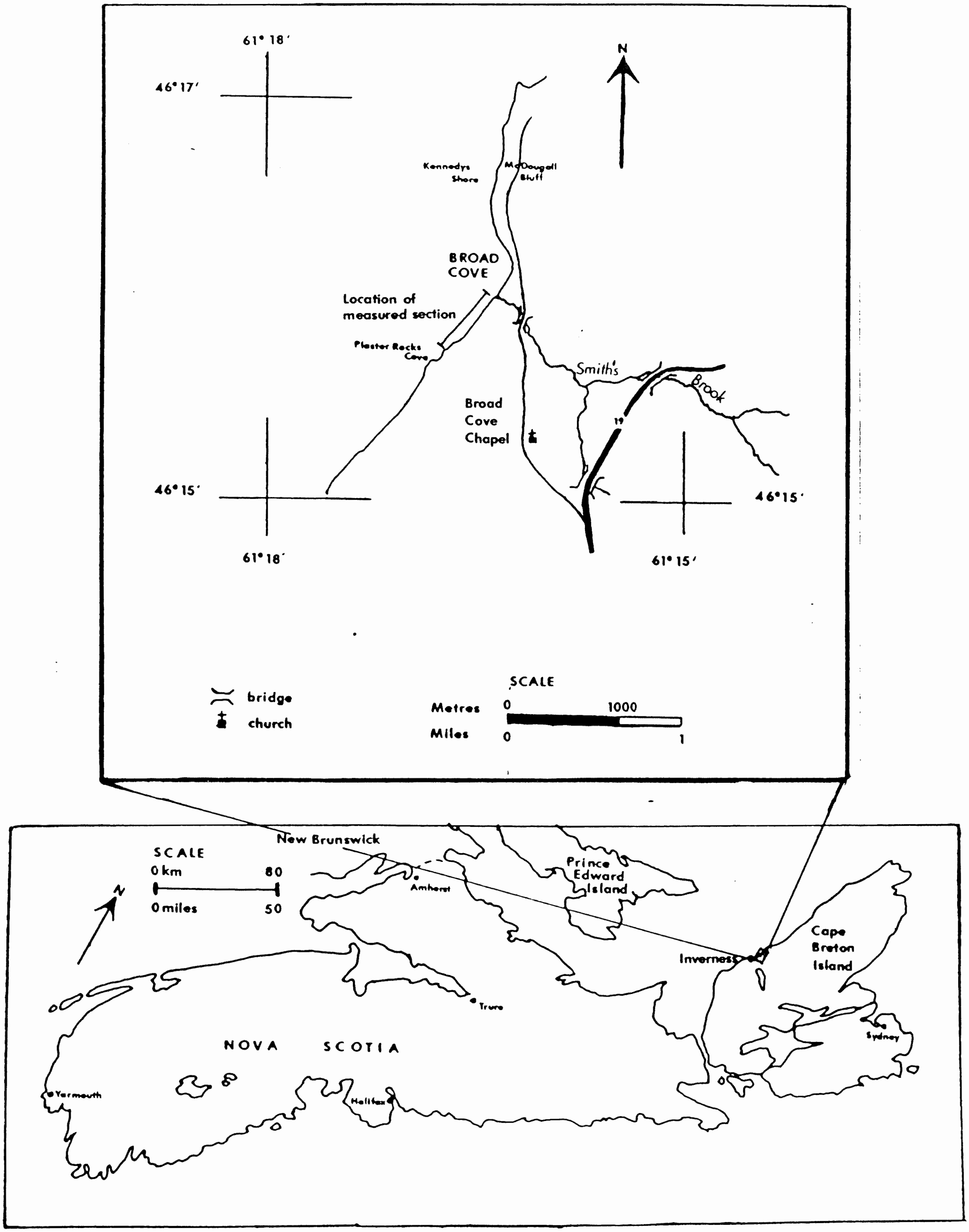


Figure 1. Location map of Broad Cove study area, Nova Scotia.

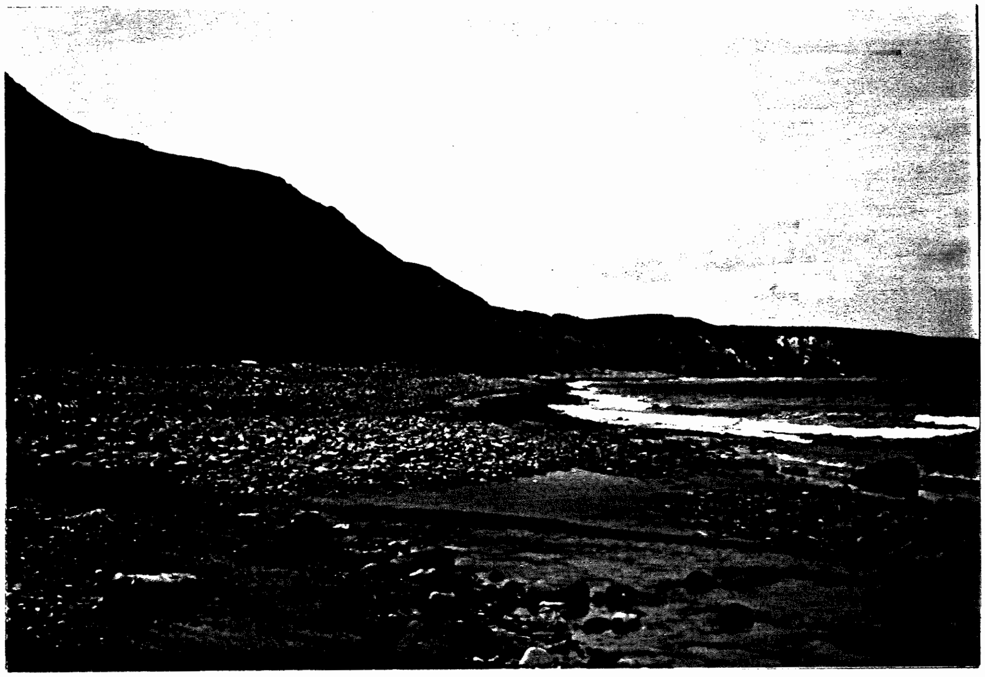


Figure 2. The study section seen from the mouth of Smith's Brook. The white rock in the distance is Windsor Group gypsum at Plaster Rocks Cove. Length of section approximately 600 m.

driveway leads down to the shore where the stream can be easily crossed on foot when the water level is low. Access through the field on the south side of the brook is an alternative when the water is high.

Exposure is generally continuous with some interruptions due to recent mud slumps. The strata are exposed perpendicular to the strike of the beds and dips range from 25° to 75° northeast. Individual units are traceable for 15 to 80 m across the exposure. No folds and only two minor faults have been recognized in the Canso strata. Bending of the beds near the cliff tops is a result of soil creep (Figure 3). Units young up section.

1.3 Previous Work

The strata at Broad Cove were mentioned as an exposure of the Carboniferous Canso Group by Bell (1927) and Norman (1935). A brief description of the section appears in a 1960 Ph.D. thesis by Rostoker. His aim was to correlate units within the Canso Group throughout Nova Scotia and he did not study the Broad Cove section in detail. Belt looked at the area during field work for his 1962 Ph.D. thesis. His general description correlates well with the more detailed work of this thesis.

1.4 Tectonic Setting

Eastern Canada is part of the Appalachian mountain chain which extends along the northeastern coast of North America

Figure 3. Typical exposure of Canso Group strata at Broad Cove. Upper bending of units is a result of soil creep. Section represented is 165-175 m (0.5 m stick for scale).

from Alabama to Newfoundland. Continental collision in Middle Devonian time, termed the "Acadian Orogeny", produced the Appalachian Mountains (Bradley, 1982). After the collision a wide intracontinental transform fault zone existed in the region now occupied by the Maritime Provinces. High-angle faults divided the area into a series of interconnected subsiding basins and surrounding stable platforms and uplifted basement blocks, collectively called the Fundy Basin (Bradley, 1982). (Figure 4). Sediments that accumulated in the fault-bound basins were derived mainly from the uplifted blocks and platform areas. Sediment accumulated in the Fundy Basin throughout the Late Devonian, Carboniferous and into the Permian. The maximum thickness of the sediments was estimated by Schenk (1978) at 13 km and by Bradley (1982) at 9 km.

The largest Late Paleozoic depocentre of the Fundy Basin was the Magdalen Basin, a sub-basin in the Gulf of Saint Lawrence, west of Cape Breton Island (Figure 4). The Magdalen Basin opened during the Late Devonian through Early Carboniferous in response to lithospheric stretching (Bradley,1982). The 25 000 km^2 basin contains 8 km of sedimentary fill, including Horton and Windsor Group rocks. The basin underwent two stages of formation: a rift phase and a thermal subsidence phase. The result was a steer's head configuration which is still observed in the western and northern parts of the basin. The steer's head configuration is not seen to the south and east of the basin because of deformation of the strata by

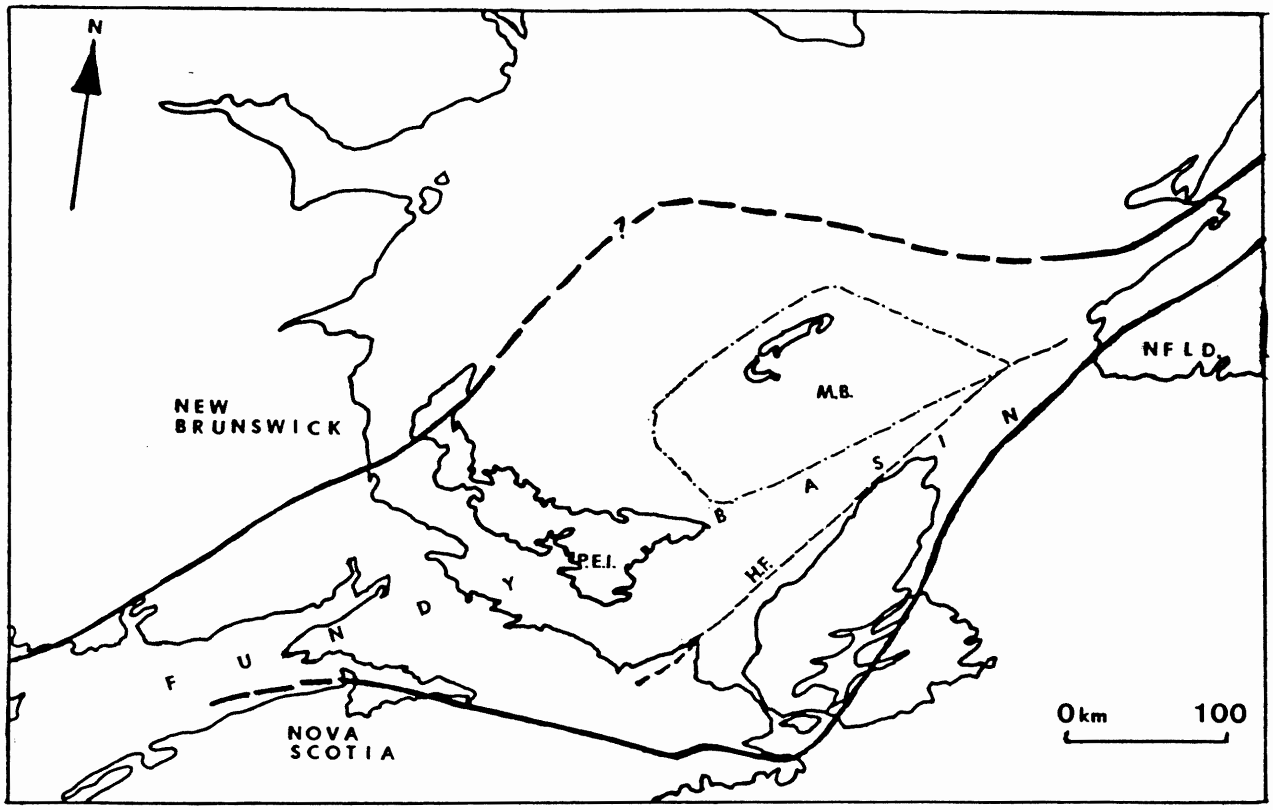


Figure 4. Extent of the Fundy Basin. The Magdalen Basin (M.B.) and Hollow Fault (H.F.) are shown. (modified after Hacquebard, 1972).

strike slip faulting which continued into the Late Carboniferous.

The Hollow Fault lies offshore parallel to the west coast of Cape Breton (Bradley, 1982). The only onshore exposure of this fault is in mainland Nova Scotia in the Cape George area (Roland, 1982). The Hollow Fault was active during the initial development of the Fundy Basin and renewed activity in the Late Visean and again in the Late Carboniferous is suggested (Yeo, 1985).

When tectonic activity declined in the Late Carboniferous, the Fundy Basin expanded onto pre-Carboniferous basement (Figure 5).

The McKenzie model of pull-apart basins applies to the Carboniferous basins of the northern Appalachians on a regional scale (Bradley,1982). The model describes a two-stage evolution of sedimentary basins. The first, or rift phase, involves stretching of the lithosphere and the subsequent formation and sinking of basins. This initial stage of stretching is accompanied by increased heat flow. During the second phase declining heat flow results in thermal subsidence of an expanded basin. The initial rift is buried beneath a blanket of sediments.

Folding of Carboniferous sediments occurred during the "Maritime Disturbance" which may have been caused by collision of North America with part of Africa (Schenk, 1978). The Late Carboniferous collision deformed the sedimentary sequences in eastern Canada.

In the Triassic, uplift and gravity faulting occurred in the

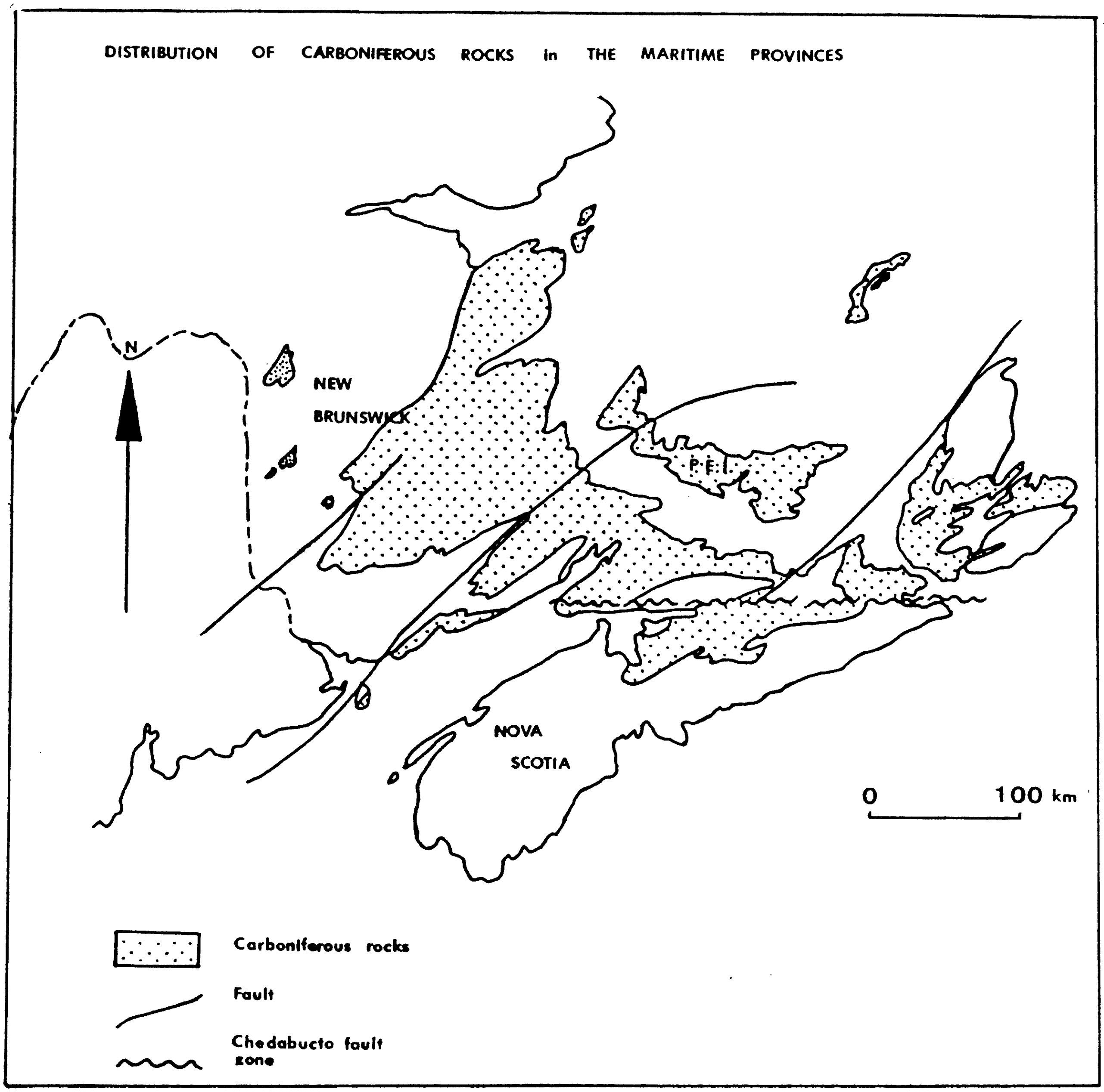


Figure 5. Distribution of Carboniferous rocks in the Maritime Provinces (modified after Rast et al., 1979).

region. This was followed by rifting and flooding by the Atlantic Ocean in the Jurassic (Schenk,1978).

1.5 Regional Stratigraphy and Sedimentation

The Carboniferous rocks of eastern Canada have been divided into six groups. The groups are, in order of decreasing age, the Horton, Windsor, Canso, Riversdale, Cumberland, and Pictou Groups (Hacquebard, 1972). The older three are of Late Devonian to Mississippian age and the younger three are Pennsylvanian to Lower Permian. Hacquebard (1972) assigned ages to the six units based on spore studies (Table 1). The group boundaries are diachronous.

Sedimentation during the Carboniferous was predominantly continental, the only exception being the marine limestones and evaporites of the Windsor Group. Hacquebard (1972) subdivided the continental strata into fanglomerate, fluvial, lacustrine, and swamp facies. The terrestrial sedimentary pattern in the Carboniferous is described by Schenk (1978) as a system of alluvial fans which graded laterally into alluvial plains with lakes.

Existing unconformities within the Carboniferous strata of eastern Canada are local (Howie, 1979). The six groups are essentially conformable as sedimentation was probably continuous in parts of the basin complex into the Early Permian. A contact between two of the groups can be unconformable adjacent to one upland and conformable adjacent to another (Kelley, 1967). In the upland areas tectonic activity

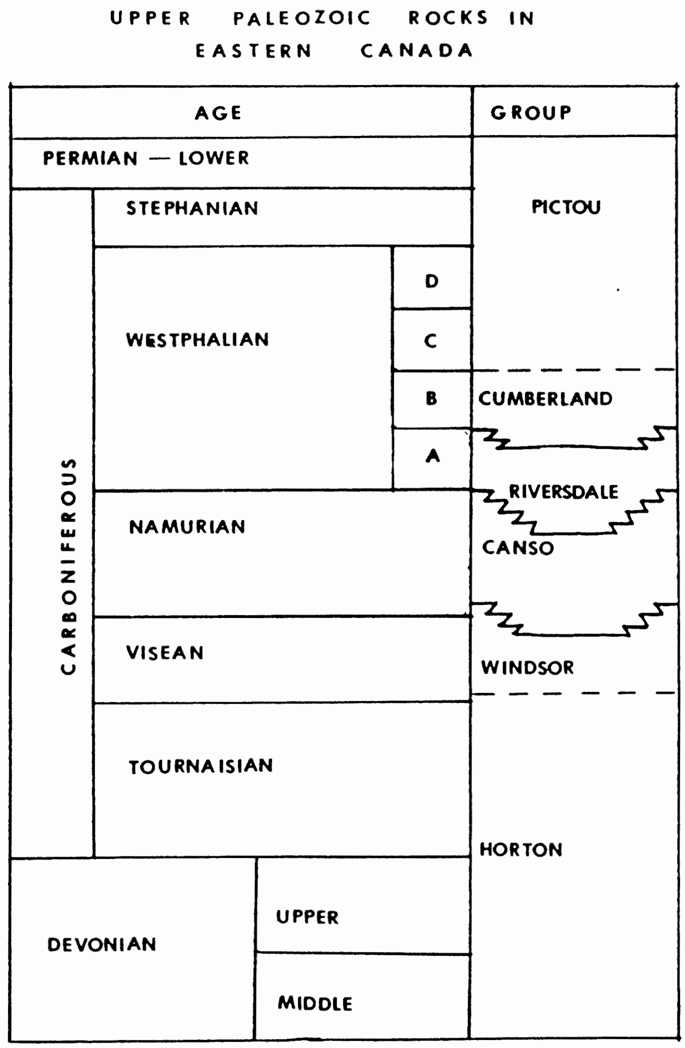


Table 1. Carboniferous rock groups in eastern Canada and their ages based on spore studies. The zigzag lines represent the diachronous character of the groups (modified after Hacquebard, 1972).

was not everywhere simultaneous and only a few kilometres from areas of tectonism sedimentation continued with no break.

Horton Group rocks, predominantly red clastics with local volcanics and nonmarine limestones and evaporites, were deposited in fault-bound basins in fanglomerate, fluvial, and lacustrine facies (Bradley,1982).

Oceanic connection(s) in Windsor time (mid- to late-Visean) permitted transgression of the shallow Windsor Sea over much of Maritime Canada (Geldsetzer, 1978). Windsor Group rock types include marine limestone and evaporite, and shale, formed in subaerial, shallow marine, and supratidal environments (Hacquebard, 1972).

Canso Group sediments were deposited after the gradual regression of the Windsor Sea under semi-arid climatic conditions (Howie, 1979) in fluviatile and lacustrine environments. Rock types include nonmarine red and grey-green shale, sandstone, and limestone. In Phanerozoic rocks the only diagnostic criterion for distinguishing lacustrine from marine deposits is the absence of marine biota in the former (Selley, 1978).

The Riversdale Group consists of red and grey sandstone, siltstone, and shale with local conglomerate and coal. The rocks were deposited under predominantly fluviatile conditions.

The Cumberland Group contains economic coal, red and grey conglomerate, sandstone, and shale. The sediments were deposited in fluvial, lacustrine, and swamp environments.

The youngest Carboniferous rocks in eastern Canada belong to the Pictou Group and the equivalent Morien and Stellarton Groups and include red and grey sandstones and shales. The sandstones and shales were deposited in fluviatile, lacustrine, swamp, and floodplain environments (Hacquebard, 1972).

1.6 Stratigraphic Setting of Study Section

In the study section a faulted contact between the Canso Group and the underlying Windsor Group gypsum is exposed at Plaster Rocks Cove. The Riversdale Group overlies the Canso strata with angular unconformity north of the mouth of Smith's Brook in the section studied by James Waterfield (B.Sc. thesis, 1986).

Chapter 2 Methods

2.1 Field Work

Two weeks of field work at Broad Cove commenced on April 22, 1985. This work was complemented by two days at the exposure in the following months.

A stratigraphic section of almost 400 m was measured using a metre stick. Thickness, lithology, colour, unit contacts, sedimentary structures, and other features were noted for each unit. Unit thicknesses are in the order of tens of centimetres. Representative hand-size samples (128) were collected. A photo-mosaic of most of the section was prepared. A Markov Chain Analysis of 942 transitions between facies was performed.

2.2 Petrographic Methods

Thin sections of 12 samples were prepared, stained with Alizarin Red to differentiate between calcite and dolomite (see Appendix for procedure) and studied with the petrographic microscope. The minerals, textures, and structures of the samples were studied and grain types, sizes, shapes, sorting, relationships, and abundance were noted.

2.3 X-ray Diffraction Methods

Six samples were crushed to silt-size and smeared onto glass slides with acetone. Each slide was analyzed at 40 kV and 20 mA with nickel-filtered Cu K-alpha radiation on the Philips x-ray diffractometer of the geology department at Dalhousie University. The scanning speed was 1°/s and the chart speed was 1 cm/min. The time constant was 4 seconds. Each slide was scanned from 2-50° 2θ.

X-ray diffraction analysis was used to determine the presence and the proportions of calcite and dolomite in the carbonate rocks. Peaks were identified using tables from Cook _et al._, (1975). The x-ray peak-height measurement procedure of Royse _et al._ (1971) was used to determine the relative proportions of dolomite and calcite.

Chapter 3 Facies

3.1 Introduction

The definition of a facies is commonly based on the field aspects of the rocks (Walker, 1984). A facies is defined by a specific set of physical traits such as lithology, colour, fossil content, and sedimentary structures (Tucker, 1982). Rocks being studied can be divided into facies following these guidelines and the facies are either named arbitrarily (using letters or numbers) or given brief descriptions (e.g. red mudstone facies). The degree of subdivision is determined by the abundance of different traits and the study objectives. Facies named in the early stages of a study will eventually be given an environmental interpretation (Walker,1984).

Seven distinct facies are recognized in the Canso Group strata at Broad Cove and are based on lithology (composition), carbonate content, sedimentary structures, grain size, carbonate grain types, bedding, and fissility on weathering (Table 2). The facies are divided into two groups: carbonate facies and clastic facies. The carbonate facies are described in order of abundance and are followed by descriptions of the clastic facies, also in order of abundance. Table 3 shows the relative abundance of each facies in the measured section.

The facies names are field terms. Additional data was obtained from microscopic and x-ray diffraction analysis.

Facies Name	Colour	Bedding	Weathering/ Parting	Sedimentary Structures	Major Minerals	Comments
Calcareous Shale	grey-green, buff, brown	1 cm thick	recessive/ platey	desiccation cracks, lamination	calcite, quartz, dolomite	grain size: less than 0.1 mm
Dolostone	grey, buff, brown	10 cm thick	resistant/ blocky	lamination, desiccation cracks	dolomite, quartz	grain size: less than 0.1 mm
Stromatolitic Limestone	green-grey, brown	unbedded	resistant/ blocky	wavy lamination	calcite, dolomite	rare ooids and stylolites
Calcareous Mud	grey	unbedded	recessive/ conchoidal	---	calcite, quartz, clay minerals	unconsolidated
Oolitic Limestone	brown	unbedded	resistant/ blocky	---	calcite	ooids abundant
Mudstone	red (minor green)	unbedded	recessive/ platey	ripples, cross-beds, rain prints	quartz, muscovite, feldspar	grain size: 0.03-0.07 mm
Sandstone	red (minor green)	1-5 cm thick	resistant/ blocky	ripples, cross-beds, rain prints, load casts, lamination	quartz, muscovite, feldspar	grain size: 0.07-0.5 mm

Table 2. Facies and their characteristics.

FACIES	ABUNDANCE (%)
Oolitic Limestone	0.2
Calcareous Mud	0.6
Stromatolitic Limestone	0.9
Dolostone	13.9
Sandstone	15.1
Calcareous Shale	30.2
Mudstone	39.1

Table 3. Relative abundances of facies in measured section.

3.2 Calcareous Shale

The calcareous shale facies consists of fine-grained (less than 0.1 mm) fissile rock with low resistance to weathering. The strata are dark green to dark brown on fresh surfaces and green-grey to buff-coloured on weathered surfaces. Beds are less than 1 cm thick. The rock has a positive reaction to hydrochloric acid.

Thin (1-2 mm) calcite veins cut across and lie parallel to the bedding locally. Rare desiccation cracks are observed. Planar and wavy laminae are generally less than 1 mm thick.

The calcareous shale and dolostone facies are commonly interbedded with abrupt contacts (Figure 6). The average thickness of the shale units, when interbedded with dolostone, is 0.25 m. Units of calcareous shale elsewhere in the sequence are commonly up to 3 m thick.

The calcareous shale consists predominantly of calcite, detrital quartz, and dolomite with minor gypsum and muscovite. The calcite to dolomite ratio is approximately 5:1. The carbonate minerals make up about 50% of the rock.

Compositional differences between laminae are associated with colour differences. Paler layers are composed mainly of detrital quartz and are 0.25-1 mm thick. Darker layers of micritic calcite are 0.5-1.5 mm thick. Anhedral patches of sparry calcite and euhedral rhombs of dolomite are present in the micrite giving a birdseye-type fabric to the rock. The patches of sparry calcite average 0.6 mm in diameter and the dolomite crystals average 0.4 mm.

Figure 6. Calcareous shale facies (C) interbedded with dolostone facies (D) (0.50 m stick for scale).

3.3 Dolostone

The dolostone is a hard rock that is resistant to weathering. In outcrop the dolostone is grey to buff-coloured. Fresh surfaces are grey-green to dark brown. Reaction with hydrochloric acid is very slow. Average bed thickness is 10 cm.

Wavy laminae less than 1 mm thick are present but are not always visible in outcrop. Desiccation cracks and pseudo-cubic cavities (average size: 0.4 mm) lined with crystals of carbonate minerals (calcite, dolomite) which average less than 0.1 mm in size are present but not common.

Dolostone and calcareous shale are generally interbedded (Figure 6). The dolostone is more resistant to weathering and thicker bedded and in the field the dolostone protrudes from the exposure whereas the calcareous shale is recessive. Average thickness of the dolostone units is 0.25 m. Abrupt basal and upper contacts are common.

The dolostone consists mainly of dolomite (70%) and quartz (20%). Muscovite, calcite, and gypsum are present as minor components. The presence of gypsum is indicated by x-ray diffraction analysis. The dolomite to calcite ratio is about 20:1.

Petrological studies revealed very thin rhythmic laminae of dolomite (with minor calcite) and detrital quartz (with minor muscovite and feldspar). The dolomite generally occurs as anhedral mosaics and less commonly as rhombic crystals 0.02 mm in size. The grain size of the detrital quartz is generally less than 0.02 mm. The average thickness of the laminae is 0.05 mm.

3.4 Stromatolitic Limestone

The stromatolitic limestone is resistant to weathering and has a grey to brown weathered surface and a green to darker brown fresh surface. The limestone units take the shape of a series of connected low domes (Figure 7. Also Figure 17). Thickness of the stromatolitic limestone ranges from 6 to 30 cm; dome diameter is 12 to 80 cm; and maximum dome height is 30 cm. Basal and upper contacts are generally sharp.

Wavy lamination is observed in outcrop (Figure 8).

Calcite and dolomite are the major minerals in this facies accounting for about 80% of the limestone. The ratio of calcite to dolomite is 4:1. Detrital quartz makes up about 15% of the rock and muscovite and gypsum/anhydrite are present in minor amounts. The average grain size is 0.02 mm.

Microscopic study indicated rhythmic pale and dark laminae. Both types are 0.1-2 mm thick with abrupt contacts.

The dark layers are composed of micrite with minor sparry calcite in anhedral patches about 0.06 mm in diameter. Secondary euhedral rhombic dolomite crystals with an average grain size of 0.05 mm were observed in the micrite-rich laminae. The pale laminae are dolomite-rich. The dolomite occurs as anhedral mosaics with some well-formed rhombic crystals which have an average grain size of 0.05 mm. The

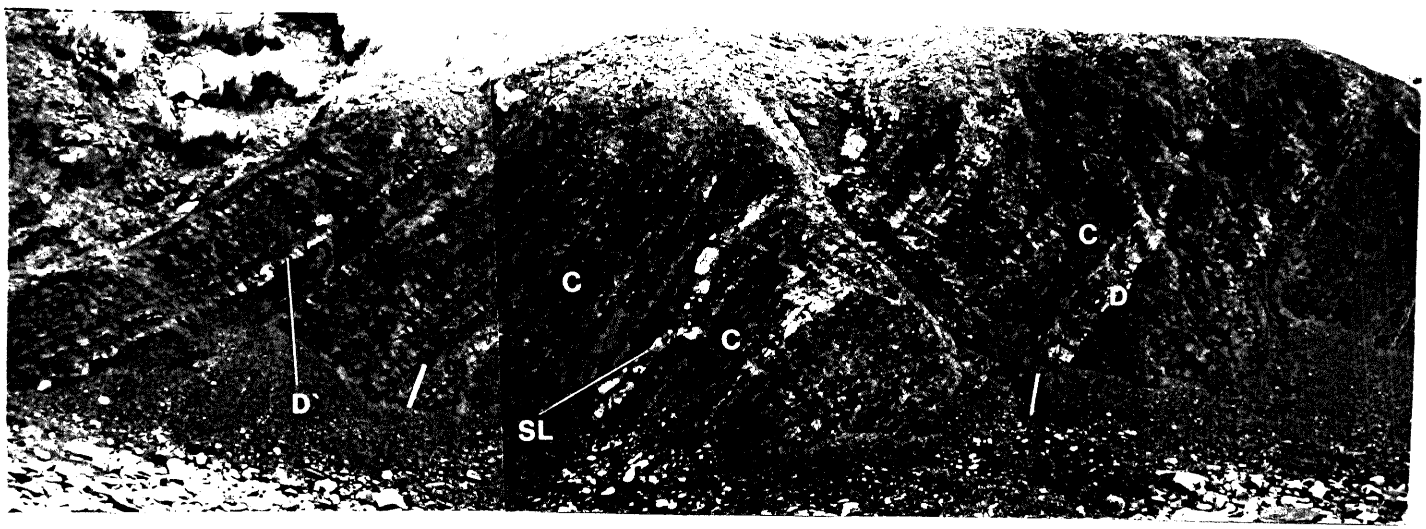


Figure 7. Stromatolitic limestone (SL), dolostone (D), and calcareous shale (C) in outcrop (0.50 m stick for scale). Section represented: 188-202 m.

Figure 8. Cross-section of stromatolitic limestone facies unit showing wavy lamination.

detrital quartz (0.02 mm in diameter), muscovite, and evaporites are found throughout the rock in both the pale and dark laminae.

The laminae are cut by veins, 1 to 2 mm wide, which consist of mixed calcite and dolomite. Rare ooids with micritized nuclei and radial rims of coarser calcite were observed in one sample of stromatolitic limestone. The ooids are cemented by calcite and dolomite and exhibit little evidence of compaction. Stylolites, indicating pressure solution, are rare. No fossils were noted.

3.5 Calcareous Mud

This facies consists of unconsolidated calcareous mud, grey to dark grey in colour. The material can be molded with the fingers. It is unbedded and commonly found as thin units 8-25 cm thick. Basal contacts are sharp, as are the upper contacts of the units. Most of the occurrences of this facies are in the lower part of the study section.

X-ray diffraction revealed that the major constituents are calcite (40%) and quartz (25%). Muscovite, kaolinite, and chlorite are the other minerals present. Muscovite makes up about 15% of the rock and kaolinite and chlorite each account for about 10%.

3.6 Oolitic Limestone

Two units of oolitic limestone were observed at Broad Cove. In outcrop the limestone is brown and resistant (Figure 9). The two units vary laterally in thickness and average 20 cm.

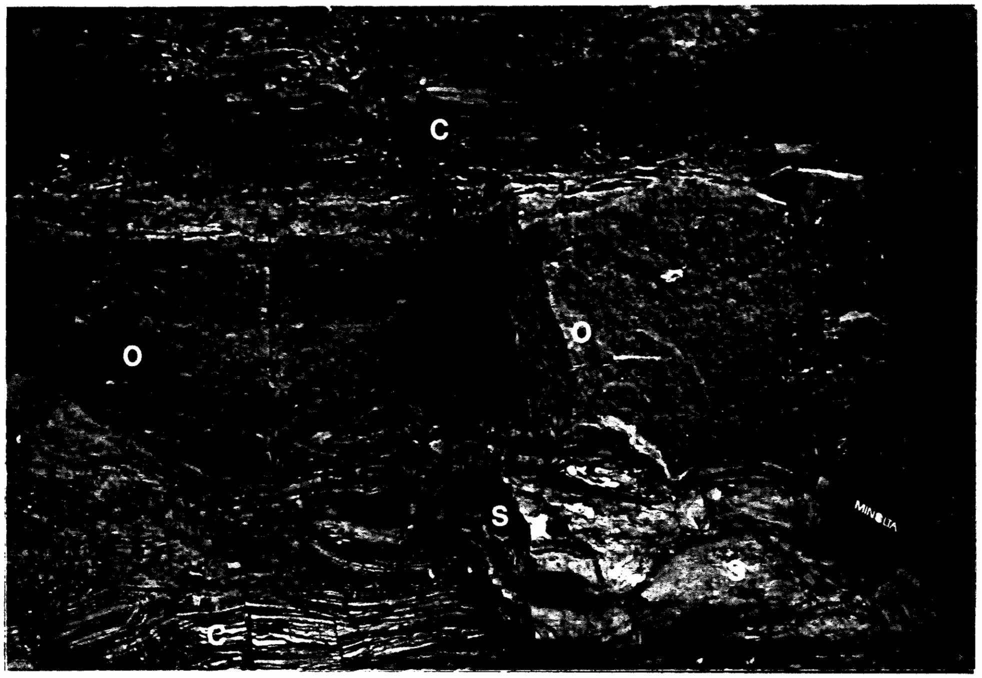


Figure 9. Oolitic limestone (O) overlying stromatolitic limestone (S). Calcareous shale (C) also present.

Upper and lower contacts are abrupt.

The limestone is composed almost entirely of calcite (over 95%) with minor dolomite. Ooid-rich and micrite-rich regions are visible in thin section. Ooids are abundant and make up almost 60% of the rock. Peloids are less common. Fossils were not observed.

Ooid diameters range from 0.2 to 1.5 mm. Nuclei (as intraclasts, peloids, and unidentified fragments) range from 0.02 to 1.0 mm in size and are circular to irregular in shape. The nucleus may account for 5-90% of the ooid. A calcite cortex with both radial and concentric structure coats the nucleus. Irregular and even coatings were observed. Neighbouring ooids are generally in contact. Long grain contacts are common (after grain contact classification in Selley, 1981). Voids are infilled mainly by sparry calcite cement and rare secondary euhedral dolomite crystals which have an avergae grain size of less than 0.02 mm.

Micrite-rich regions appear to be of intraclasts of algal material which exhibit wavy lamination.

3.7 Mudstone

The mudstone is a fine-grained, predominantly red rock which is not resistant to weathering. Platey weathering is most common but minor conchoidal partings are noted. Over 80% of the mudstone in the study section is red, the remainder being green.

Sedimentary structures that are present include ripple marks on exposed bedding surfaces, cross-beds (up to 0.50 cm in height), and rain prints. Thin clay layers (1-3 cm thick) cut across the plates locally.

Interbedded mudstone and sandstone is common (Figure 10), with abrupt contacts. Mudstone unit thickness ranges from 0.50 to 3 m.

The mudstone is composed of quartz, feldspar, and muscovite. The grain size range is 0.03 to 0.07 mm

3.8 Sandstone

The sandstone consists of fine- to medium-grained sand and is predominantly red with minor green units. Bed thickness ranges from 1 to 5 cm and the sandstone is generally resistant to weathering.

Sedimentary structures include: ripples and cross-beds (Figure 11) (average height: 0.5 cm, average wavelength: 3 cm); ripple-drift cross-lamination (height: up to 0.5 cm, wavelength: 3-4 cm); rare large-scale planar cross-beds (height: 0.5 m); planar laminae (less than 1 mm thick); and load casts and rain prints. The sedimentary srtuctures were not observed to occur in any sequence - they occur randomly throughout the units.

Plant fragments were found in one sandstone unit in the upper strata of the measured stratigraphic section (Figure 12). The sandstone of this unit is green. Most of the plant fragments have been coalified and one has been surrounded by native copper and malachite (Figure 13).

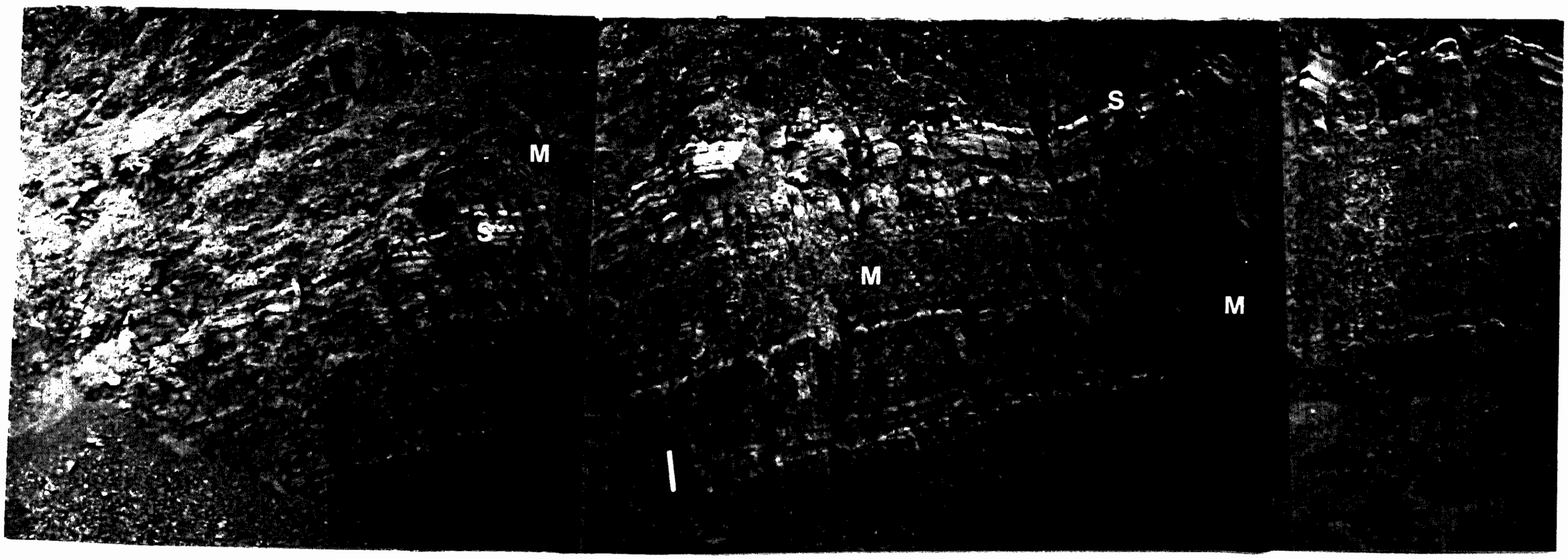


Figure 10. Mudstone facies (M) interbedded with sandstone facies (S) (0.5 m stick for scale). Section represented: 333-337 m.

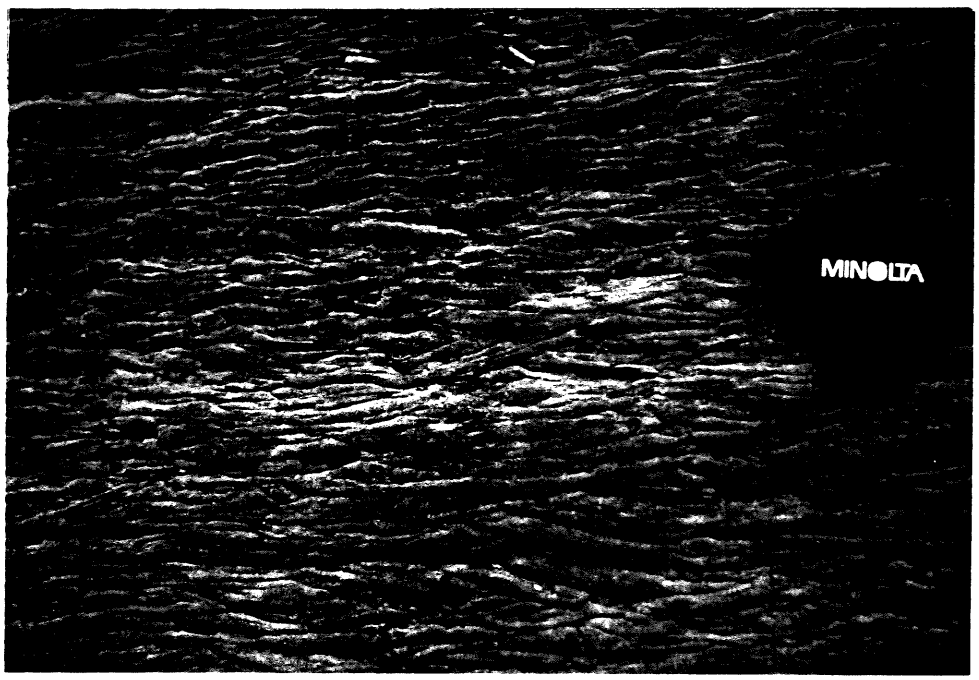


Figure 11. Small-scale cross-bedding in fine sandstone.

Figure 12. Sandstone unit in which coalified and copper/malachite-surrounded plant fragments occur (P) (0.5 m stick for scale). Section represented: 373-378 m.

Figure 13. Copper- and malachite-surrounded plant fragment.

Units of sandstone average 0.5 m in thickness but one sequence of continuous sandstone reaches a thickness of about 10 m. The basal and upper contacts are commonly planar and abrupt.

The sandstone comprises quartz, feldspar, and muscovite. Hematite cement is present.

Chapter 4 Stratigraphy

4.1 Measured Section

The basis of this study was the measuring of 389 m of Canso Group strata at Broad Cove from Plaster Rocks Cove (gypsum outcrop) to just south of the mouth of Smith's Brook. The facies distribution in the lower 375 m of the section is shown schematically in the appendix. (The upper 14 m were not studied in detail and so are not included in the stratigraphic column.) Sedimentary structures are noted to the right of the column at the appropriate locations. Since the differences in grain size between some facies are not substantial and composition varies widely, grain size is not shown on the diagram. The column profile indicates resistance to weathering.

4.2 Facies Assemblages

4.2.1 Introduction

Groups of facies are commonly found together in a stratigraphic sequence and can be called facies assemblages or facies associations (Tucker, 1982). The facies of a facies assemblage are all deposited in the same overall environment. The different facies in an assemblage may be the result of fluctuating conditions or different depositional processes, or may represent local depositional settings.

Two major facies assemblages are recognized in the strata at Broad Cove: the carbonate assemblage and the siliciclastic assemblage. A third mixed assemblage consists of interbedded carbonate and siliciclastic units. Table 4 shows the proportions of the different facies in each facies assemblage. Proportions of facies within the assemblages remain constant throughout the section with the exception of the calcareous mud and oolitic limestone. The former decreases in abundance up section and the latter is only observed in two occurrences of the carbonate assemblage, near the midpoint of the measured section.

4.2.2 Carbonate Facies Assemblage

The five facies which consist predominantly of carbonate minerals generally occur together and are grouped as the carbonate facies assemblage. The calcareous shale and dolostone are the most abundant in the group and are commonly interbedded. The calcareous mud, stromatolitic and oolitic limestone facies are less common.

The average thickness of intervals formed by the carbonate assemblage is 17 m. Thickness ranges from 8 to 30 m.

FACIES	Proportion of facies in facies assemblage (expressed as %)		
	Carbonate Assemblage	Siliciclastic Assemblage	Mixed Assemblage
Calcareous Shale	61.8	1.8	39.3
Dolostone	31.5	1.1	11.8
Calcareous Mud	1.2	0.2	0.6
Stromatolitic Limestone	2.1	0.0	0.7
Oolitic Limestone	0.5	0.0	0.0
Mudstone	2.9	68.2	37.4
Sandstone	0.0	28.7	10.2

Table 4. Proportions of facies in the facies assemblages.

4.2.3 Siliciclastic Facies Assemblage

This assemblage consists of the mudstone and sandstone facies. The two generally occur as thin, interbedded, laterally continuous units but rare thick sequences of one facies do exist. The range in thickness of the siliciclastic assemblage is 6-60 m with an average of 20 m.

4.2.4 Mixed Facies Assemblage

The distinction between the mixed assemblage and the individual carbonate or siliciclastic assemblages is abitrary. Where a thick succession of 90% of one set of facies exists the strata are assigned to that assemblage. Where both the carbonate and siliciclastic units are interbedded and thicknesses of the individual units are not great (i.e. less than 1 to 3 m) the term "mixed facies assemblage" is applied. The mixed assemblage occurrences are not as thick as the other assemblages and range from 4 to 15 m.

4.3 Facies Assemblage Distribution

Figure 14 is a simplified stratigraphic column showing the distribution of facies assemblages. In the lower part of the measured section the carbonate facies assemblage predominates. The siliciclastic assemblage is more prevalent in the upper part. The mixed assemblage is found throughout the section.

The carbonate facies assemblage makes up 36% of the measured strata whereas the siliciclastic facies assemblage

STRATIGRAPHIC SECTION —— ROCK ASSEMBLAGES: BROAD COVE

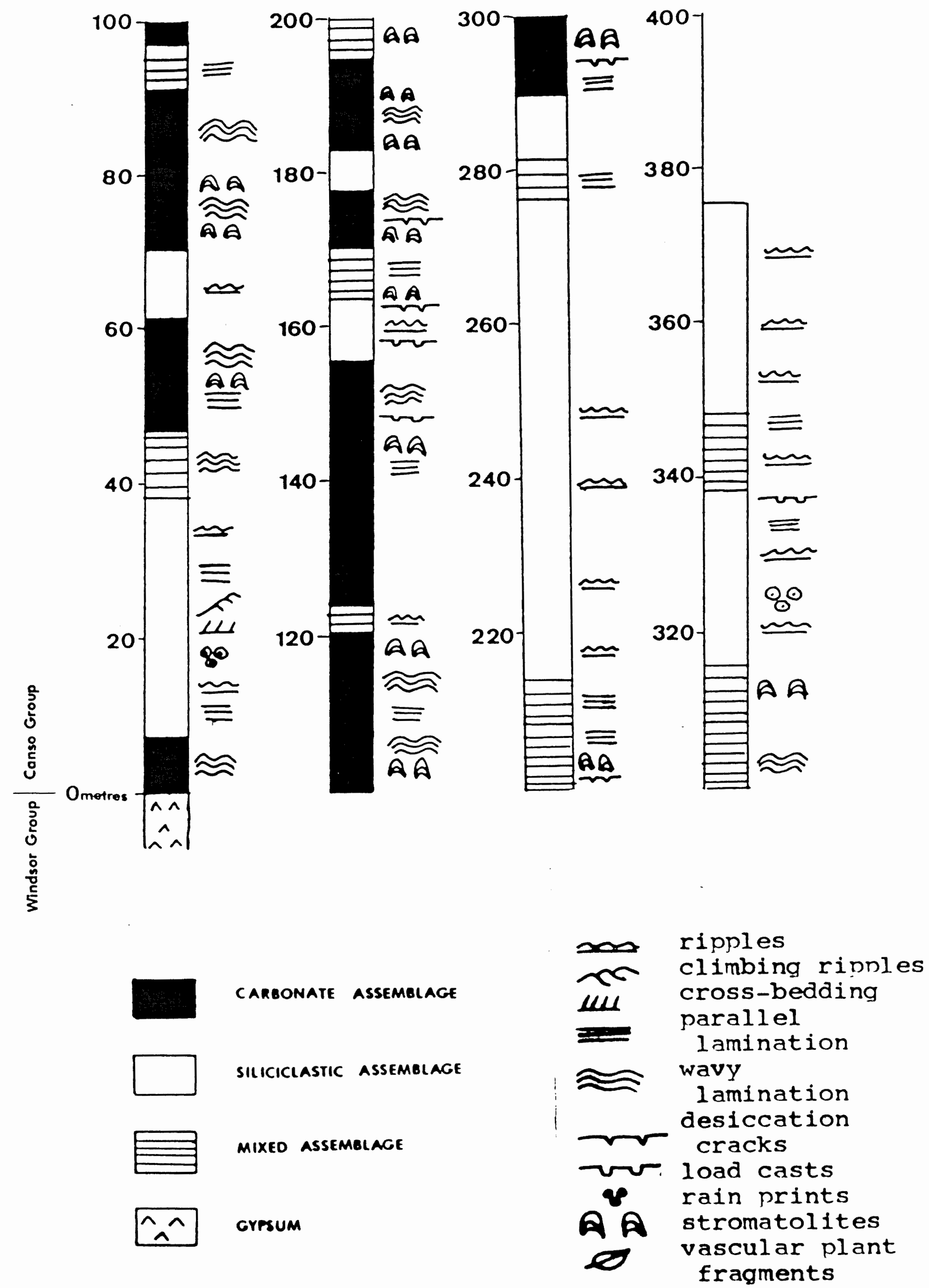


Figure 14. Distribution of facies assemblages.

makes up 44%. The mixed facies assemblage accounts for the remaining 20%.

In three instances, the mixed assemblage represents a transition between the other two assemblages. Generally the contacts between the carbonate and siliciclastic assemblages are abrupt. The mixed assemblage is commonly observed between two occurrences of the carbonate and siliciclastic assemblage. The average thickness of the mixed assemblage increases up section but no consistent trend in thickness of the other two assemblages is recognized.

4.4 Cyclicity

Statistical procedures can be used to aid in the interpretation of depositional environments. Markov Chain Analysis is a simple statistical method which tests for cyclicity. A Markov analysis allows the deduction of a certain state's occurrence by the knowledge of the immediately preceding state.

The Canso Group at Broad Cove was analyzed using Markov Chain Analysis. In this case the states are the 7 facies, each being assigned an arbitrary number for convenience (Table 5).

Changes of state, i.e. transitions from one facies to another different facies are recorded over the entire section. The analysis follows the procedure of Miall (1973) (see Appendix).

The transition count matrix, independent trials

Facies	Number
Calcareous Shale	1
Dolostone	2
Stromatolitic Limestone	3
Calcareous Mud	4
Oolitic Limestone	5
Mudstone	6
Sandstone	7

Table 5. Facies with corresponding numbers used for Markov Chain Analysis.

probability matrix, transition probability matrix, and difference matrix are shown in table 6.

Results of the Markov Chain Analysis on the 942 transitions are shown in figure 15. A difference value of 0.10 is taken as the lower limit of significance.

The calcareous shale and dolostone are closely related and are interbedded throughout the section. The mudstone and sandstone show a similar relationship. The high significance of the transition from oolitic limestone to calcareous shale is taken as a provisional result as there are only two occurrences of oolitic limestone and both are overlain by calcareous shale. Calcareous shale is commonly preceded by stromatolitic limestone.

The results of the analysis correlate well with the strata as seen in outcrop. There is a definite association of the carbonate facies in the section. The siliciclastic facies are also closely associated.

The carbonate assemblage is overlain abruptly by the siliciclastic assemblage several times in the lower 215 m of the section (Figure 16). Other occurrences of the carbonate assemblage contain intervals of the mixed assemblage. The siliciclastic assemblage is overlain by either the mixed or the carbonate assemblage or the carbonate assemblage with intervals of mixed units. The general trend is from carbonate, through siliciclastic, mixed, and into carbonate. The average thickness of the cycles is 50 m. The siliciclastic and mixed assemblages

TRANSITION COUNT MATRIX

	1	2	3	4	5	6	7	
1	0	252	14	11	1	30	6	314
2	261	0	5	6	0	8	0	280
3	13	5	0	0	1	2	0	21
4	9	8	0	0	0	6	1	24
5	2	0	0	0	0	0	0	2
6	22	13	2	3	0	0	127	167
7	7	1	0	3	0	123	0	134
	314	279	21	23	2	169	134	942

INDEPENDENT TRIALS PROBABILITY MATRIX

	1	2	3	4	5	6	7
1	.000	.444	.033	.037	.003	.269	.213
2	.474	.000	.032	.035	.003	.255	.202
3	.341	.303	.000	.025	.002	.183	.145
4	.342	.304	.023	.000	.002	.185	.146
5	.334	.297	.022	.024	.000	.180	.143
6	.405	.360	.027	.030	.003	.000	.173
7	.389	.345	.026	.028	.002	.209	.000

TRANSITION PROBABILITY MATRIX

	1	2	3	4	5	6	7
1	.000	.803	.045	.035	.003	.096	.019
2	.932	.000	.018	.021	.000	.029	.000
3	.619	.238	.000	.000	.048	.095	.000
4	.375	.333	.000	.000	.000	.250	.042
5	1.00	.000	.000	.000	.000	.000	.000
6	.132	.078	.012	.018	.000	.000	.760
7	.052	.007	.000	.022	.000	.918	.000

DIFFERENCE MATRIX

	1	2	3	4	5	6	7
1	.000	.359	.012	-.002	.000	-.173	-.194
2	.458	.000	-.014	-.014	-.003	-.226	-.202
3	.278	-.065	.000	-.025	-.002	-.088	-.145
4	.033	.029	-.023	.000	-.002	.065	-.104
5	.666	-.297	-.022	-.024	.000	-.180	-.143
6	-.273	-.282	-.015	-.012	-.003	.000	.587
7	-.337	-.338	-.026	-.006	-.002	.709	.000

Table 6. Markov Chain Analysis matrices.

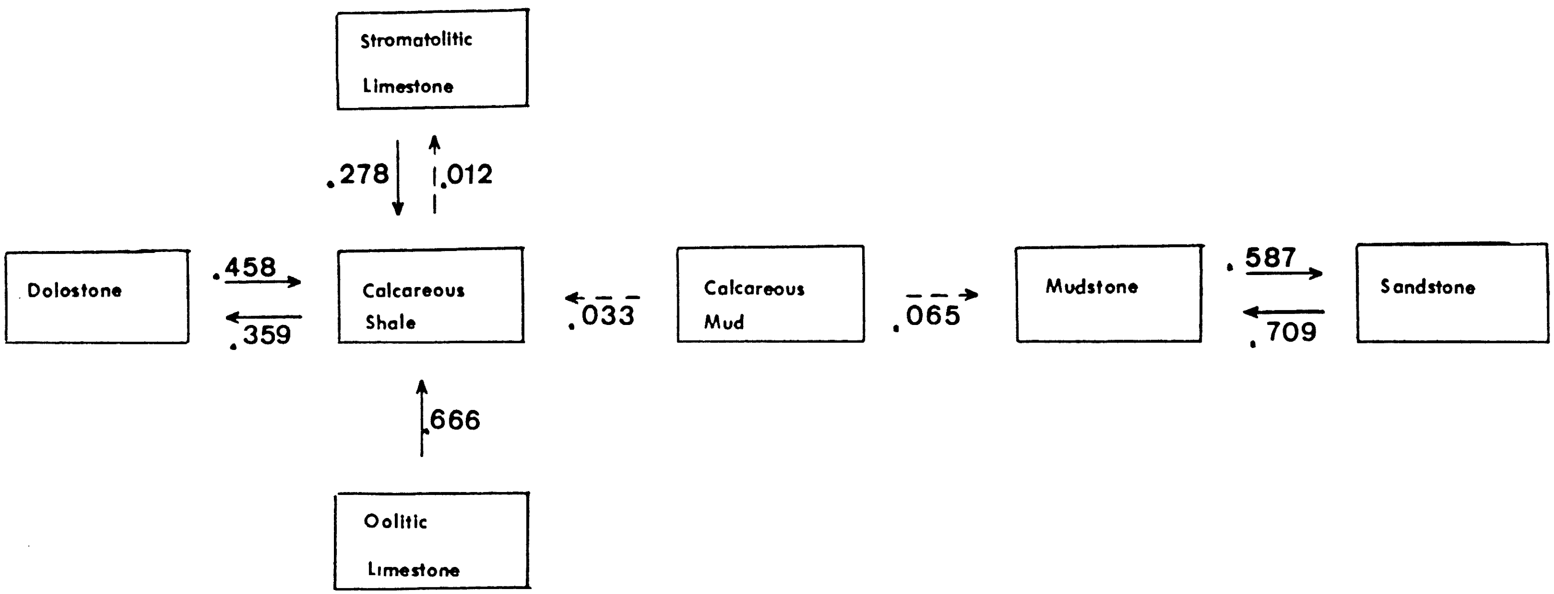
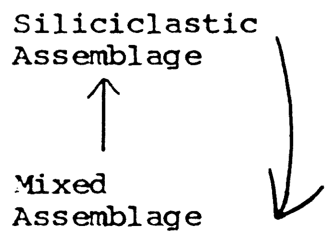


Figure 15. Markov Chain Diagram. Solid arrows indicate a high probability for the corresponding transition while lower probabilities are represented by dashed arrows. The diagram includes all positive difference values.

Upper strata:



Lower strata:

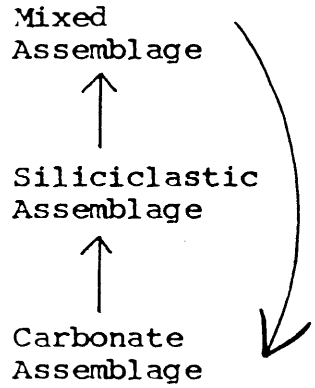


Figure 16. General trends of assemblages in measured section (lower strata: 0-215 m; upper strata: 215-375 m).

alternate in the upper strata.

Chapter 5 Algal Stromatolites

5.1 Introduction

Algal stromatolites are defined by Logan et al. (1964) as laminated structures composed of particulate sediment, which have been formed by the trapping and binding of detrital sediment particles by an algal film. The organic film present during formation of the stromatolite is a complex that consists mainly of green (Chlorophyta) and blue-green (Cyanophyta) algae.

Algal stromatolites form in the shallow subtidal to supratidal marine environments and in fresh to hypersaline lakes and marshes (Tucker, 1981). Insufficient light, extensive desiccation, and grazers, such as gastropods, inhibit stromatolite growth.

Lamination of algal origin is characterized by small corrugations and irregularities in thickness (Tucker, 1981). The laminae make up larger-scale structures such as domes and columns. In modern stromatolites alternating pale and dark laminae are mineral-rich and organic-rich respectively. Ancient stromatolites consist of rhythmic layers of carbonate grains and dense micrite. The latter may be dolomitized.

5.2 Structure of Stromatolites

Twenty-one stromatolitic units have been recognized at Broad Cove. Both cross-sections and upper surfaces of stromatolites are exposed (Figure 17). The stromatolites occur as sheet-like units made up of many small domes or hemispheroids. Adjacent hemispheroids are linked laterally by laminae. The space between neighbouring hemispheroids is generally less than the diameter of the domes.

Dome height is up to 30 cm and the average diameter is 20 cm. The stromatolite units are generally traceable laterally across the outcrop. In one example, the stromatolite surrounds a mound of shale and reappears discontinuously along the same horizon.

The stromatolites are classified as laterally-linked hemispheroids (LLH) after the nomenclature devised by Logan et al. (1964) (Figure 18). Most of the stromatolites are of the close-linked (LLH-C) type.

5.3 Algal Lamination and Carbonate Grains

The stromatolitic limestone in the Broad Cove strata consists of rhythmic layers of calcite and dolomite. Both types of lamination are wavy and range from 0.1 to 2 mm in thickness. The calcite laminae are made up of micrite and sparry calcite. Detrital quartz and muscovite are found throughout the rock in both calcite- and dolomite-rich laminae.

Rare ooids were observed in some of the stromatolitic

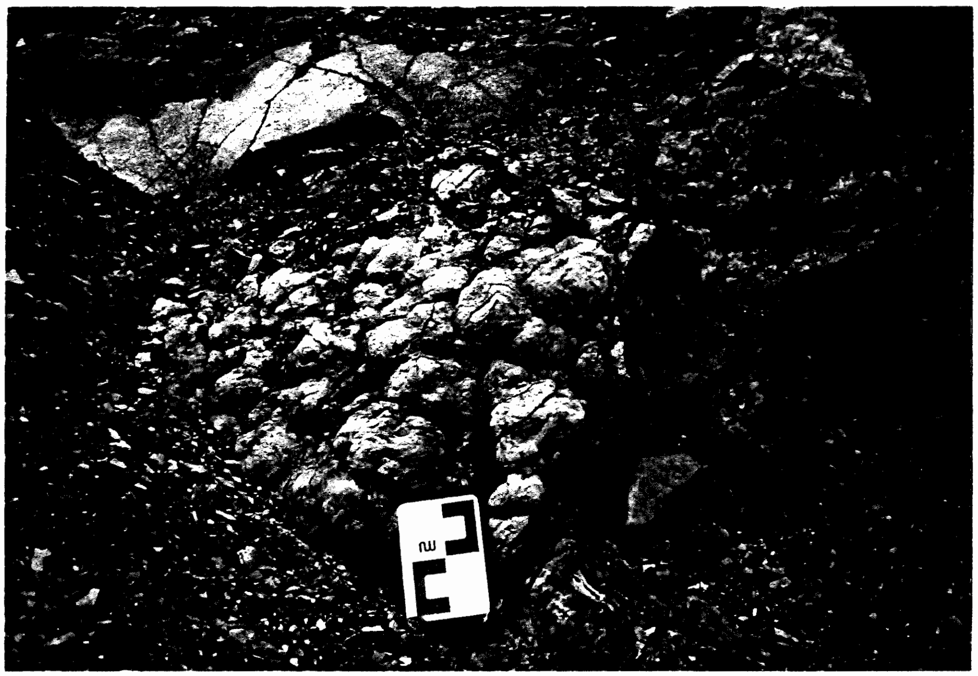


Figure 17. Exposed upper surface of stromatolitic limestone (18.5 cm long field notebook for scale).

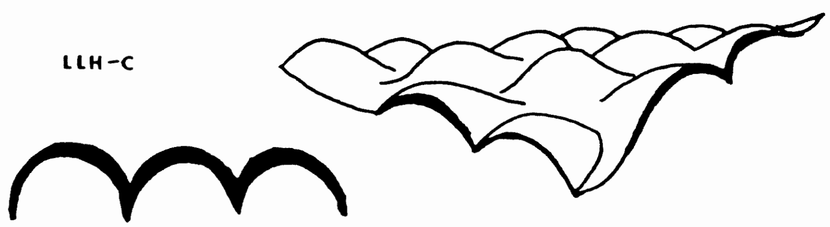


Figure 18. Laterally-linked hemispheroid structure of stromatolites. LLH-C: close-linked hemispheroids (from Logan et al., 1964).

limestone. Fossils were not observed.

5.4 Modern Algal Stromatolites

Algae of modern stromatolites can precipitate rhythmic layers of aragonite and high magnesium calcite which become calcite and dolomite in the rock record (Friedman et al., 1972). The carbonate minerals precipitate when the algae withdraws carbon dioxide (CO_2) from water during photosynthesis.

Alternatively, Gebelin and Hoffman, (1971) exnlain the dolomite laminae as a result of algal magnesium in organic complexes. During diagenesis, the algal magnesium is reformed as dolomite in the organic layer.

Generation of ooids in modern algal mats in a hypersaline pool in the Gulf of Aqaba is noted by Friedman et al. (1972).

5.5 Environmental Framework

Algal mats exhibiting laterally-linked hemispheroids develop in protected areas of the marine intertidal mudflat environment or in shallow parts of continental lakes (Logan et al., 1964). The absence of marine biota in the stromatolites of the study area suggests a lacustrine origin. The presence of ooids suggest slightly agitated water.

Aragonite or calcite was precipitated by the algae or may have been precipitated from the lake water and bound by the algae. Diagenesis caused dolomitization of either high magnesium calcite (precipitated by the algae) or algal magnesium. Detrital quartz and muscovite, probably transported from adjacent terrain, were also bound by the algae.

Doming may occur over pre-existing irregularities or be caused by evolution of gas beneath the algal mat, greater sediment accretion on dome crests, or lateral growth expansion of the continuous mat (Logan et al., 1964). At Broad Cove, some evidence of doming over pre-existing irregularities (e.g. mound of shale) was observed. Most of the stromatolites however, have grown on a flat surface and lateral growth expansion of the mat produced the doming.

Chapter 6 Discussion

6.1 Carbonate Facies

The thin, laterally extensive, interbedded calcareous shale and dolostone suggest deposition in relatively shallow water. The absence of marine fossils in the rocks implies that the deposition occurred in a lacustrine environment.

Tables 7, 8, and 9 summarize the important observations made about the carbonate rocks and the corresponding inferences.

Observation	Inference
Absence of marine fossils	Lacustrine origin
Rhythmic lamination of carbonate and detrital grains	Carbonate minerals precipitated from lake water/pulses of detrital input
Rare desiccation cracks	Periodic subaerial exposure of lake bed
Secondary dolomite	Diagenesis of high magnesium calcite or aragonite

Table 7. Observations and inferences made from carbonate facies (calcareous shale, dolostone, calcareous mud).

Observation	Inference
Presence of algal mats	Formed in shallow water
Laterally-linked hemispheroid structure	Formed in protected situations in intertidal mudflats or lakes
Good preservation of mats	No grazers were present
Rhythmic, wavy lamination of calcite and dolomite	Diagenesis of aragonite or calcite and magnesium-rich layers in the stromatolite

Table 8. Observations and inferences made from stromatolitic limestone.

Observation	Inference
Abundance of ooids	Agitated water, supersaturated with calicium carbonate
Intraclasts of algal material	Agitated water (fragmented algal material incorporated in rock)
Almost entirely of calcite	Little clastic input
Rarity of rock	Conditions of formation were not common

Table 9. Observations and inferences made from oolitic limestone.

The abundance of carbonate minerals suggests that the lake water was saline and calcite, and perhaps dolomite, were precipitated. Layers of detrital grains indicate input of clastics. Periodic subaerial exposure of parts of the lake bed produced desiccation cracks. The desiccation features suggest that the climate during deposition was somewhat dry.

The stromatolitic limestone was formed in water that was sufficiently shallow to allow penetration of sunlight which is required by the algae during photosynthesis. The good preservation of the mats and the absence of fossilized fauna suggest that no grazers were present. The absence of grazers indirectly supports the theory of saline water as most grazers which inhibit mat growth are not tolerant of saline water. The laterally-linked hemispheroid structure of the stromatolites suggests formation in locations protected from heavy wave action.

The abundance of ooids in the oolitic limestone suggests formation of the rock in agitated water. This is also implied by the presence of intraclasts of algal material which have been incorporated into the rock. Water currents must have been strong enough to tear fragments from algal stromatolites nearby. The rarity of the oolitic limestone indicates that the agitated conditons under which it formed were not common. During these conditions there was almost no clastic input - the rock is composed of over 95% calcite.

Calcite, aragonite, and high magnesium calcite commonly precipitate from saline lake water but primary precipitation of dolomite is not common (Leeder, 1982). Dolomite is precipitated from hypersaline lakes in Coorong Lagoon, Australia, during dry periods. Inversion of aragonite or high Mg calcite during diagenesis is a common method of dolomite formation.

Increased salinity (through brine concentration by evaporation) leads to the precipitation of gypsum and halite and potassium salts. The rarity of gypsum and the absence of halite and other salts suggests that the lake water did not reach sufficiently high salinities for common precipitation of gypsum or for halite and other salts to begin to precipitate.

The Markov Chain Analysis showed an association between the oolitic limestone and the calcareous shale and between the stromatolitic limestone and the calcareous shale. Stromatolites and oolites generally form in shallow water. Hence, the calcareous shale probably has a shallow water origin. The dolostone formed in deeper water. The abundance of the calcareous shale/dolostone couplet represents minor fluctuations in the water level of the lake. The presence of undisturbed lamination in these rocks indicates deposition in calm water. Detrital input was common.

6.2 Siliciclastic Facies

The occurrence of sandstone and mudstone as relatively thin, laterally persistent beds with sharp, parallel contacts suggests a lacustrine depositional setting (Yuretich et al., 1984). Lenticular sandstones with erosional bases that typify fluvial deposits are not common in the study section.

The sedimentary structures observed in the mudstone and sandstone and the inferences drawn from these structures are summarized in table 10.

Cross-beds and rippled surfaces are common in shallow lake sands (Picard and High, 1981). The average wavelength of the ripples at Broad Cove is 3 cm. Such a wavelength suggests that the lake was relatively small with a restricted fetch (Tanner, 1971). Ripple-drift cross-lamination was produced by climbing ripples which suggest an increased sediment input. The rarity of large-scale planar cross-beds in the sandstone indicates an uncommon increase in flow strength. No vertical sequence of sedimentary structures is observed and hence no consistent upward trend in hydraulic regime is proposed. Rain prints imply periodic subaerial exposure of parts of the lake bed.

The scarcity of vascular plants, the red colouration of the mudstones and sandstones, and the hematite cement of the sandstones collectively suggest climatic aridity during deposition.

Sedimentary Structure	Inference
Ripple marks, cross-beds	Ripples formed by low velocity flow
Ripple-drift cross-lamination	Climbing ripples formed by increased rate of net vertical deposition
Rare large-scale planar cross-beds	Migration of larger-scale bedforms/increased flow strength (uncommon)
Rain prints	Periodic subaerial exposure

Table 10. Inferences from major sedimentary structures in the mudstone and sandstone.

Plant fragments are found in only one sandstone unit. Most of the fragments have been coalified. The plant fragments are probably allochthonous. One of the plant fragments observed was surrounded by native copper and malachite. The copper may have been leached from surrounding rocks and precipitated where the fragments were coalified. The malachite indicates oxidation of the copper, presumably after the fragments were transported.

6.3 Assemblages

Thickness of the interbedded assemblages ranges from 10 to 60 m. The interbedding of the carbonate and siliciclastic assemblages suggests periodic abundant clastic influx and lack of clastic influx. A maximum of ten major changes in amount of influx is suggested by the strata at Broad Cove.

Periods of lack of influx are characterized by continuous deposition of carbonate rocks. Evaporation of the lake water under arid conditions led to precipitation of carbonate minerals and formation of desiccation features.

Deposition of clastics occurred when flood waters inundated the lake. Clastic sediments were carried into the lake from surrounding areas by flood waters and surface runoff during storm events. The tabular, sheet structure of the sandstones and mudstones suggests deposition of the sediments by simple "settling out" from suspension after the turbulence of the water subsided.

The mixed assemblage represents a transition between the other two assemblages in three instances. In these instances, the change from abundant influx to almost no influx (or vice versa) was gradual. The contacts between the carbonate and siliciclastic assemblages are generally sharp and suggest an abrupt switch in influx conditions. Occurrences of the mixed assemblage that do not act as transitions may indicate random flooding.

Up section there is an increase in the proportion of the siliciclastic facies which indicates greater input of clastics to the lake from the surrounding terrain and more (and prolonged) flood events. This suggests a decrease in climatic aridity.

6.4 Depositional Setting

Saline lakes are common in arid to semi-arid environments and are generally found in low areas of drainage basins (Kendall, 1984). Surrounding upland areas provide sediment to the basin. The sediment is transported by flood waters across alluvial fans at the base of the highlands and onto the alluvial plains where saline lakes are found. Nickel (1982) noted that the contribution of carbonates to the overall sequence of such a setting increases with increasing distance from the fan.

The Broad Cove Canso Group strata were deposited under arid climatic conditions. The proposed depositional setting is depicted in figure 19. The basin corresponds to part of the fault-bounded Fundy Basin and the stable highlands to the uplifted blocks and stable platforms that surround the Fundy Basin. Local faults were not active during deposition of the lake sediments. This is suggested by the absence of coarser grained material in the section.

Alluvial fans form at the base of the highlands and grade laterally into the alluvial plain. The carbonate facies of Broad Cove were deposited within a saline lake on an alluvial plain. No paleocurrent information is available but the siliciclastic sediments were likely transported from the stable highlands by flood waters and surface runoff of storms.

Chapter 7 Conclusions

Carboniferous Canso Group strata exposed at Broad Cove were deposited in a sub-basin of the Fundy Basin under conditions of climatic aridity. Surrounding uplifted blocks and stable platforms provided clastic sediments which were carried into the basin by surface runoff during storm events. The sediments were transported across alluvial fans at the base of the highlands and onto the alluvial plain. There the sediments were deposited in saline lakes in which precipitated abundant carbonate

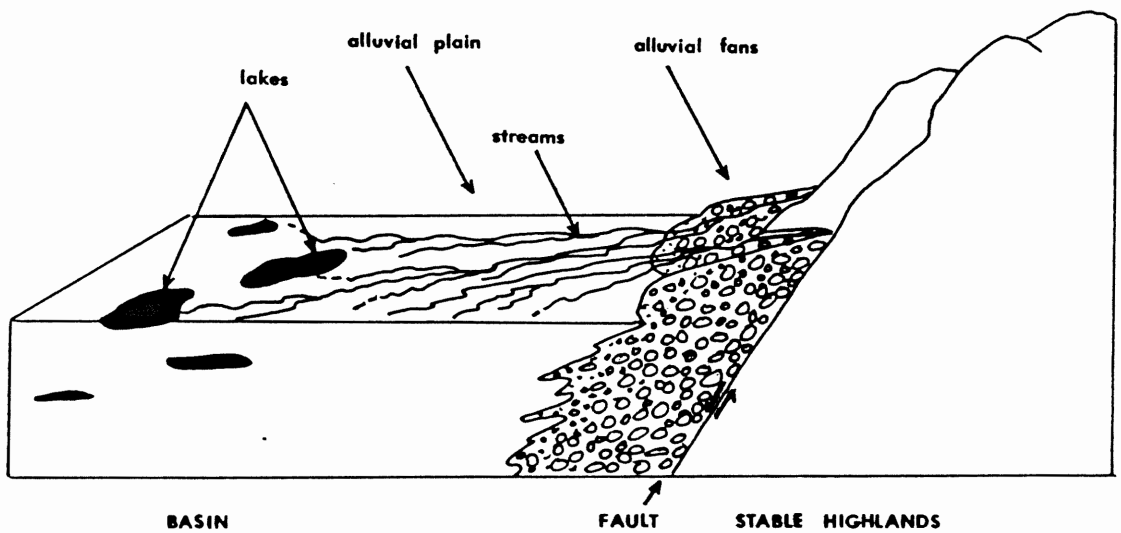


Figure 19. Depositional setting of study area (modified after Kendall, 1984).

minerals.

The carbonate facies at Broad Cove were precipitated and deposited in a shallow saline lake on an alluvial plain under conditions of climatic aridity. Carbonates precipitated as evaporation proceeded when clastic input was low. Storm events produced flood waters which inundated the lake. These waters transported clastic sediments from the highlands across the alluvial plain and deposited them in the saline lake, forming the siliciclastic facies now recognized at Broad Cove.

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Appendix

A.1 Stratigraphic Column of Measured Canso Strata at Broad Cove

The section begins at the lower left corner of the first page and continues for 11 pages. Each of the 7 bars per page is 5 m, therefore maximum total thickness represented per page is 35 m.

Grain size is not represented on the diagram. Wider units are rocks that are resistant to weathering processes and thinner sections indicate less resistant rocks. The seven recognized facies and their associated sedimentary structures are depicted.

Key:

Facies:

- Calcareous Shale
- Dolostone
- Calcareous Mud
- Oolitic Limestone
- Stromatolitic Limestone
- Mudstone
- Sandstone
- Gypsum

Contacts:

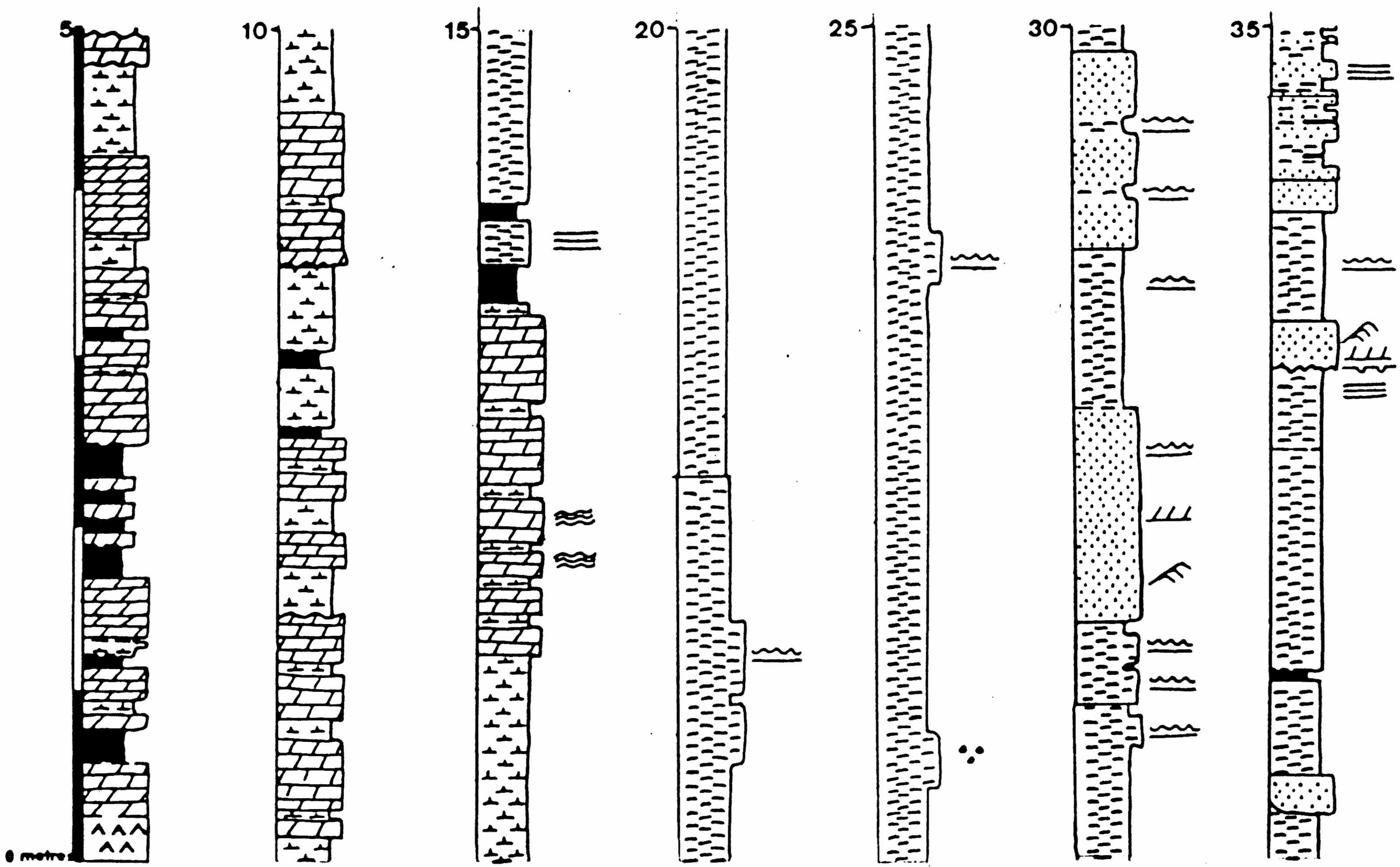
- gradational
- sharp and planar
- sharp and irregular

Resistance to weathering:

- resistant
- not resistant
- unconsolidated

Sedimentary Structures:

- wavy lamination
- planar lamination
- ripples
- climbing ripples
- small-scale cross-bedding
- large-scale cross-bedding
- load casts
- desiccation cracks
- rain prints
- vascular plant fragments



5
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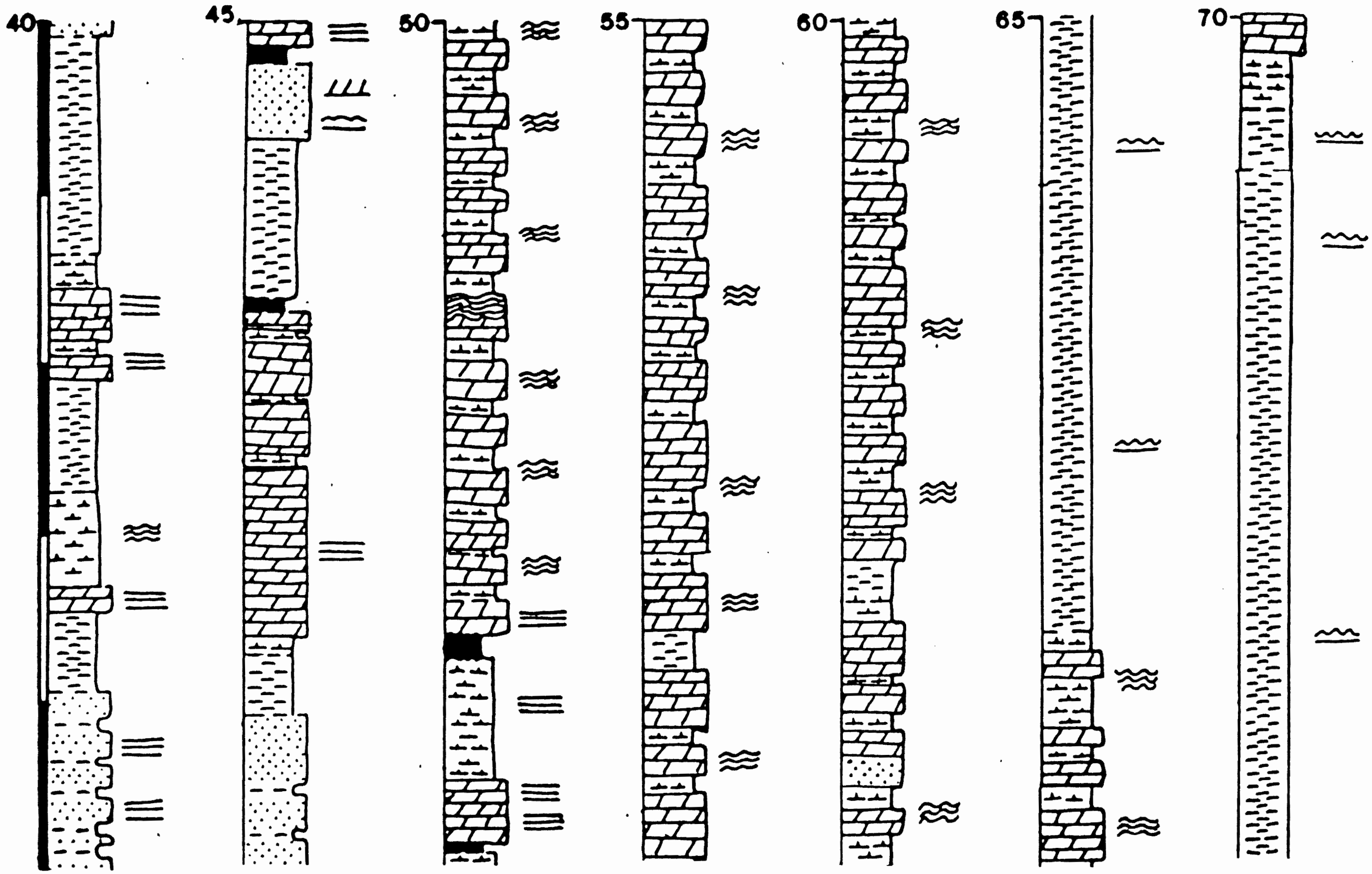
15
20
25
30
35
0 metres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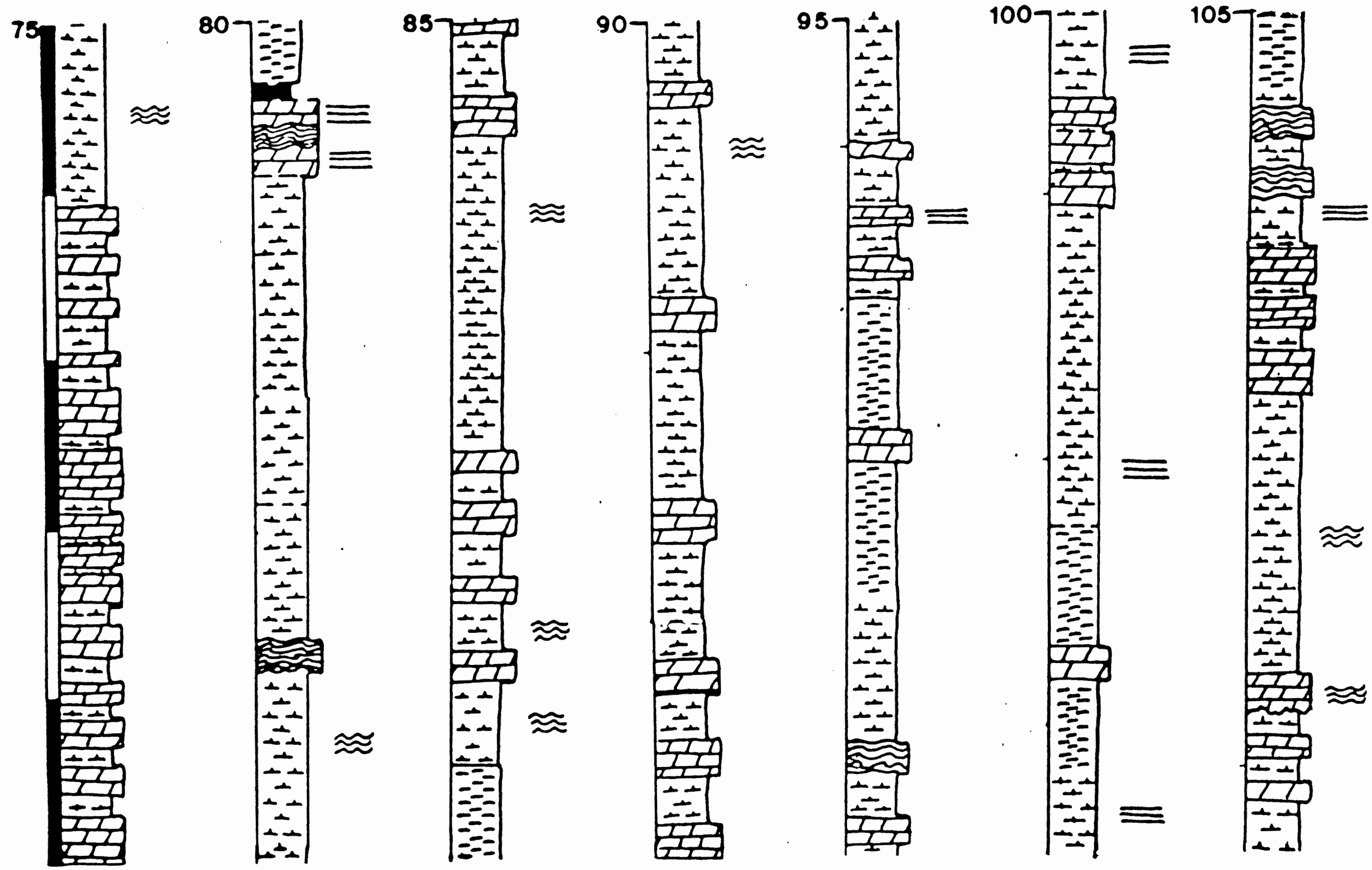
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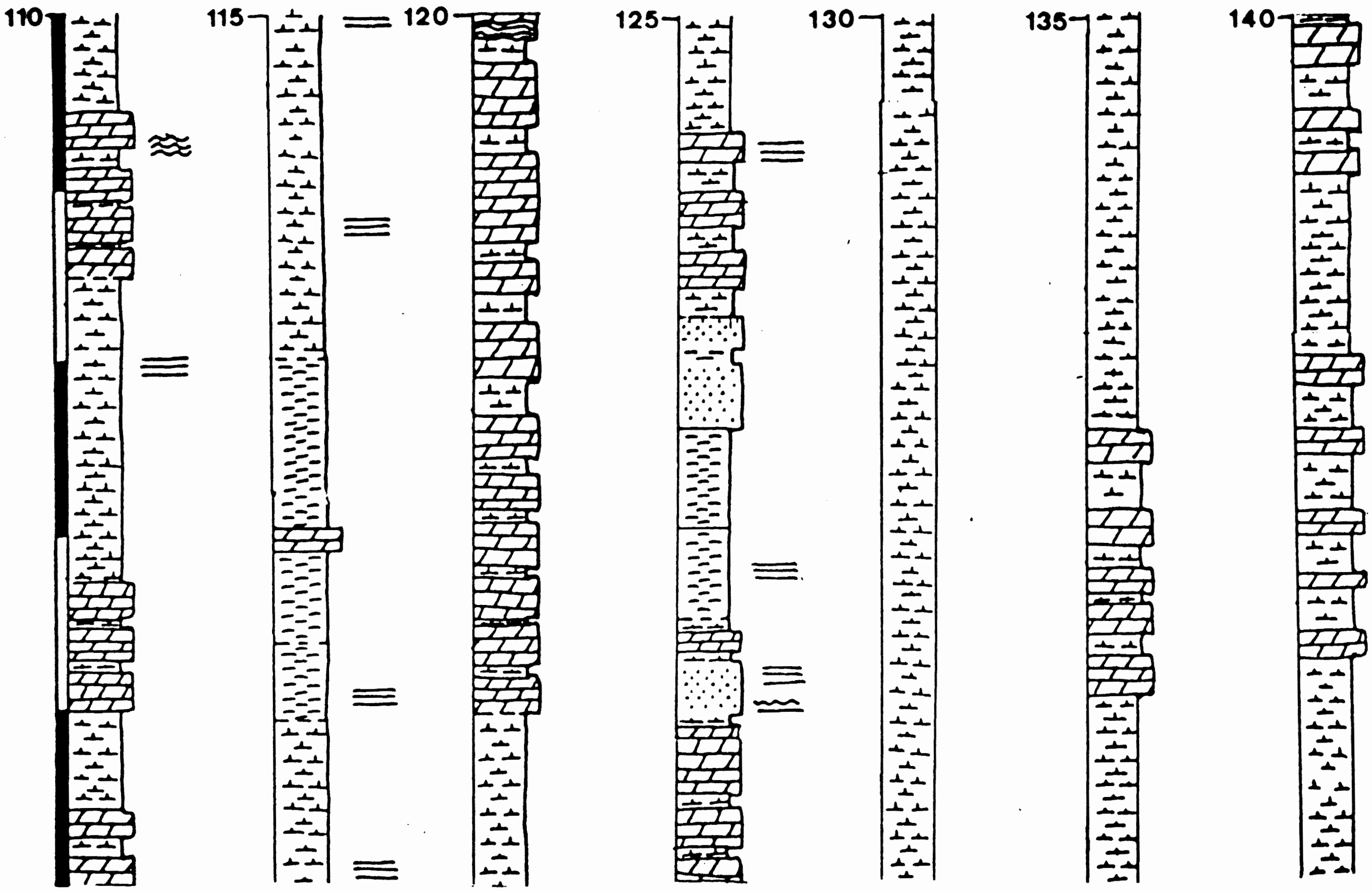
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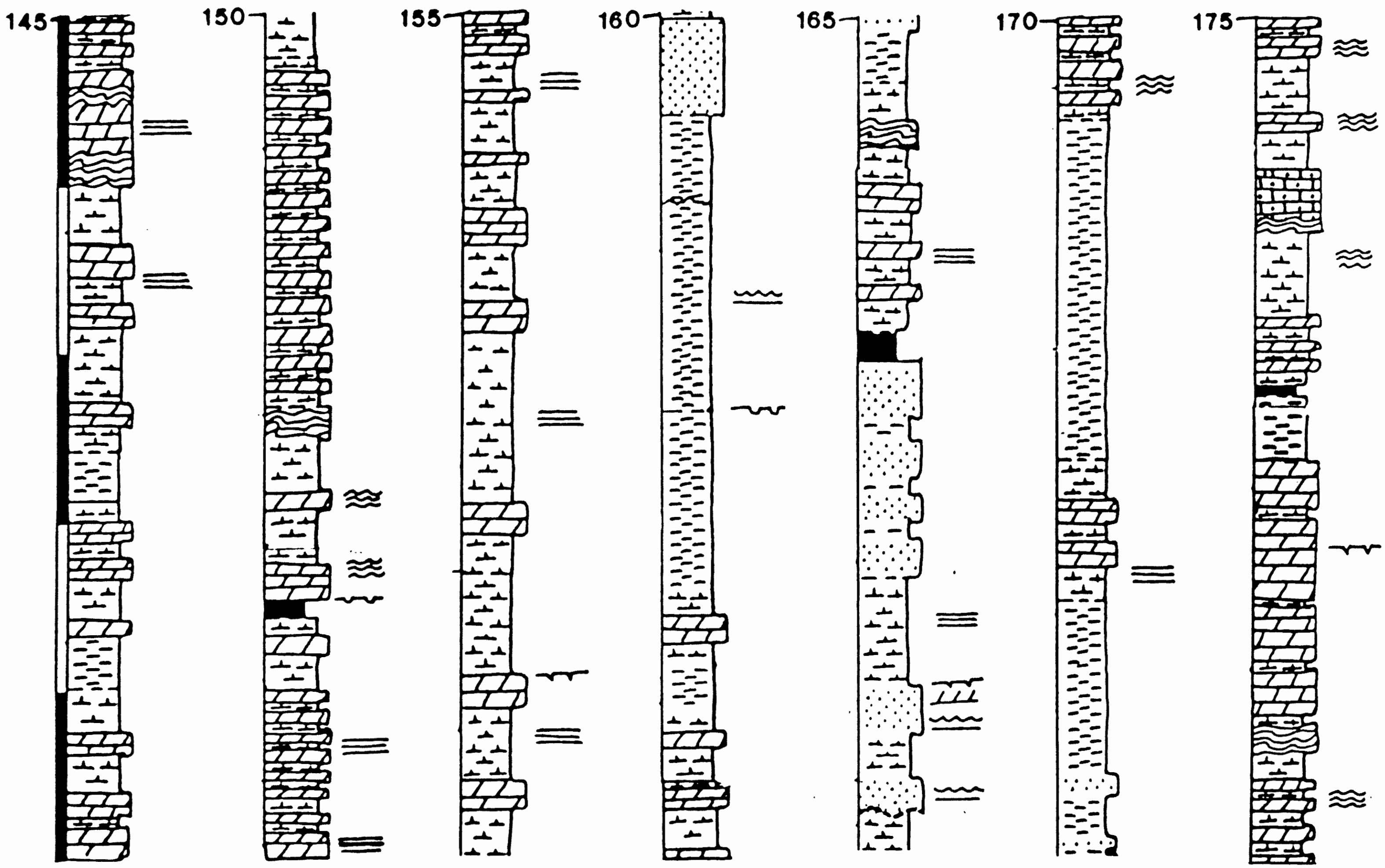
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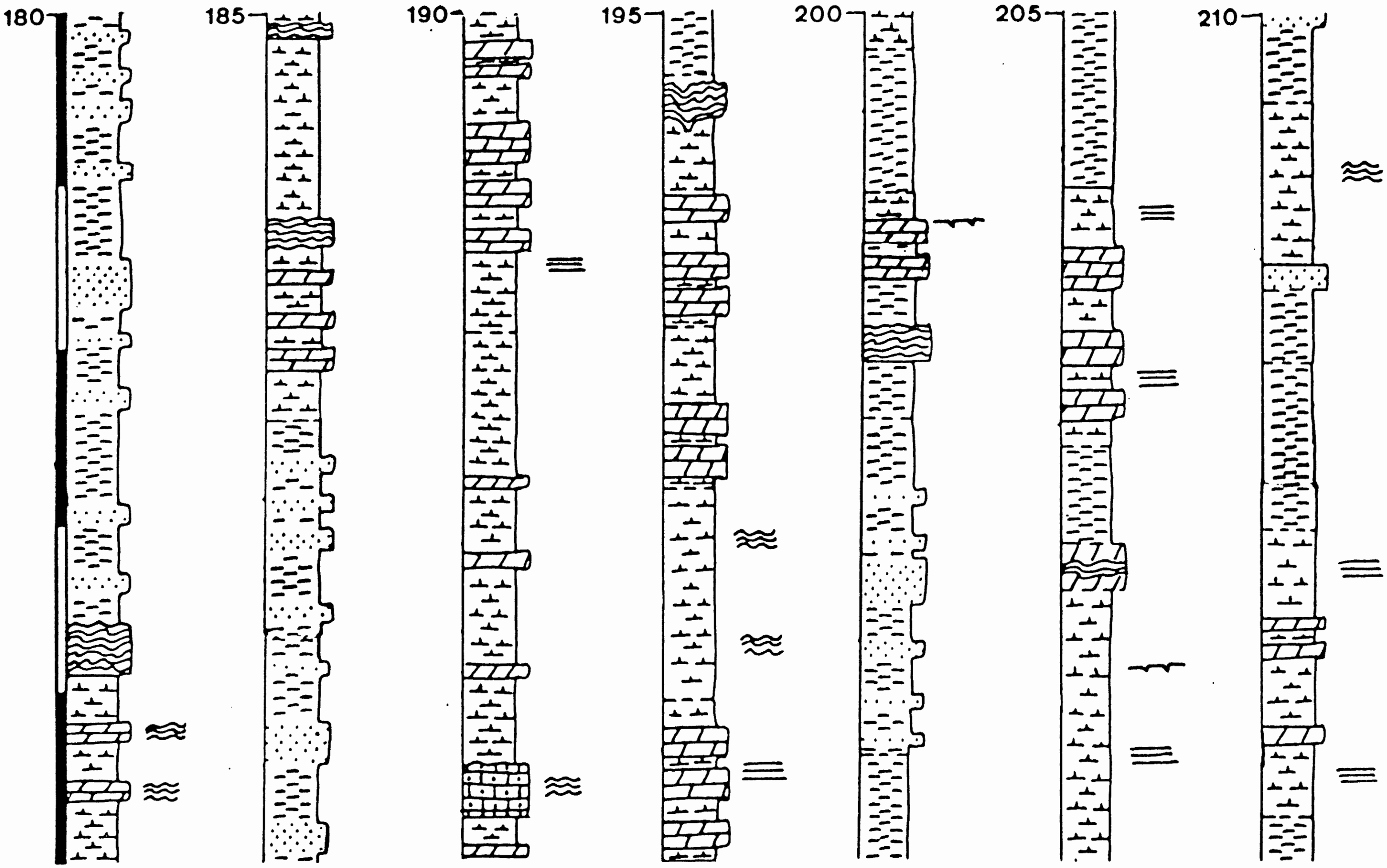
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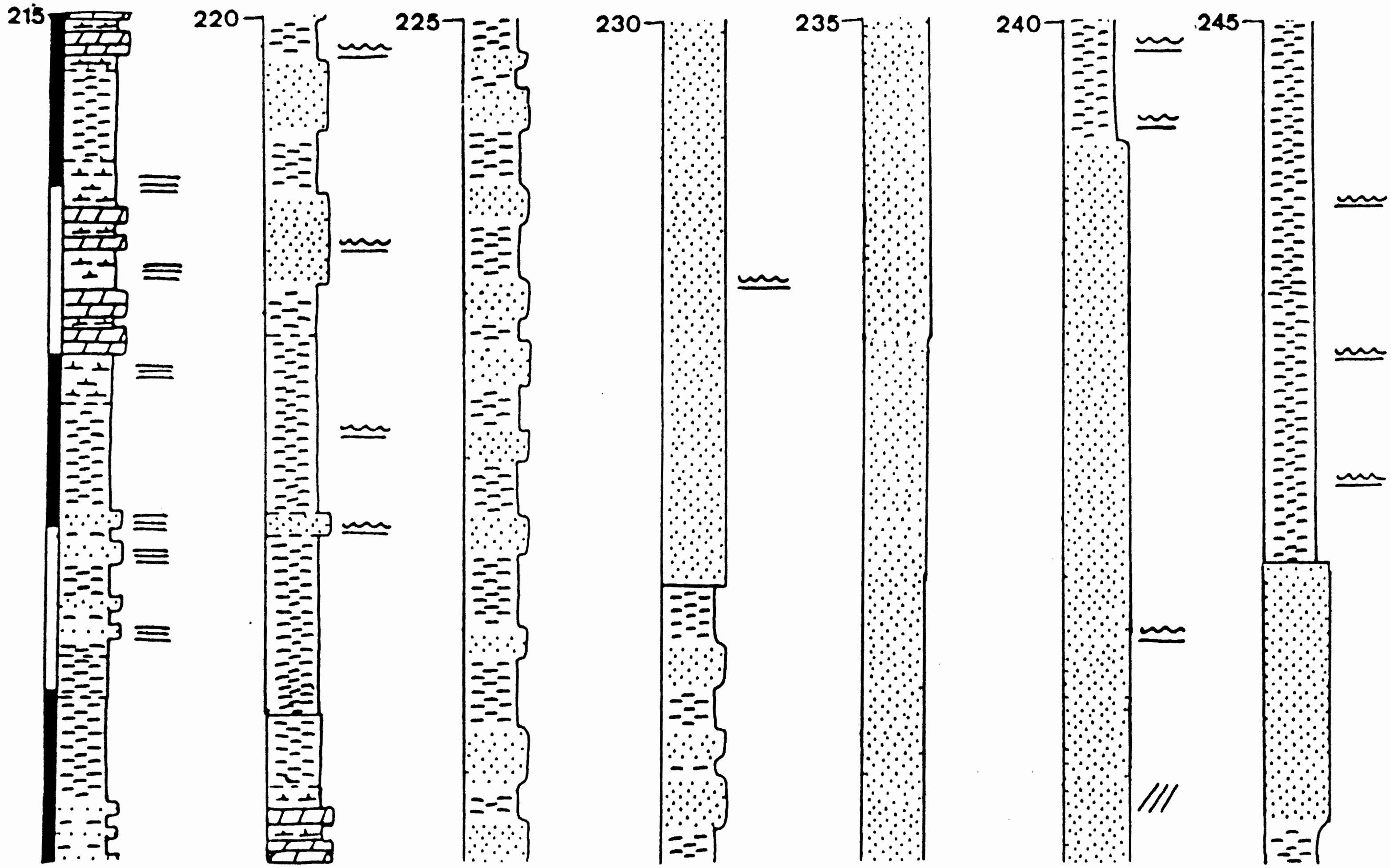
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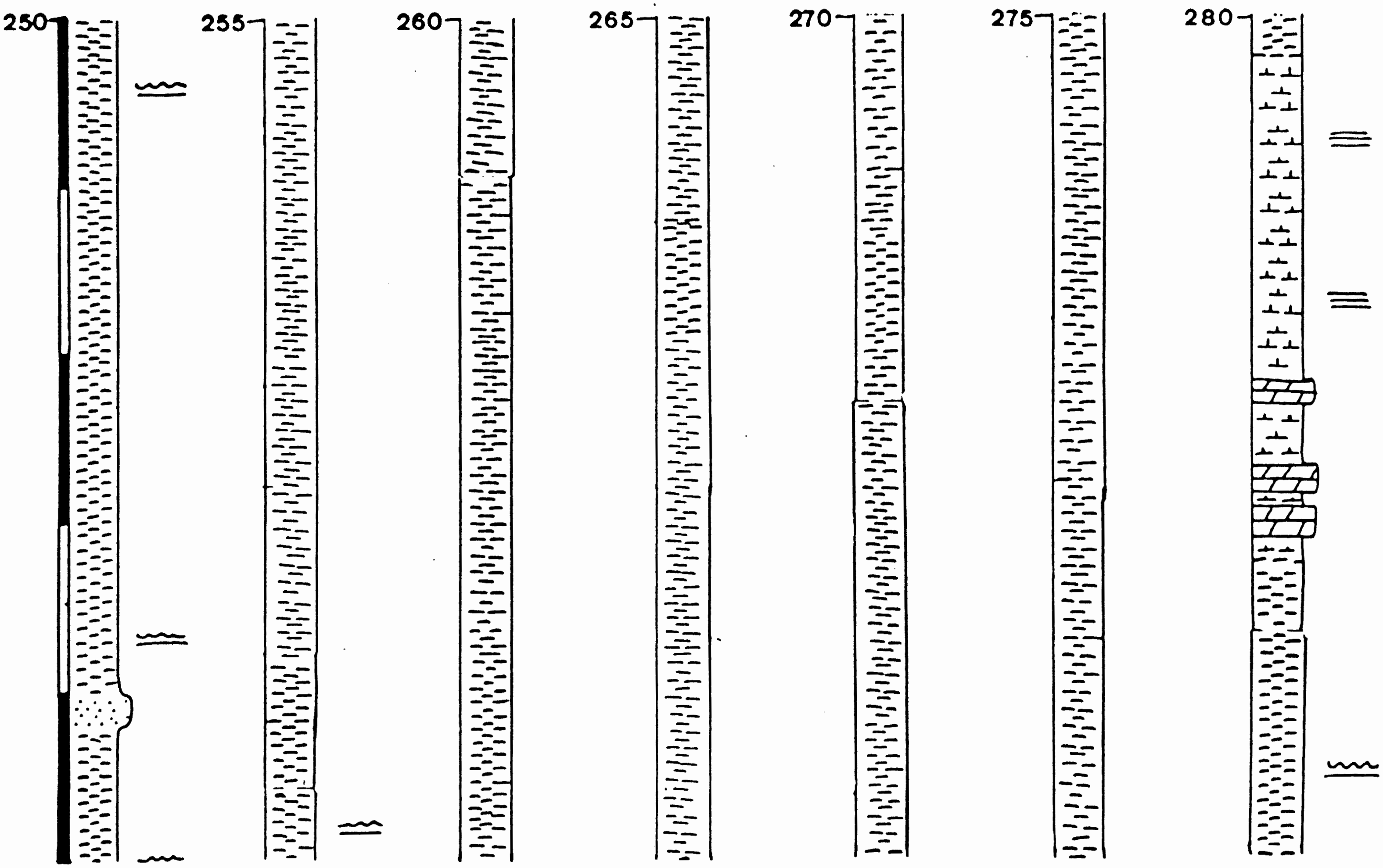
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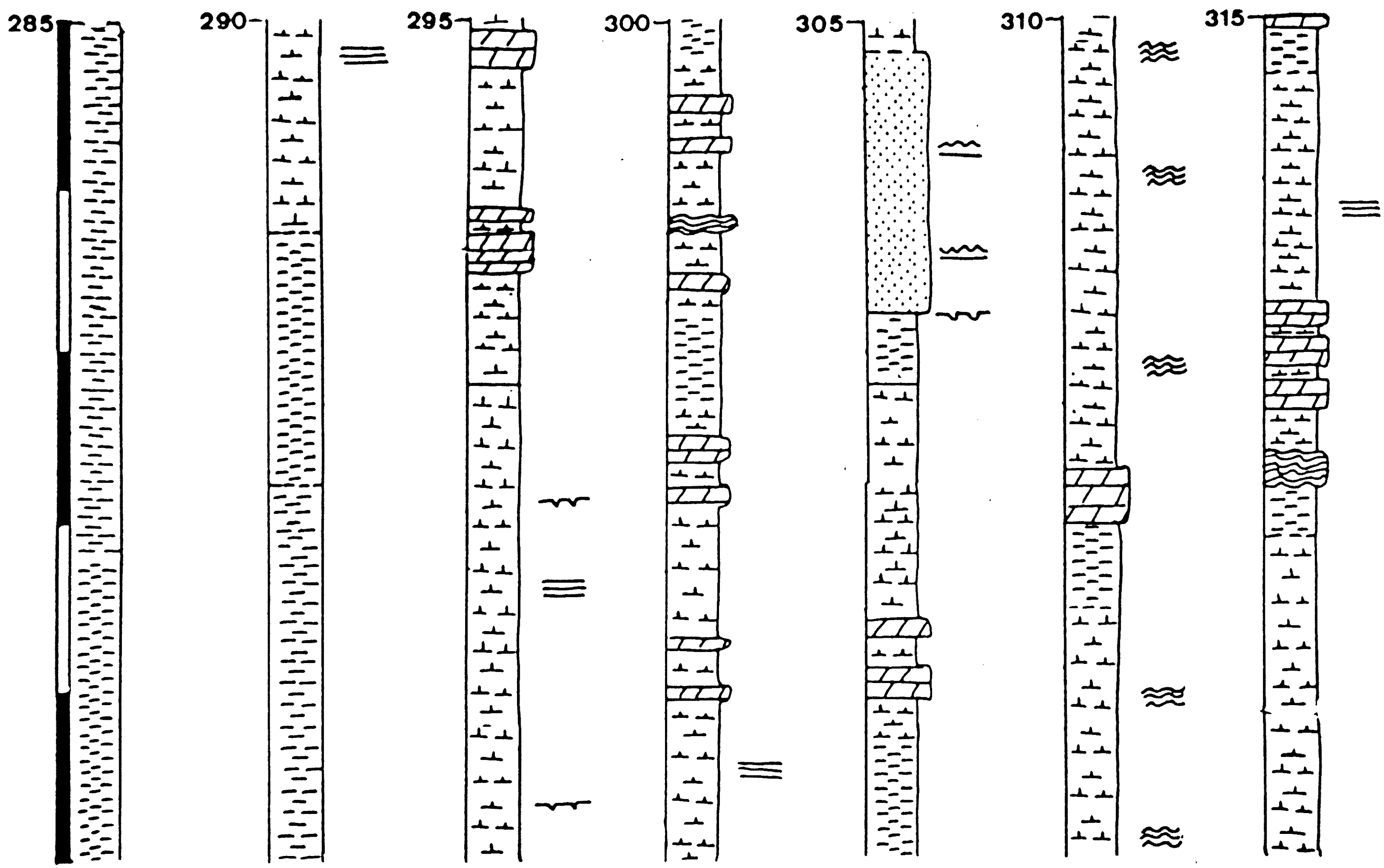
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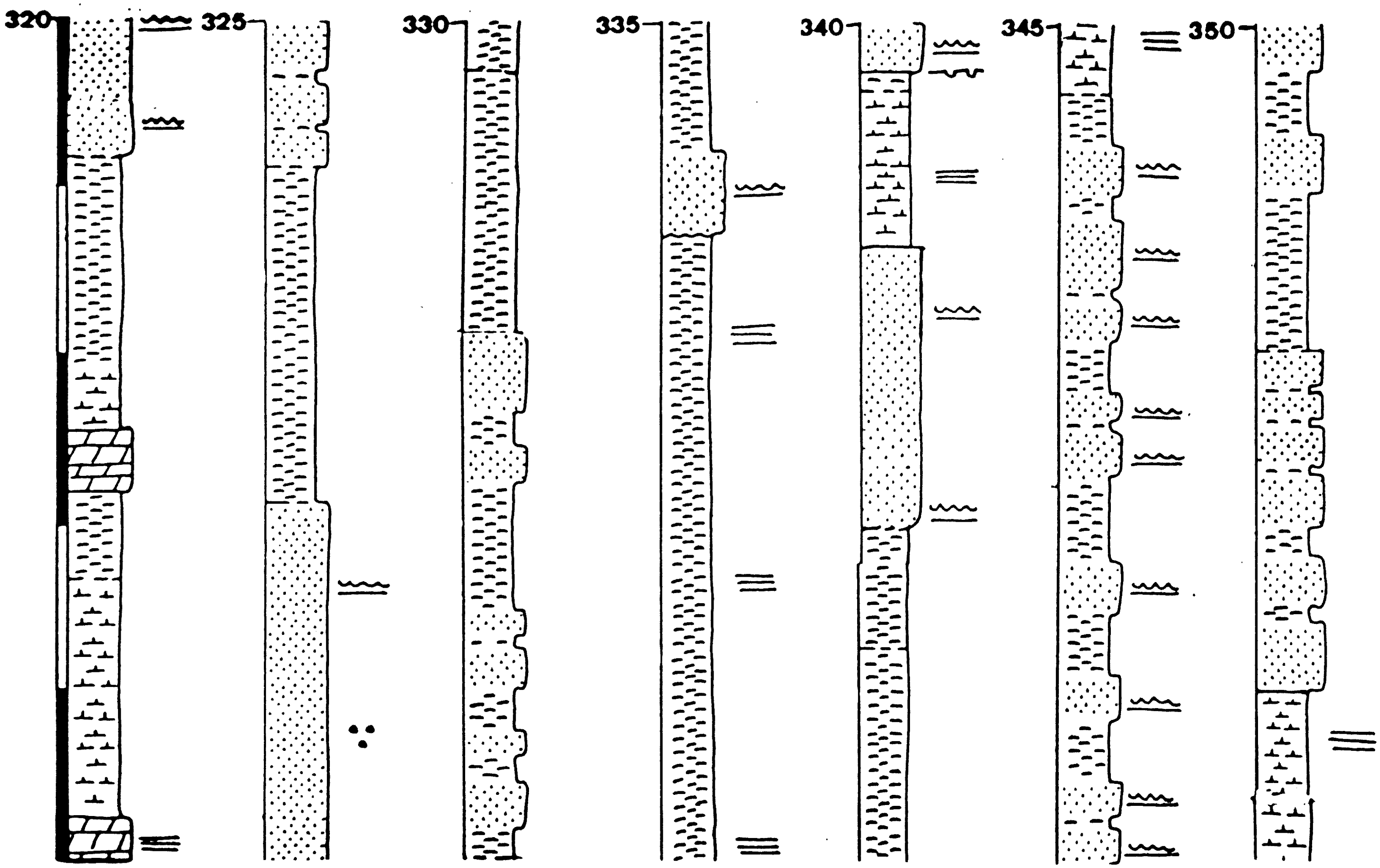
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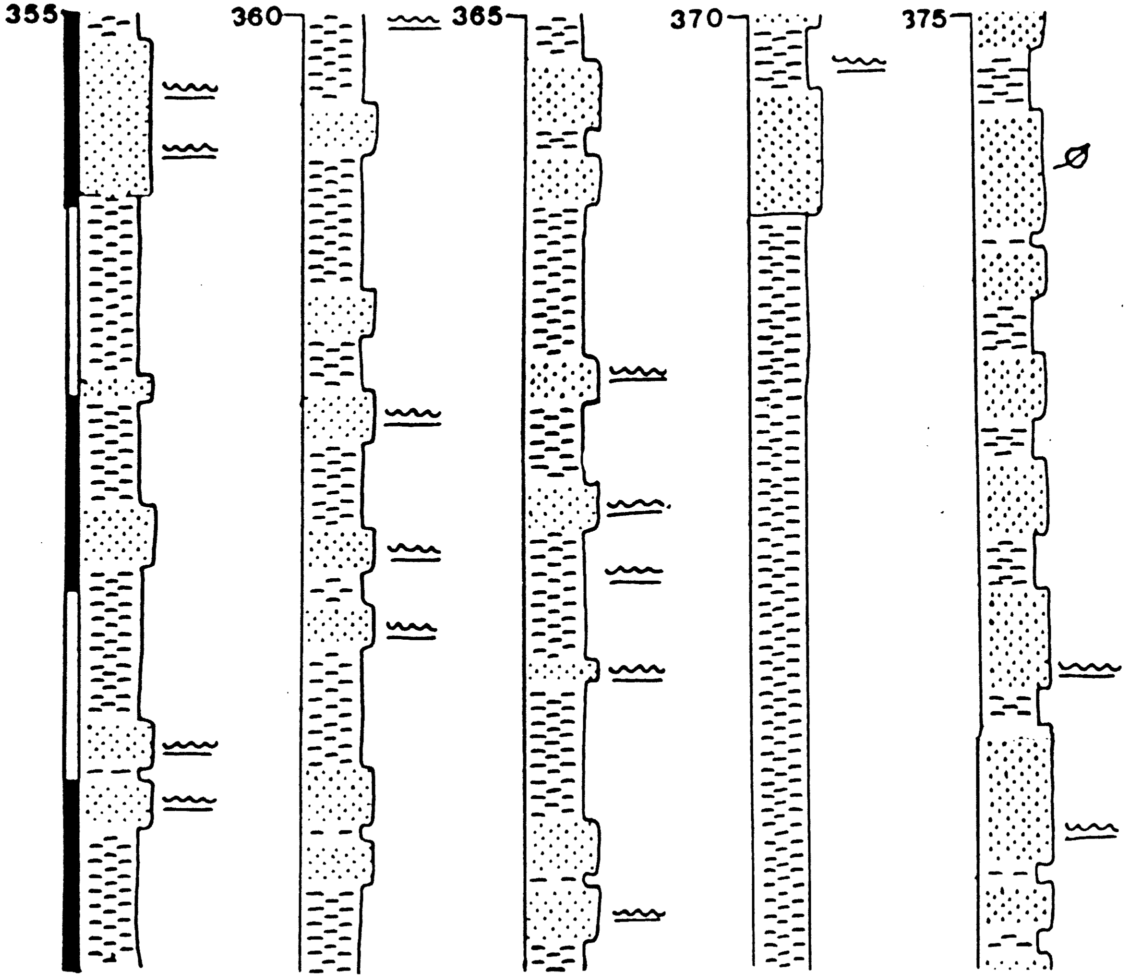
355
360
365
370
375

A.2 Thin Section Staining Technique (after Dickson, 1965)

Each uncovered thin section is etched in 1.5% hydrochloric acid (HCl) for 10 to 15 seconds and then rinsed with distilled water. The sections are then placed in 0.2% Alizarin Red solution (ARS) in 1.5% HCl for 30 to 45 seconds for staining and then washed again with distilled water.

Calcite and ferroan calcite are stained pale pink to red and dolomite and ferroan dolomite remain colourless.

A.3 Markov Chain Analysis

The procedure (following Miall, 1973) that was used to produce the Markov Chain Diagram (Figure 15) from the matrices (Table 6) is presented.

The transition count matrix records the actual transitions between the facies types. Rows and columns are summed individually (S_i and S_j respectively) and the total number of transitions is noted (t). Each element in the matrix is the frequency of transition from one facies to another (f_{ij}).

Each element in the independent trials probability matrix is given by:

$$r_{ij} = \frac{S_j}{(t - S_i)}$$

Individual elements are theoretical values that result when only the proportion of the facies and the total number of transitions are given.

Given the actual values of the transition count matrix and the frequency of each facies type, observed values can be determined and are displayed in the transition probability matrix. Each element is given by:

$$p_{ij} = \frac{f_{ij}}{s_i}$$

Elements of the difference matrix are determined by subtracting the theoretical value (r_{ij}) from the observed value (p_{ij}). Positive values indicate that the observed value is higher than is theoretically probable.