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**Sedimentology of the Upper Jurassic - Lower
Cretaceous Hibernia Member of the Missisauga Formation
in the Hibernia Oil Field, Jeanne d'Arc Basin**

by

Don M. Brown, B.Sc.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of
Masters of Science

Department of Geology
Carleton University

Ottawa, Ontario

October, 1985

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Cretaceous Hibernia Member of the Missisauga Formation
in the Hibernia Oil Field, Jeanne d'Arc Basin**

submitted by Don M. Brown, B.Sc.

in partial fulfillment of the requirements for
the degree of Master of Sciences

Thesis Supervisor

Chairman, Department of Geology

Carleton University

December, 1985

ABSTRACT

The Upper Jurassic - Lower Cretaceous Hibernia member of the Missisauga Formation, averaging 200m thick, occurs at depths varying between 3475-4180m within the Hibernia oil field. Based on downhole log responses and sedimentological characteristics, the member can be divided into a lower "Main Hibernia zone" overlain by the "Upper Hibernia zone".

The Main Zone, comprising up to two-thirds of the vertical section, dominantly consists of thick bodies of cross-stratified, well-sorted, medium- to very coarse-grained quartz arenites, commonly exhibiting fining-upward cycles. These sandstones, interbedded with siltstones and mudstones, are interpreted as distributary channel deposits with associated overbank fines of a deltaic plain environment.

The contact between the Main Zone and the Upper Zone is gradational, as relatively thin bodies of very fine- to medium-grained, well-sorted, quartz arenites with interbedded mudstones and siltstones become dominant. This zone probably represents deposits of a shallow, delta-front environment, formed during a period of marine transgression.

The reservoir sandstones have observed porosities ranging from less than 3 percent up to 23 percent. The higher porosities are attributed to dissolution of carbonate cement and framework grains. This late porosity enhancement resulted in the excellent reservoir quality of the Hibernia sandstones. Since decarbonatization preceded main hydrocarbon migration, it is partially responsible for the large reserves and potential producibility of the field.

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1.1 General

The Hibernia oil field (46° 45'N 48° 45'W) is located on the Grand Banks approximately 320 kilometers southeast of Saint Johns, Newfoundland (Fig. 1). It lies in a southwesterly extension of the East Newfoundland Basin in water depths varying from 76 - 86 meters (Benteau and Sheppard, 1982).

The Hibernia P-15 well, drilled in 1979, was the first major oil discovery off the east coast of Canada. To date, nine other wells have been drilled in the field. The Hibernia field contains estimated reserves of 648 million barrels of recoverable oil (Canadian Petroleum Association, 1985), and 2 trillion cubic feet of associated gas, defining it in the "giant class" oilfield category (Procter et al., 1984).

There are four hydrocarbon-bearing sandy units in the field; the Jeanne d'Arc member of the Jurassic Mic Mac Formation, and the Hibernia, Catalina and Avalon members of the Upper Jurassic - Lower Cretaceous Missisauga Formation.

Several publications describe the regional geology and sedimentation patterns of the area. However, little has been published on the petrography of the reservoir sandstones and their diagenetic histories.

1.2 Geologic Setting

The post-Paleozoic tectonic and sedimentary history of Canadian Atlantic coast can be described in terms of the passive continental margin model of Bally et al (1980). McIver (1972),

Fig. 1

GRAND BANKS BASEMENT STRUCTURE

(after McMillan, 1982)

Figure 1: Grand banks basement structure and location of the Hibernia oil field.

FIG 2- Depositional Basins, East Coast-Canada

after Jansa and Wade 1975a

Figure 2: Depositional basins, East coast, Canada, showing location of the Avalon Uplift.

(after McMillan, 1982)

Figure 3: Basement structure of the Avalon Uplift and related basins. Contour interval is 2000m.

Sherwin (1973), Jansa and Wade (1975a, 1975b), Wade (1978), and Grant et al. (in press), have provided reviews of the Mesozoic and Early Cenozoic tectonic development and resultant stratigraphy and sedimentation of the Atlantic continental shelf upon which the following discussion is based. Information on the local geology of the Hibernia region is summarized from McKenzie, (1980, 1981), Arthur et al., (1982), McMillan, (1982), Benteau and Sheppard, (1982), and Handyside and Chipman, (1983).

1.2.1 Structural Elements of the Grand Banks and the Hibernia Region.

The three major Mesozoic-Tertiary depositional areas bordering the Grand Banks area, are the East Newfoundland, Flemish, and Scotian Basins (Fig. 2). The Avalon Uplift (Fig. 2), consisting of Paleozoic to Middle Jurassic rocks, separates the Scotian Basin from the East Newfoundland Basin.

The Avalon Uplift can itself be divided into several northeast-southwest trending basins and intervening stable areas (Fig. 3), formed during the initiation of North Atlantic sea-floor spreading (McMillan, 1982). These troughs contain accumulations of Cretaceous, Jurassic and Triassic sediments up to and exceeding six kilometers in thickness. This whole area is overlain by Tertiary marine sediments. The main troughs have been designated the Whale, Horseshoe, Carson and the Jeanne d'Arc Basins (Amoco Canada Petroleum Co. Ltd. and Imperial Oil Ltd., 1973).

The Jeanne d'Arc Basin as used herein, is actually the southwesterly extension of the East Newfoundland Basin (Figs.

1, 3, and 4). It is a relatively narrow northward-plunging trough which is 100 kms wide in the north and narrows to the south. McKenzie (1980) subdivided this basin into two separate "subbasins" (Figs. 4 and 5): the Jeanne d'Arc "subbasin", defined by subcrops of Jurassic rocks below the "middle"-Cretaceous regional unconformity; and the Avalon "subbasin" (commonly referred to as the Avalon Basin in recent publications), defined by a thick section of Lower Cretaceous rocks below the same regional unconformity. This basin nomenclature has resulted in confusion since the name "Jeanne d'Arc" has been applied to both the entire southwesterly extension of the East Newfoundland Basin (Grant et al., in press), and to a restricted southern part of it (McKenzie, 1981; Benteau and Sheppard, 1982). The term "Avalon Basin" is currently used by the petroleum industry to refer to the northern part of the Jeanne d'Arc Basin.

If the subbasin nomenclature is retained, the present writer proposes that the "Jeanne d'Arc subbasin" (the southern subdivision of the main basin), be renamed the "Bonavista subbasin", while the term "Avalon subbasin" be retained for the northern part. The new name "Bonavista subbasin" is considered to be suitable since this basinal segment is situated directly adjacent to the Bonavista platform (Fig. 4). Throughout the remainder of this text, the southwesterly extension of the East Newfoundland Basin will be referred to as the Jeanne d'Arc Basin, with its southern (Bonavista) and northern (Avalon) subbasins.

The tectonic framework of the Avalon subbasin includes four major elements (Fig. 6): a stable shelf; a hinge zone; the

Fig. 4- Jeanne d'Arc Basin

Modified after Grant et al. (in press)

Figure 4: Total Mesozoic-Cenozoic sediment thickness in the Jeanne d'Arc Basin and surrounding area. B-B' and A-A' are positions of cross-sections shown in Figures 5 and 6.

Figure 5: The random-dashed pattern represents Paleozoic basement, and the crossed-pattern represents Upper Triassic-Lower Jurassic evaporites. Location of section on Figure 4.

Figure 6: Symbols as in Figure 5. Location of section on Figure 4.

Fig.-7
**TIME SEISMIC STRUCTURE MAP OF
 THE LOWER CRETACEOUS LIMESTONE
 MARKER HORIZON**

Contour Interval=100 msec

(after Arthur et al., 1982)

Figure 7: Time-seismic structure map of the B-seismic marker (McKenzie, 1980, 1981). Contours are in seconds, two-way time.

northward plunging trough; and a ridge complex (Benteau and Sheppard, 1982; McKenzie, 1980; Arthur et al., 1982). The stable shelf, also known as the Bonavista platform, consists of a relatively thin, undeformed, upper Lower Cretaceous to Tertiary marine sedimentary section unconformably overlying a Precambrian - Paleozoic metamorphosed basement complex (McKenzie, 1980). East of the stable shelf is the highly faulted hinge zone which is a boundary zone separating the stable shelf to the west and the graben to the east. The western hinge zone includes a relatively thick (up to approximately 5000m), deformed, Lower Cretaceous and Jurassic sedimentary section unconformably overlain by undeformed Upper Cretaceous and Tertiary marine sediments (Benteau and Sheppard, 1982). A major north-northeast trending, down-to-the-basin listric normal fault, known as the Murre fault (Rayer, 1981), separates the stable shelf from the hinge zone. Faults within the hinge zone trend either sub-parallel to the Murre fault, or in a southeasterly direction. Most of the faults terminate at or below the "middle"-Cretaceous unconformity, but some penetrate into the overlying sediments. The Hibernia field is situated in the western hinge zone just south of an east-southeast trending trans-basin fault system (Fig.4). McKenzie (1980) described the structure of the field as a large roll-over anticline (Fig. 7).

East of the western hinge zone, the northward plunging Avalon subbasin contains a very thick Lower Cretaceous sedimentary section overlying older Jurassic and late Triassic rocks. The maximum sediment thickness along the axis of the

Avalon Basin may exceed 15000m (Benteau and Sheppard, 1982; Grant et al., in press). Salt diapirs rising from the late Triassic - early Jurassic section reach various levels within the basin (Fig. 6). Salt flowage may also have influenced structural features of the basin (Grant et al., in press).

The eastern Ridge Complex is a structural high which forms the eastern flank of the Jeanne d'Arc Basin. It is composed of differentially tilted, basement-cored fault blocks with Lower Cretaceous and Jurassic strata of varying thicknesses preserved beneath the "middle"-Cretaceous unconformity. Figure 4 illustrates that the northern segment of the Ridge Complex is composed of structurally disturbed Jurassic sediments which are stratigraphically equivalent to those within the basin (Grant et al., in press). However, these sediments terminate against probable Appalachian Paleozoics towards the south (Grant et al., in press).

1.2.2 Regional Stratigraphy and Geological History of the Jeanne d'Arc Basin

The stratigraphic nomenclature used for the Jeanne d'Arc Basin in this thesis (Fig. 8) follows that of Grant et al. (in press), which was defined by McIver (1972) for the Scotian Shelf and subsequently extended to the Grand Banks by Amoco Canada Petroleum Co. Ltd. and Imperial Oil Ltd. (1973), Jansa and Wade (1975a, 1975b) and Arthur et al. (1982). The attempt to apply the Scotian Shelf stratigraphic nomenclature to the Grand Banks (East Newfoundland and Jeanne d'Arc Basins) presents some difficulties, because the geologic histories of the two areas differ.

The break-up of west-central Pangaea began in the Late Triassic (Sherwin, 1973), and is recorded in eastern Canada by fluvial and lacustrine red beds of the Eurydice Formation deposited during a time of little physiographic relief (Grant et al., in press). The Eurydice Formation unconformably overlies a Paleozoic metasedimentary basement (Jansa et al., 1976).

During latest Triassic and Early Jurassic times, the incursion of hypersaline waters from the Tethyan Sea resulted in evaporite deposition of the Argo Formation (Jansa and Wade, 1975a; Grant et al., in press). Thin subaerial basaltic flows within the evaporites represent igneous events related to Early Jurassic rifting (Grant et al., in press).

By Sinemurian time, salt deposition ceased and normal marine conditions resulted in the build-up of shallow water carbonates of the Iroquois Formation, representing lagoonal and neritic environments. The Iroquois Formation is overlain by the Whale Unit consisting of shales with interbedded carbonates, representing neritic to subtidal conditions.

Major rifting in the Grand Banks region was initiated in late Middle and early Late Jurassic time (Grant et al., in press), after substantial separation of the North American and African plates in the Scotian Shelf region. A transform fault probably developed along the southwest margin of the Grand Banks and the southern Iberian Peninsula, accompanying the North American - African sea floor spreading event (Fig. 9; Auzende, et al., 1970; Jansa and Wade, 1975a, 1979b). Consequently the southern portion of the Grand Banks stayed with the North

FIGURE 8-Generalized Jeanne d'Arc Basin Stratigraphy

(after Grant et al., in press)

BSC

Figure 9: Middle Jurassic Paleogeography and plate boundaries of Eastern Canada.

Figure 10: Late Jurassic-Early Cretaceous paleogeography and plate boundaries of Eastern Canada. (from Jansa and Wade, 1975a).

American continent, resulting in the prominent eastward projecting step of the North American continental margin (Jansa and Wade, 1975a, 1979b).

The Middle and early Late Jurassic Mic Mac Formation, consisting of deltaic and shallow marine clastics with localized carbonate banks, represents the initiation of regional tectonic adjustments and resultant sedimentation during the initial stages of separation between Europe and North America (Grant et al., in press; Jansa and Wade, 1975a). This regional tectonic episode would last until the end of Early Cretaceous time (Grant et al., in press). Tectonic adjustment resulted in the Avalon Uplift (Figs. 2 and 10) being a dominant elevated land mass which influenced sedimentation throughout most of this period (Arthur et al., 1982; Jansa and Wade, 1975a; Grant et al., in press). The upper Mic Mac Formation is characterized by complex facies dominated alternately by marine and terrestrial influences resulting from the combinations of episodic basin deepening and elevation of the Avalon Uplift, coupled with eustatic sea level rise (Grant et al., in press).

The Avalon Uplift was re-elevated during the latest Jurassic and Early Cretaceous, and consequently subjected to erosion (Grant et al., in press). Detritus was transported northward and deposited as progradational deltaic-like sequences of the Missisauga and Logan Canyon Formations. These sediments exhibit an overall fining-upward trend and also become finer grained and more marine northward at increased distance from the Avalon Uplift (Grant et al., in press).

A regional "middle"-Cretaceous break-up unconformity developed as a result of restructuring in the Grand Banks region after sea floor spreading became active. This unconformity is angular at the basin edge, but becomes intraformational within the basin (Jansa and Wade, 1975a and 1975b; Arthur et al., 1982; Grant et al., in press). Barss et al. (1979) dated this "middle"-Cretaceous unconformity as Albian.

Transgressive marine sediments of the Upper Cretaceous Dawson Canyon Formation, consisting dominantly of shales, were deposited during a time of eustatic sea level rise, indicating that sea-floor spreading was well underway by approximately 106 Ma (Arthur et al., 1982; Jansa and Wade, 1975a), establishing a proto-Atlantic Ocean.

The Tertiary clastic sediments of the Banquereau Formation were deposited unconformably on Upper Cretaceous sediments in most areas, but on Lower Cretaceous units of the Ridge Complex (Fig. 6). Early Tertiary sediments in the Jeanne d'Arc Basin consist of shale, siltstone and minor sandstone, representing deep neritic and bathyal conditions. Conditions shallowed during Oligocene to Lower Miocene time, and much of the Grand Banks region could have been exposed to subaerial conditions by middle to late Miocene (Grant et al., in press).

1.2.3 Stratigraphy of the Hibernia field

Most of the following discussion is summarized from Arthur et al. (1982), and Benteau and Sheppard (1982).

Figure 11 shows an idealized cross-section of the Hibernia

Fig.-II
SW-NE STRUCTURAL GEOLOGIC CROSS-SECTION
AND GENERALIZED STRATIGRAPHY

Figure. II: Southwest-northeast generalized cross-section across the Hibernia structure.

structure. The stratigraphy of the Hibernia field can be divided into two large divisions separated by the "middle"-Cretaceous unconformity (Arthur et al., 1982). Below the unconformity, the stratigraphic section is deformed and consists of Jurassic (Oxfordian-Tithonian) mixed clastic and carbonate sediments, and mainly clastic units of Lower Cretaceous (Berriasian - Albian) age. Above the unconformity the section consists of a basinward-thickening wedge of relatively undeformed Upper Cretaceous and Tertiary marine sediments towards the east and north (Figs. 5 and 6).

-Units Below the "middle"-Cretaceous unconformity

To date, the Jurassic Mic Mac Formation is the oldest sedimentary unit drilled in the Hibernia field. It consists of terrestrial and shallow marine clastics and carbonates deposited during a time of structural readjustments and sea-level oscillations. The cored Jurassic section within the K-18 well (3859-3889m), consists of light to medium gray shales, siltstones and thinly bedded limestones. Brachiopod and pelecypod shell fragments were observed by the present writer, and bioturbation is prevalent. Carbonaceous stringers and shale wisps are also quite common.

The Jeanne-d'Arc "zone" was first defined by McKenzie (1980), and later designated as an informal member of the Mic Mac Formation by Arthur et al. (1982). It consists of interbedded conglomerates and sandstones interpreted by Arthur et al. (1982) to be of fluvial origin. Conglomeratic zones cored in both the P-

15 and O-35 wells are polymictic, with clasts up to 10 cm in diameter. The conglomerate clasts are composed of limestone, chert, mudstone, shaly sandstone and metaquartzite. In the P-15 well, the conglomerates exhibit disrupted packing within a coarse-grained, lithic arenite matrix. These clasts exhibit low degrees of roundness and sphericity, indicating probable derivation from a proximal area of high local relief. In the O-35 well, on the other hand, the conglomerates are framework supported, with subrounded to rounded clasts.

Arthur et al. (1982) assigned the Jeanne d'Arc member to the Tithonian. Grant et al. (in press) however, regard the member as being Kimmeridgian based on palynological and micropaleontological data, (ostracod and calcareous benthic foraminiferal zones) from mudstones above and below the Jeanne d'Arc member.

The Late Jurassic - Early Cretaceous Missisauga Formation contains three sandstone-rich units which contain the principle reservoir rocks within the Hibernia oil field: the Hibernia, Catalina and Avalon members. Shales, mudstones and thin limestone units separate these sandy members.

The Hibernia "zone" was first described by McKenzie (1980) and later designated as an informal member of the Missisauga Formation by Arthur et al. (1982). Detailed stratigraphy of the Hibernia member is discussed in section 2. Arthur et al. (1982), regarded the Hibernia member as being mainly Valanginian, while Grant et al. (in press) assign it to the interval Tithonian - Berriasian.

The "B" seismic marker zone" (Benteau and Sheppard, 1982) is synonymous with the "C" member of Arthur et al. (1982), and also the Catalina member of the Chevron and Mobil well history reports (Chevron Canada Resources Ltd., 1979; Mobil Oil Canada Ltd., 1980a, 1980b, 1981). This unit consists of at least two discrete sandstone units separated by a shaly unit, and directly overlies the arenaceous carbonate marker known as the "B" seismic marker (McKenzie, 1980; 1981). The thin, slightly calcareous, fine-grained sandstones are laterally continuous throughout the field (Benteau and Sheppard, 1982). Arthur et al. (1982), regard the age of this member as Valanginian, whereas Grant et al. (in press) assign the member to Late Berriasian and Early Valanginian.

The Avalon "zone" (McKenzie, 1980) was informally designated the Avalon member by Arthur et al. (1982). Considered originally to be a member of the Missisauga Formation, the Avalon member is now interpreted by Grant et al. (in press) to include coarse-grained time-equivalents of the Logan Canyon Formation as well as the upper part of the Missisauga Formation (Fig. 8).

The sandstones of this member consist of very fine- to fine-grained, well-sorted, quartz-rich arenites with variable amounts of calcareous skeletal fragments and cement (Benteau and Sheppard, 1982). The Avalon sandstones show highly complex vertical and lateral relationships with little continuity. The member is thickest in the western part of the field adjacent to the Murre fault, and thins in an easterly direction (Fig. 11). The easterly thinning is abrupt, resulting in the absence of this

member in the B-08 well. Whether this thinning is the result of non-deposition or erosion in the east, is not clear, but Benteau and Sheppard (1982) and Arthur et al. (1982) prefer the latter possibility.

Arthur et al. (1982) placed the Avalon member entirely in the Hauterivian, whereas Grant et al. (in press), assign this member to the interval Hauterivian to Albian.

The Verrill Canyon Shale was first defined on the Scotian Shelf by McIver (1972), and was subsequently extended to the Grand Banks by Jansa and Wade (1975a), it is the basinward equivalent of the Mic Mac and Missisauga Formations. The Verrill Canyon Shale in the Hibernia field was deposited during a period of marine transgression (Grant et al., in press).

An earlier Kimmeridgian transgression resulted in the deposition of an organic rich shale (containing up to 6 weight percent organic carbon and consisting of Type II kerogen) in an anoxic environment. This shale is believed to be the dominant source rock in this region (Grant et al., in press; Arthur et al., 1982). Swift and Williams, (1980), Bujak et al., (1977a, 1977b), showed it to be rich in oil-prone organic matter and thermally mature enough to have generated liquid hydrocarbons. Powell (1984), in a study of oil-source relationships, interpreted that this shale is the source of the liquid hydrocarbons in the Jeanne d'Arc Basin.

-Units above the "middle"-Cretaceous Unconformity

Undeformed shallow to deep marine sediments of the Upper

Cretaceous Dawson Canyon and Wyandot formations unconformably overlie the deformed pre "middle"-Cretaceous unconformity section. The base of the undeformed, deep marine Tertiary Banquereau Formation is also marked by a major basinward-sloping (east and north) unconformity (Figs. 5 and 6).

1.3 Previous Work On The Hibernia Member

McKenzie (1980, 1981) and Arthur et al. (1982) presented thorough summaries concerning the stratigraphy and complex structural aspects of the field. They also defined the major seismic reflectors in the field. McKenzie (1980) postulated that the Hibernia Zone probably represents deltaic-shoreline sandstones.

Benteau and Sheppard (1982), presented a petrophysical and geological review of the field, with emphasis on the three Lower Cretaceous. Isopach, structural, and porosity contour maps, as well as stratigraphic cross sections for the Avalon, Catalina and Hibernia members, were presented. These authors postulated that the Hibernia member represents deposition within a deltaic environment; the main reservoirs consisting predominantly of homogeneous channel sands with less variation and better reservoir continuity than the sandstones within the Avalon member.

Handyside and Chipman (1983), focused on the development and exploitation of the field. These authors postulated that the Avalon and Hibernia members were both derived from an easterly prograding Early Cretaceous delta system. The Hibernia sandstones

were postulated to represent nearshore sands linked with the distributary system of a delta, deposited at the boundary between the deltaic plain and deltaic front environments.

As of yet, publications concerning detailed petrographic studies and diagenesis of the Hibernia member are lacking.

1.4 Purpose of Present Study

This study is an investigation of the sedimentary petrography, stratigraphy and environments of deposition of the Upper Jurassic - Lower Cretaceous Hibernia member of the Missisauga Formation within the Hibernia oil field. Detailed petrographic studies of the sandstones are used to propose a diagenetic history of the Hibernia member.

1.5 Methods

The Hibernia member was identified and correlated in the subsurface using down-hole logs (essentially the Electric, Gamma-Ray, and Sonic logs), and observed lithology where possible.

Of the ten wells drilled within the Hibernia field (C-96, B-08, K-14, P-15, K-18, B-27, J-34, O-35, I-46, and G-55), (Fig. 15), seven have penetrated the Hibernia member (C-96, B-08, P-15, K-18, K-14, B-27, and O-35). Only five wells have retrieved conventional cores from the Hibernia member (C-96, B-08, K-14, K-18, and B-27). Samples for this study were collected from the latter four, since the C-96 cores were not available for sampling when this study was being undertaken.

Approximately 280 metres of core were examined, mainly to

identify sedimentary structures, and textural and compositional characteristics. Megafossils and ichnofossils were also observed and identified, but no detailed taxonomy was attempted.

Eighty-six samples from conventional core were thin sectioned and examined using the petrographic microscope. Forty-three thin sections were investigated quantitatively using a "Swift" automatic point counter. Most samples were impregnated with colored epoxy to facilitate the recognition of porosity. Samples containing significant quantities of carbonate were stained with both Alizarin Red-S and potassium ferricyanide, based on methods documented in Dickson (1965, 1966), to help identify the carbonate minerals. Sodium cobalt nitrate was also used to stain five samples for potassium feldspar recognition.

Selected samples were examined using a "Cambridge" S.E.M. and energy dispersive X-ray (E.D.X) at Chevron Canada Resources Limited in Calgary. Microprobe and X-ray analyses of selected samples were undertaken at Carleton University to aid in mineral identification.

1.5.1 Petrographic Methods

Compositional percentages are based on 350 points counted in an approximate 2.5 x 1.5cm grid for each thin section. A coarse-meshed grid was used during the analyses so that the distance between points exceeded the maximum grain size, hence minimizing the sampling error.

The relatively low compositional variability of the Hibernia sandstones did not justify a larger number of points per section.

Three hundred-fifty point counts is considered statistically valid for determining compositional percentages in these sandstones. Appendix 3 is a graph developed by Nentwich (1980), after Chayes (1956) and Kelly (1971), representing the minimal error as a function of the calculated percentage of a component at the 75% level of confidence, based upon 350 point counts. For example, if the calculated percentage of polycrystalline quartz grains in a thin section is 20 percent, this curve shows that the probable error at the 75% level of confidence is 2.5 percent. Therefore, three out of four analyses of the thin section would give polycrystalline quartz percentages between 22.5% and 17.5%.

1.5.2 Method of Grain Size Analysis

Grain sizes were measured using a micrometer eyepiece. The longest apparent grain dimensions were recorded unless the detrital component exhibited signs of dissolution and/or compaction, in which cases the grains were neglected for size analysis.

Eighty to one-hundred grain measurements were recorded per thin section. The measured grains were objectively selected using the "Swift" automatic point counter. For three thin sections, size distributions based on 250 grains were compared to those based on 100 grain measurements. The variation from the lower-count results were insignificant and hence the lower number was used for the remainder of the size analyses in this study.

Cumulative size frequency curves were produced from the data collected (Figs. 17 and 18), and were used for determining sorting indices (refer to section 3.4.3).

2.

STRATIGRAPHY OF THE HIBERNIA MEMBER

The present writer takes the upper boundary of the Hibernia member to be the top of the uppermost, well-defined sandstone body of this thick sandstone sequence (Fig. 12). This uppermost sandstone occurs at least 250m below the "C" member of Arthur et al. (1982), and below a thick siltstone-shale succession within the Missisauga Formation, separating the "C" member from the Hibernia member. The basal boundary is considered to be the base of the lowest prominent, thick sandstone body of this sandstone succession (Fig. 12), which overlies the mudstone, siltstone, and thinly bedded carbonates of the Verril Canyon Shale. The Hibernia member as defined averages approximately 200m in thickness and occurs at depths varying between 3475 - 4180m within the oil field.

Figure 13, is a composite section of the Hibernia member showing both lithological and gamma-ray characteristics. The present writer has divided it into two lithologic zones based on downhole log responses and sedimentological characteristics observed in drill cores (Brown and Yole, 1985): 1/ the lower Main Hibernia zone, and 2/ the Upper Hibernia zone. The boundary between the zones is gradational.

The Main Hibernia zone (M.H.Z.) makes up the lower two-thirds of the composite section (Fig. 13), and consists of thick, sandstone bodies (varying up to 18m), of cross-stratified, moderately to well-sorted, medium- to very coarse-grained, quartz arenites. Although the sandstone bodies exhibit a blocky, uniform log motif in most cases, fining-upward cycles were observed in

cores of these sandstones. The sandstone bodies compose up to 76 percent of the M.H.Z. section with interbedded siltstone and mudstone units. The sandstone:shale ratio of the M.H.Z. ranges from 0.4:1 to 3.3:1 (Figure 23).

The arbitrary contact between these two zones (Figs. 13 and 14) is picked at the upper contact of the uppermost thick sandstone bed (>5m, except in the B-27 well, where it overlies a 12m thick interbedded sandstone and mudstone unit).

The Upper Hibernia Zone (U.H.Z.) consists of relatively thin (commonly 0.5 - 2m) bodies of very fine- to medium- grained, moderately- to well-sorted, quartz arenites with interbedded mudstones and siltstones. A low sandstone:shale ratio, ranging from 0.2:1 to 0.7:1 within the field, is characteristic of the U.H.Z. (Fig. 24).

Definitions for Table 1 Abbreviations:

<u>Det</u>	-Total percentage of detrital framework components
<u>Qm</u>	-Monocrystalline quartz
<u>Qp</u>	-Polycrystalline quartz
<u>Cd</u>	-Dark chert
<u>Cl</u>	-Light chert
<u>F</u>	-Feldspars (plagioclase and/or potassic feldspars)
<u>Sh</u>	-Shale clast
<u>St</u>	-Siltstone clast
<u>Wm</u>	-Woody material (now coaly matter)
<u>Sf</u>	-Shell fragments
<u>Si</u>	-Silica cement
<u>Ca</u>	-Carbonate cement
<u>Cy</u>	-Clay (matrix and authigenic clay)
<u>Ap</u>	-Authigenic pyrite
<u>Tl</u>	-Total porosity
<u>Dc</u>	-Dissolution of carbonate cement
<u>Df</u>	-Dissolution of framework grain
<u>Pr</u>	-Primary porosity
<u>Mo</u>	-Modal class (st-silt; vf-very fine sand; f-fine sand; m-medium sand; c-coarse sand; vc-very coarse sand)
<u>X</u>	-Mean grain size in mm
<u>Osd</u>	-Estimated phi standard deviation
<u>Rnd</u>	-Roundness (A-angular; sA-subangular; sR-subrounded; R-rounded; wR-well rounded)
<u>Sph</u>	-Sphericity
<u>mr</u>	-minor occurrence (<3%)

Table 1 is arranged that sample data for the U.H.Z. and M.H.Z. are separated. For the M.H.Z., data for each well are arranged in descending order of increasing mean-grain size. Data from the two wells with samples from the U.H.Z. are grouped together, but also arranged in order of increasing grain size.

Table 1: Sandstone Composition and Grain Size Analyses of the Ribemba Member

Sample #	Depth (m)	Detrital components recalculated to 100%										Cement		Ap	Porosity		P _t	Textures		U.H.Z. Samples		
		Det	Qm	Qp	Cd	Cl	P	Sh	Sc	Wm	Sf	Sl	Ca		TL	Dc		Df	Mo		X	Qsd
B-08-2-A	3485.1	90.9	67.7	12.3	—	2.6	2.3	0.5	—	3.5	—	1.1	6.0	10.8	—	0.6	—	—	st-vf	0.09	1.11	SA-SR 7-9
K-14-7-749	3862.8	72.0	81.3	12.7	—	—	2.8	2.8	0.4	—	0.3	7.1	3.7	1.1	—	16.0	12.3	3.7	vf-f	0.16	0.56	SA-SR 7-9
K-14-8-752	3871.8	69.0	83.6	11.1	0.5	1.9	2.4	0.5	—	—	0.3	11.0	5.6	0.6	—	13.3	12.6	0.6	m	0.17	0.38	SA-R 7-9
B-08-2-2	3487.1	76.6	80.6	13.1	0.4	2.6	1.1	—	1.5	0.7	—	6.6	0.6	4.3	0.9	10.0	7.4	2.3	f-m	0.25	0.43	SA-R 7-9
B-08-2-4	3488.0	76.8	66.5	15.6	1.1	—	2.6	—	2.3	6.7	5.2	4.3	1.2	6.3	1.7	10.0	6.9	3.1	m	0.62	0.65	SA-SR 7-9
K-14-12-773	3934.5	70.5	79.3	15.7	1.0	3.2	—	1.0	—	—	—	11.4	1.6	0.3	—	16.2	13.3	2.9	m	0.35	0.52	SA-SR 7-9
K-14-13-776	3944.0	68.0	84.0	14.0	0.72	0.72	—	0.7	—	—	—	12.5	—	0.5	4	19.0	11.5	7.5	m	0.38	0.41	SA-SR 7-9
K-14-10-759	3901.8	75.5	87.3	10.2	0.6	1.3	—	1.0	—	—	—	6.7	—	2.8	—	15.0	13.9	0.8	m	0.40	0.51	SA-SR 7-9
K-14-12-769	3927.0	76.3	78.6	19.6	0.45	0.45	0.43	0.43	—	—	—	8.0	0.6	—	—	15.0	9.0	5.6	m	0.4	0.58	SA-SR 7-9
K-14-12-763	3922.2	77.6	83.7	15.0	0.4	0.4	0.4	—	—	—	—	7.6	—	—	—	14.6	14.0	0.6	f-m	0.42	0.60	SA-SR 7-9
K-14-14-778	3961.2	67.0	82.6	12.4	2.0	1.0	—	1.0	—	—	—	17.0	8.0	0.3	0.6	7.0	4.0	2.9	m	0.44	0.52	SA-SR 7-9
K-14-14-785	3971.5	69.4	84.0	12.8	1.2	1.2	—	0.8	—	—	—	12.0	0.5	—	0.2	17.7	10.0	7.7	m	0.48	0.68	SA-SR 5-9
K-14-14-782	3969.0	70.6	92.5	6.5	0.5	—	—	0.5	—	—	—	11.3	1.0	—	—	17.0	10.3	6.2	m	0.58	0.48	SA-SR 7-9
K-14-12-766	3924.4	79.6	78.0	21.0	0.4	—	1.0	—	—	—	—	5.3	—	—	—	15.0	8.3	6.6	m	0.65	0.50	SA-SR 7-9
B-27-7-700	3889.0	82.5	91.5	5.5	—	—	3.0	—	—	—	—	9.5	0.5	0.5	—	5.0	5.0	—	st	0.05	0.52	SA-SR 5-9
B-27-10-708	3915.2	88.5	76.3	8.0	—	0.6	3.0	—	—	—	—	7.5	0.5	—	—	3.0	2.5	0.5	vf	0.14	0.58	SR 5-9
B-27-5-688	3849.0	75.3	85.0	12.4	0.9	0.4	1.3	—	—	—	—	10.6	1.0	—	—	12.0	12.0	—	f-m	0.25	0.28	SA-SR 7-9
B-27-10-705	3907.5	80.0	85.1	13.6	0.3	—	0.5	0.4	—	—	—	8.1	—	—	—	10.9	10.9	—	m	0.31	0.40	SA 7-8
B-27-1-698	3887.0	76.0	82.0	15.4	1.9	—	0.75	—	—	—	—	9.4	1.2	0.3	—	12.6	8.3	4.2	m	0.37	0.30	SA-SR 7-9
B-27-5-691	3854.2	70.6	84.0	15.0	1.0	—	0.5	—	—	—	—	13.0	0.3	—	—	16.0	11.7	4.9	m	0.38	0.43	SA-R 7-9
B-27-9-703	3901.7	73.4	80.0	18.3	—	1.3	0.4	—	—	—	—	10.6	0.9	—	—	12.8	11.25	1.3	m	0.51	0.41	SA-SR 7-9
B-08-6-2	3621.0	93.3	65.0	10.4	1.6	1.6	1.0	0.3	—	—	—	3.4	0.3	0.3	—	0.9	0.3	0.6	st-vf	0.15	1.21	A-SR 7-9
B-08-6-11	3630.2	78.9	87.0	8.0	—	1.8	0.4	0.7	—	2.2	—	11.4	2.9	1.2	0.3	5.4	5.1	0.3	f	0.18	0.50	SA-R 7-9
B-08-6-5	3626.5	76.0	85.0	12.8	0.8	1.1	0.4	—	—	—	—	8.3	1.4	3.1	—	9.7	6.9	2.9	f-m	0.24	0.56	SA-R 7-9
B-08-4-2	3562.8	68.0	87.4	9.7	1.7	0.4	0.6	—	—	—	—	2.6	24.6	—	0.6	4.3	3.7	0.6	f-m	0.3	0.62	A-R 7-9
B-08-3-A	3558.5	71.1	83.1	11.6	1.2	1.6	0.4	—	—	2.0	—	5.1	0.6	6.3	0.9	15.4	6.9	6.9	m	0.38	0.56	SA-R 7-9
B-08-6-7	3688.5	76.6	84.7	13.1	0.6	0.6	0.6	—	—	—	—	6.0	0.9	2.6	0.6	13.4	11.4	1.7	m	0.49	0.54	A-R 5-9
B-08-6-9	3629.5	78.0	82.1	13.5	1.3	1.3	0.6	1.3	—	—	—	5.0	0.5	5.5	—	11.0	7.0	4.0	m	0.58	0.60	A-R 7-9
B-08-5-B	3613.0	73.6	80.5	15.8	1.4	1.4	1.0	—	—	0.5	—	5.3	2.6	7.3	0.3	10.3	6.0	3.3	m	0.67	0.31	SA-SR 5-9
K-18-3-9	3804.1	74.5	93.0	2.6	1.9	—	1.5	—	—	—	—	2.0	1.14	1.14	0.2	21.0	18.0	3.0	m	0.12	0.54	SA-R 5-9
K-18-5-6	3825.5	73.3	94.0	2.2	—	1.2	2.7	—	—	—	—	3.4	0.6	1.7	1.0	20.0	10.0	10.0	f	0.17	0.45	SR-R 7-9
K-18-5-15	3833.0	78.0	89.0	8.1	1.1	1.1	0.7	—	—	—	—	5.1	1.4	4.6	0.3	10.6	8.3	2.3	m	0.20	0.70	A-R 7-9
K-18-6-13	3856.1	78.5	88.9	3.3	—	1.9	3.8	—	—	4.0	—	4.6	3.9	9.5	0.6	4.0	2.9	1.14	m	0.26	0.75	SA-SR 7-9
K-18-3-11	3808.8	72.3	91.7	7.3	2.0	0.4	1.0	—	—	—	—	6.5	1.0	0.9	—	19.1	14.9	4.3	m	0.28	0.45	SA-R 7-9
K-18-5-4	3823.7	82.5	93.2	4.4	—	0.7	1.4	—	—	2.2	—	7.7	2.9	5.1	2.0	4.9	2.3	1.7	m	0.32	0.95	SR-R 8-9
K-18-3-12	3809.9	73.9	82.4	6.2	0.5	0.5	0.3	0.2	—	—	—	5.4	1.7	1.0	0.6	17.4	16.0	1.3	m	0.32	0.44	SR-R 3-9
K-18-5-8	3834.5	71.1	95.0	3.7	0.4	0.4	1.6	—	—	0.4	—	6.0	1.0	4.3	0.3	18.3	11.7	6.6	m	0.37	0.54	SA-R 5-9
K-18-6-9	3852.2	70.5	93.1	4.4	—	2.4	0.8	—	—	—	—	4.3	0.6	3.2	—	21.4	18.0	3.4	m	0.37	0.54	SA-R 3-9
K-18-5-11	3829.8	68.7	92.5	4.6	1.0	1.5	1.2	—	—	—	—	5.1	1.8	2.3	—	22.0	14.3	7.4	m	0.39	0.49	SA-R 5-9
K-18-5-19	3837.0	74.3	91.3	5.7	1.5	0.8	—	—	—	—	—	4.0	1.0	3.7	—	16.9	10.6	6.3	m	0.48	0.66	SA-SR 5-9
K-18-6-2	3839.5	71.2	87.4	4.9	1.0	1.0	—	—	—	5.6	—	4.6	0.3	7.4	0.6	16.9	9.7	6.9	m	0.52	0.62	SA-R 7-9
K-18-6-8	3842.8	74.9	93.5	6.1	—	0.4	1.1	—	—	—	—	3.1	1.0	5.2	0.9	14.9	10.9	4.0	m	0.64	0.52	SA-R 5-9
K-18-4-B	3817.1	74.1	68.3	6.3	0.5	0.5	0.3	—	—	—	—	2.6	—	—	—	14.3	8.6	5.1	m	0.64	0.42	SA-R 7-9

M.H.Z.
Samples

3.1 Framework Grains

Percentages of the main detrital constituents of the Hibernia sandstones are tabulated in Table 1. Detrital quartz grains are ubiquitous in the sands, ranging from 68.3 to 99% of the detrital constituents. Chert (both light and dark) and feldspars occur in minor amounts throughout the Hibernia sandstones. Accessory minerals including zircon, sphene, tourmaline, and less commonly amphibole, are usually present. Carbonaceous material is present in minor amounts in most thin sections, although in one section it composes greater than 20% of the detrital components. Other minor detrital constituents include rock fragments of shale, siltstone, and very fine-grained sandstone, as well as rare shell fragments (refer to section 5.3), which tend to be more common in the U.H.Z..

Most of the sandstones studied can be classified as quartz arenites (Fig. 16), using the classification scheme proposed by Pettijohn (1954) and modified by Dott (1964). The sandstones would also be classified as quartz arenites using Folk's (1974) classification scheme.

3.1.1 Quartz

Both monocrystalline and polycrystalline quartz were recognized in the petrographic study.

Monocrystalline quartz is the most common of the two, varying from 65% to 92.5% and averaging approximately 82% of the detrital constituents. Because the original grain boundaries of

some quartz grains are not detectable because of the absence of dust rims, these percentages probably include a small proportion of authigenic quartz overgrowths. Undulose extinction of monocrystalline quartz grains is very common. Fluid inclusions and microlites (usually muscovite) are present in some monocrystalline quartz grains.

Four types of polycrystalline quartz can be recognized in the Hibernia sandstones, based on the criteria of Folk (1974): plutonic; metamorphic (sheared and schistose); and minor amounts of hydrothermal quartz. In the samples examined, polycrystalline quartz ranges from 5.5% to approximately 23% of the detrital constituents, with an average of 13%. The amount of polycrystalline quartz grains generally increases in relative proportion in the coarser grained arenites (Table 1). All polycrystalline quartz grains exhibit undulose extinction. Intragrain sutured contacts are common in the metamorphic quartz grains.

Evidence suggests that at least a small percentage of detrital quartz clasts have been recycled, despite difficulty in distinguishing the criteria because of diagenetic alteration. Plates 4a and 4b, illustrate well-rounded, abraded overgrowths, most likely developed during the recycling of sands, surrounded by in situ, euhedral quartz overgrowths. Plate 4c illustrates a quartz-cemented, very fine-grained composite sandstone clast, also indicating recycling of sedimentary rocks. Recycling of sediments is thus one reason why these sandstones are very quartz-rich. Quartz grains exhibit moderately- to well-rounded

original grain boundaries where they can be observed, along with moderate to moderately high sphericities (Plates 6e and 6f).

3.1.2 Chert

Dark and light coloured chert grains are present in small amounts throughout the Hibernia member, occurring in all but one of the thin sections examined. Total chert percentages range from 0.3% to 4.2%, averaging 1.7%. Rare intragranular porosity within chert grains (Plates 4d and 4e), probably resulted from the removal of remnant carbonate (which was not replaced by silica during chert formation in limestones).

The light coloured chert is characteristically microcrystalline and colourless or light yellowish. The dark chert is characteristically light to dark brownish and microcrystalline. Light coloured chert constitutes up to 3.2% of the detrital grains, averaging 1%. Dark coloured chert constitutes up to 2% of the detrital grains, averaging 0.8%.

Most chert grains observed are angular to sub-rounded. This could result from a number of possible processes including the following: a closer provenance than most quartz grains; a shorter history of sedimentary recycling than most quartz grains; or post-depositional corrosion. The latter is interpreted for the grains exhibiting irregular outlines, probably resulting from partial dissolution (Fig. 4d).

3.1.3 Feldspars

Both plagioclase and potassic feldspars are present in minor to trace amounts in the Hibernia sandstones (Table 1).

Plagioclase is the more common and was recognized on the basis of polysynthetic twinning. Potassic feldspars were identified on the basis of sodium cobaltnitrate staining of five thin sections, and elsewhere on the basis of physical properties, particularly alteration. Rare microcline was identified on the basis of grid twinning.

Dissolution of plagioclase has occurred to varying degrees (Plates 1a, 1b and 1c), producing moldic porosity with complete dissolution (Plate 1b), and "honeycombed" grains due to partial dissolution (Plate 4f). E.D.X. analysis has revealed that most of the plagioclase is albite. A greater percentage of feldspars occur in sandstones of the U.H.Z. relative to those of the M.H.Z.. All feldspars observed exhibit at least partial alteration, being replaced by clays, sericite and carbonate. Most feldspar shapes are lathlike.

3.1.4 Micas

Micas are present rarely in the sandstones. Muscovite is more prevalent than biotite, which is very rare. Abundant flakes of fine-grained muscovite along the bedding planes are most prevalent in interbedded mudstones.

3.1.5 Accessory Minerals

Petrographic microscopy and E.D.X. analysis have revealed that zircon, sphene, tourmaline, amphibole and possible (but very rare) ilmenite, are minor constituents in the Hibernia sandstones. Zircon is the most common accessory mineral (usually

<1.0%). It is usually moderately well-rounded, supporting evidence of sedimentary recycling.

3.1.6 Rock Fragments

Shale, mudstone and siltstone rock fragments are present in minor amounts in most thin sections examined. Of the samples quantitatively examined, mudstone clasts are most common with quantities up to 1.3%, averaging approximately 0.4%. Most of these rock fragments exhibit distorted, irregular shapes, most likely resulting from compaction into grain interstices (Plates 5d and 7c), suggesting that they were not well indurated at the time of deposition.

Light-grey mudstone wisps (Plate 8a) commonly occur throughout the Hibernia sandstones, with no obvious preferential association with fine or coarse textured sandstones. These mudstone wisps vary in dimensions up to 8cm long and 2.5cm thick. Their similarity to nearby bedded mudstones, and their consistent deformation suggests that these wisps are rip-up clasts.

3.1.7 Carbonaceous material

Carbonaceous stringers and fragments are common within the Hibernia section occurring in both the sandstones and mudstone facies (Plates 8b, 8c and 10a). The carbonaceous material includes identifiable carbonized plant material such as branches, leaves, and wood chips, as well as fine comminuted debris.

In one sample examined quantitatively (K-14-4-B), carbonaceous material accounted for 21.3% of the detrital

constituents. Other thin sections, not quantitatively analysed, have been observed to contain similar amounts of carbonaceous material.

3.2 Matrix

The described sandstones are clean (Table 1), with little or no matrix. However, irregularly distributed visible matrix is present in other sandstones not quantitatively analysed, commonly resulting from obvious burrowing features. The matrix consists of silt-sized and finer silicates and clays.

Matrix is more abundant within the very fine-grained sandstones and siltstones (Table 1), as well as in the few poorly sorted sandstones. Since many of the samples were collected from "rubble", some porous sandstones may superficially appear to be matrix-rich because of drilling-mud invasion.

3.3 Authigenic minerals

Authigenic quartz, carbonate, clays, sericite, siderite, and pyrite are present in the Hibernia member.

Authigenic quartz, occurring as overgrowths around detrital grains, is the most common cement (Plates 1f, 2f, 5e, 6c, 6e and 6f). Authigenic quartz constitutes 1.1 to 17.0% of the total rock composition, averaging 7%. The samples exhibiting high proportions of quartz cement are generally <1.5m from a mudstone, or interbedded mudstone and fine-grained sandstone facies.

Carbonate is the next most common authigenic mineral. It is present as intergranular, pore-filling cement and also as an

alteration mineral replacing detrital feldspars and quartz (Plates 3b, 3e, 3f, 5e, 6b, 7a, 7b and 7c). E.D.X. analysis has revealed that the carbonate cement is calcite containing trace amounts of iron. In most samples containing abundant calcite cement, the cement is coarse (spar) and poikilitopic, composing a mosaic of subequant calcite crystals. In one sample (K-14-7-5, not quantitatively analysed), the intergranular carbonate consists of micrite. Calcite cement can constitute greater than 25% of the total rock composition, but in most samples, calcite cement is scattered (Plates 7b and 7d), probably representing remnant "patches" after mesogenetic dissolution. Textural relationships suggest that calcite cementation followed the earlier silica cementation event (Plates 5e and 5f).

S.E.M. and E.D.X. analyses have determined that kaolinite, illite and sericite are present in minor amounts. Kaolinite is the most common clay observed, but is rarely in sufficient quantities to hinder the migration of fluids through the sandstones. Pore-filling kaolinite is commonly in the form of stacked pseudohexagonal platelets and booklets coating framework grains and quartz overgrowths (Plates 1e, 1f, 2a, 2e and 6d). Kaolinite also occurs as an alteration product of feldspar (Plate 1a and 1d).

Illite occurs sporadically as intergranular clays (Plate 2b), in the form of wispy, irregular flakes lining pores. Illite is also present as an alteration product of feldspars and possibly micas.

Sericite is rarely present as an alteration product of

feldspars, forming irregular platelets (Plate 1d).

Reddish-brown to black sphaerosiderite (siderite microconcretions exhibiting a radial-concentric growth habit, commonly around a pyritic nucleus) are locally abundant (Plates 5a and 5b). These sphaerosiderite microconcretions are normally less than 1mm in diameter and occur most frequently within mudstones. These microconcretions are considered to have grown in situ because of their textural habit of "engulfing" detrital quartz grains, and commonly being several times larger than surrounding silicate grains (Plates 5b). The sideritic composition was confirmed by petrographic microscopy, microprobe and E.D.X. analysis.

Pyrite occurs sporadically throughout the Hibernia section. It commonly occurs in three forms: euhedral cubic crystals, irregular patches, and framboids (Plates 2c and 2d). Pyrite is most common in units that are rich in carbonaceous matter.

Glaucinite has not been observed in any of the samples studied, although trace amounts of glauconite have been reported in the U.H.Z. (B-08 well, well history report; K-14, AGAT consultant report).

3.4 TEXTURES

3.4.1. Grain size

Although the Main Hibernia Zone is characterized by medium- to coarse-grained sandstones, the range of grain sizes vary from very coarse- to very fine, with most having modal classes within the medium-grained range (Table 1; Figs. 17 and 18). Commonly, fining-upward trends from coarse- or very coarse-grained arenite to fine-grained arenite are both evident from cores and reflected in log motifs (Figs. 13 and 14).

Mudstone, shale and siltstone occur between the main sandstone bodies of the M.H.Z. Locally, very fine- to fine-grained sandstones, thinly bedded or laminated, occur within these interbedded mudstone sequences (Figs. 13 and 14).

The thicker sandstones within the Upper Hibernia Zone range from coarse- to very fine-grained, but in contrast to those of the M.H.Z., most are very fine- and fine-grained arenites (Figs 13 and 14). These sandstone beds are locally laminated and thinly interbedded with mudstone and siltstone and most exhibit abrupt contacts with the interbedded mudstone units. Though mainly uniform in texture, local coarsening-up and fining-up trends within the sandstone bodies have been observed in cores (Fig. 14).

Mean grain size determinations (Table 1: $\bar{X}$), were derived arithmetically by averaging the sum of the 80 - 100 grains counted as explained in section 1.5.3.

FIGURE 17a- Cumulative Size Frequency Curves - K-18 M.H.Z. Samples

FIGURE 17b - Cumulative Size Frequency Curves - B-08 M.H.Z. Samples

FIGURE 17c - Cumulative Size Frequency Curves - K-14 M.H.Z. Samples

3.4.2. Grain Shape

Grain shape determinations are based on original grain boundaries where they can be detected. Detrital quartz sand grains throughout the Hibernia member vary in roundness values (based on Powers, 1953) from 0.20 to 0.85 (angular to well rounded), with a predominance of subrounded grains. Roundness values do not appear to vary significantly relative to vertical and lateral stratigraphic positions within the Hibernia member. Sphericity values (based on Krumbein and Sloss, 1963, Fig. 4-10) for these sandstones range from 0.3 to 0.9 (low to high sphericity), with the majority of the samples exhibiting moderately high (.7) to high (.9) values.

Feldspars, and rock fragments are usually less rounded and of lower sphericity values than accompanying quartz grains.

The presence of well-defined dust rims in some quartz grains demonstrates the well rounded aspect of original grains. It is likely that many of the more angular and low sphericity quartz grains reflect either secondary overgrowth shapes, where original grain boundaries are not detectable, or post depositional corrosion of quartz by carbonate (section 7).

3.4.3. Sorting

For all samples quantitatively analysed, phi standard deviations (Table 1: ϕ_{sd}) were derived from cumulative size frequency curves (Figs. 17 and 18), based on methods described in Folk and Ward (1957). Based on the verbal classification table of Folk (1959), the sandstones range from poorly- to very well-

sorted. Most of the quantitatively analysed sandstones are moderately- and well-sorted as illustrated in the cumulative frequency curves (Fig. 17 and 18).

3.4.4. Packing

Most of the sandstone samples examined from the Hibernia member show intact packing (Plate 5c). However, many display inhomogeneous packing (Plate 5d), with areas of disrupted or intact packing and high intergranular porosities occurring adjacent to areas of condensed packing with low intergranular porosities. This inhomogeneity of packing probably reflects an earlier inhomogeneity in the distribution of soluble matrix or cement (Schmidt and McDonald, 1979b, 1979c). Condensed packing is the result of mechanical compaction in areas where intergranular matrix or cement was lacking during deep burial.

3.5 Conglomeratic Beds

Conglomerates occur locally within the sandstone and mudstone facies of the M.H.Z. (Plates 9a and 9b; Fig. 14, well B-08 core #6, well K-14 cores #5 and #3, well B-27 core #7). They are composed of prolate to equant clasts of siderite, pyrite, silicified mudstone, chert, and quartzite clasts. In the limited core available no organized fabric such as imbrication was visible. These conglomeratic beds are characterized by abrupt or scoured basal contacts and rapidly fine-upward into overlying finer grained sandstones, siltstones or mudstones. The matrix is either sandy (in conglomeratic sandstones), or silty to sandy (in conglomerates of the mudstone units).

4.1 Cross-bedding

Both planar and trough cross-bedding have been observed in the sandstone bodies throughout the Hibernia member (Table 2; Plates 9c and 9d). Cross-stratification is best defined where carbonaceous fragments occur along the bases of the laminae and/or beds.

Both large scale ($>10\text{cm}$) and small scale ($<10\text{cm}$) sets of high angle ($>10^\circ$, ranging up to approximately 30°) and low angle cross-stratification are abundant in the thick sandstone bodies of the M.H.Z.. Some of the larger cross-sets range up to 20cm in thickness. Trough and planar cross-bedding are equally abundant and commonly occur in the same sandstone body along with horizontal (parallel) bedding.

Cross-bedding in the U.H.Z. is dominated by small-scale sets of low-angle cross-bedding, although rare high-angle cross-bedding occurs locally. Planar cross-bedding is most abundant in the U.H.Z., with only minor occurrences of trough cross-bedding.

Other sedimentary structures commonly associated with cross-bedding include horizontal bedding, graded-bedding, and locally ripple cross-stratification (Appendix 1).

Herringbone cross-bedding was not observed in the available cores.

4.2 Horizontal Bedding

Horizontal bedding (parallel bedding) is common in the sandstone facies of both the M.H.Z. and U.H.Z., frequently

occurring in close association with cross-bedding.

4.3 Ripple Cross-Lamination

Ripple cross-lamination is abundant throughout the Hibernia section (Fig. 14; Appendix 1). Three types of ripple cross-laminations have been observed; asymmetric, climbing and starved. These structures are most frequently associated with the very fine- and fine-grained sandstones and the laminated and interbedded fine-grained sandstones occurring between the thicker sandstone bodies.

Asymmetric ripple cross-lamination is the most common ripple structure observed in the Hibernia sequence, occurring throughout the section.

Climbing ripples locally occur in sandstones of the M.H.Z. (Appendix 1: well B-27 core #10; well K-14 core #10), but were not observed in the U.H.Z..

Starved ripples were observed locally in laminated fine-grained sandstones (Appendix 1: well K-14 core #14) and also rarely in siltstones (Appendix 1: well K-14, core #10). Starved ripples were not observed in the U.H.Z..

4.4 Graded Bedding

Normal grading occurs locally in the sandstone bodies of the M.H.Z.. Thin graded units are usually 1-2cm thick and fine upward from very coarse- or coarse-grained arenite into medium-grained arenite (Appendix 1: well B-08 cores #3, #6; well K-18 core #5; well K-14 cores #13, #12, #10). Such graded units are observed in close spatial association with cross-bedding,

occurring as foreset laminae within cross-stratified sets and also as isolated sets.

Normal graded bedding also occurs in the laminated fine grained sandstones of both the M.H.Z. and U.H.Z., where individual laminae grade from fine- or very fine-grained arenite into siltstone or mudstone.

Reverse graded bedding is rarely present in the laminated and thinly bedded sandstones of the M.H.Z. (Appendix 1: well K-14, core 14).

4.5 Scoured Contacts

Most sandstone bodies observed in core from both the M.H.Z. and the U.H.Z. have scoured basal contacts (Plates 8a, 10a and 10b). Internal (intrastratal) scoured contacts have been observed in some sandstones of the M.H.Z., suggesting that the thicker sandstone bodies are complexes of two or more sandstone bodies. The internal scoured contacts truncate adjacent laminae and bedding and locally are directly overlain by conglomerates and rip-up clasts.

4.6 Wavy - Lenticular Bedding

Wavy and lenticular bedding have been observed in the laminated fine-grained sandstones and mudstones, occurring in both the M.H.Z. and the U.H.Z. (Plates 8c, 9a and 10c).

4.7 Soft Sediment Deformation

Evidence of soft sediment deformation is abundant throughout the Hibernia member. Most abundant are intrastratal contortions

(disrupted to convoluted bedding), (Plate 10b). Very fine- or fine-grained sandstone laminae locally exhibit sedimentary boudinage due to intrastratal tensional stresses (Appendix 1: well K-14 core #14). Small-scale load casts and flame structures are common in the laminated sandstones and thinly interbedded sandstones throughout the Hibernia section (Appendix 1).

Small-scale syn-sedimentary faulting has also been observed in the laminated fine-grained sandstones.

4.8 Concretionary Structures

Orange to reddish-brown, in situ, siderite concretions occur throughout the Hibernia sequence. These concretions normally range in thickness between 1 and 4 cm, although maximum thicknesses can range up to 10cm. The siderite concretions are generally ovoid with long axes parallel to the bedding planes. They are common in the mudstone facies and rare in the sandstone bodies.

Reddish-brown to black, sphaerosiderite micro-concretions (refer to section 2.3) occur in local concentrations in the mudstones of the Hibernia member (Appendix 1: well B-08 cores #6 and #5; well K-14 cores #7, #9 and #12; well B-27 cores #10 and #7).

5.1 Micropaleontology

From micropaleontological studies of the Hibernia member, Williamson (pers.comm.) concluded that calcareous planktonic foraminifera are rarely present in the Hibernia member. The few calcareous foraminifera observed from the U.H.Z. of well B-08, are abraded, indicating that they were subjected to reworking. Agglutinated forams however, are common in both the U.H.Z. and M.H.Z., indicating a brackish to freshwater environment (Williamson, pers. comm.). Pyritized, probably freshwater ostracodes were also found in the M.H.Z. according to Williamson (pers. comm.).

Biostratigraphic analysis of the Hibernia area, based on ostracod and calcareous benthic foraminifera assemblage zones in four wells (B-08, K-18, O-35, and P-15), (Ascoli et al., 1984), suggests that the Hibernia member ranges in age from Tithonian to Berriasian (Fig. 12). According to Ascoli et al., (1984), the Berriasian is identified by the marine foraminifera assemblage zone "Epistomina minutereticulata - Epistomina sp.2 - Epistomina sp.3 Zone", and the dominantly marine ostracod assemblage zone "Schuleridea juddi Zone". The base of the Berriasian corresponds with the top of the underlying Tithonian, identified by the foraminifera "Epistomina uhligi - Epistomina stellcostate assemblage Zone", and the "Hutsonian gr. collinensis - Galliaecytheridea postrotunda - Schuleridea sp.1 ostracod assemblage Zone" (Ascoli, 1984). In Figure 12, the Berriasian -

Tithonian boundary in the K-18 well appears anomalously high. The present writer assumes the boundary is probably misplaced because of either an error in sampling depths or a repetition by faulting, however the reason is unknown at this time.

Similarly, it is possible that the "Schuleridea juddi Zone" pick in the P-15 well, located approximately 25 meters below the upper contact of the Hibernia member (Fig. 12), is too low. It should be noted that all of these biostratigraphic horizons were picked on the basis of chip samples.

5.2 Palynology

Palynological analysis of the Hibernia area by Davies (pers. comm.) suggests slightly diachronous upper and lower boundaries of the Hibernia member. Davies documented 4 zones within close association of the Hibernia member; the Glossodinium dimorphum, Amphorula #EA, Striatella #EJ, and the Muderongia McWhaei Zones, recognized and identified numerically as zones 4, 5A, 5B, and 5C, (Fig. 12).

Late Kimmeridgian (4), Tithonian (5A and 5B), and Late Tithonian - Berriasian (5C) ages are inferred. These palynological biostratigraphic zones appear to be relatively consistent throughout the field (Fig. 12).

It should be noted that all but two of these biostratigraphic horizons were picked on the basis of chip samples, therefore most of the horizon picks are approximations and minor fluctuations are expected. The two exceptions are located within cored intervals: 5A, in the B-08 well, and

4, in the K-18 well.

5.3 Megafofossils

Fossilized shell fragments are rarely present in the mudstones of the M.H.Z. and the sandstones and mudstones of the U.H.Z. (Fig. 14: well K-14 cores #7, #8, #13, and B-08 core #4). Where preservation permits identification, the majority of the fragments are derived from pelycypods, with minor gastropod and ostracod debris. These shell fragments are randomly oriented (Plate 7f), indicating rapid transportation and deposition or post-depositional disturbance due to bioturbation or dewatering. Molds of shell fragments (Plate 10d; Appendix 1: well K-14 core #8 - 3871.5m, 3875.5m) are present in a few of the U.H.Z. sandstones locally enhancing the porosity (refer to chapter 8).

5.4 Ichnofossils

Trace fossils are present throughout the Hibernia section. Ichnofossil identification was based on comparison with illustrations in Chamberlain (1978). Ichnofossils observed in the mudstone facies of the M.H.Z. are tentatively identified as Chondrites, Skolithos, Teichichnus, Diplocraterion, Arenicolites, and Asterosoma. In the sandstone bodies of the M.H.Z. Arenicolites and Skolithos are rarely present.

The U.H.Z. is more bioturbated than the M.H.Z.. Ichnofossils tentatively identified in the mudstone facies of the U.H.Z. include Rhizocorallium, Skolithos, Asterosoma, and Chondrites. In the sandstone bodies of the U.H.Z., Skolithos and Asterosoma are present.

Table 2 -

STRATIGRAPHIC DISTRIBUTION OF KEY
COMPONENTS, TEXTURAL FEATURES AND
SEDIMENTARY STRUCTURES OF HIBERNIA MEMBER

MINERALS	M.H.Z.			U.H.Z.	
	M-sst	sst/mdst	M-mdst	U-sst	U-mdst
glauc				*	*
hem					*
sid	**	***	****	**	***
sphasid		**		*	**
SEDIMENT. FEATURES					
coal bd		*			
rootlets		**			**
shl fgmt		*	***	**	**
bioturb		**	****	**	***
trgh x-bdg	****	***		*	
plan x-bdg	****	**		***	
hor bdg	****	***		***	
asy rpl	***	****		****	****
clmb rpl	*	*			
strv rpl		*			
sft sed def		***	***	***	****
rp-up mdcls	****	**		**	
scr bas etc	****	**		***	
intstr scr	***				
carb strngr	****	***	**	**	*
carb frag	****	****	***	****	****
cgl bds	**	*			*
lam f sst		***			***
nrm gd bdg	**				
fng-up trd	***				
crs-up trd				**	

glauc (glauconite), hem (hematite), sid (siderite), sphasid (sphaerosiderite), coal bd (coal bed), shl fgmt (shell fragments), bioturb (bioturbation), trgh x-bdg (trough cross-bedding), plan x-bdg (planar cross-bedding), hor bdg (horizontal bedding), asy rpl (asymmetric ripples), clmb rpl (climbing ripples), strv rpl (starved ripples), sft sed def (soft sediment deformation), rp-up mdcls (rip-up mudclasts), scr bas etc (scoured basal contact), intstr scr (intrastratal scour), carb strngr (carbonaceous stringers), carb frag (carbonaceous fragments), cgl bds (conglomeratic beds), lam f sst (laminated fine-grained sandstone), nrm gd bdg (normal graded bedding), fng-up trd (fining-upward trend), crs-up trd (coarsening-upward trend)

*-rare
**-local

***-common
****-abundant

6. LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS
OF THE HIBERNIA MEMBER

6.1 Lithofacies of the Hibernia Member

The Hibernia member was subdivided into five lithofacies (Table 2) which are distinguishable on the basis of their lithologies and their occurrence in either the Upper or Main Hibernia zone.

The three general lithofacies recognized in the Main Hibernia zone include; a/ the M-sandstone facies, b/ the sandstone - mudstone facies, and c/ the M-mudstone facies (the "M" indicates lithofacies that occur in the Main Hibernia zone).

The M-sandstone facies comprises relatively thick sandstone bodies, generally greater than 2m and ranging up to 18m (eg. Fig 14: well K-14, cores #12 and #13), which occur throughout the M.H.Z..

Between the units defined as the M-sandstone facies in the M.H.Z., mudstone and/or siltstone are interbedded with relatively thin sandstone bodies (ranging in thickness from laminae (<1cm) to 2m, eg. Fig. 14: well K-18, core #5, 3827-3825m) and are assigned to the sandstone - mudstone facies.

The M-mudstone facies of the M.H.Z. is a distinct, relatively thick, succession of mudstone and siltstone. It has been observed in well B-27 core #6 and well K-14, cores #13 and #14, and is inferred to be present in wells O-35, C-96 and P-15, on the basis of gamma-ray log motifs (Fig. 14).

The two lithofacies recognized in the Upper Hibernia zone (Table 2); are the U-sandstone facies, and the U-mudstone facies

(the "U" being used to differentiate these facies from those in the M.H.Z.).

The U-sandstone lithofacies comprises sandstone units 0.2m to 4m thick but commonly between 0.5 and 2m (eg. Fig. 14: well B-08, core #2, 3466-3490m).

The U-mudstone lithofacies are intercalated between the U-sandstone facies, and composed of mudstone and siltstone, with local laminated and thinly bedded (<0.2m) very fine- and fine-grained sandstones (eg. Fig. 14: well K-14, core #7, 3857-3863m).

6.2 Sedimentary Structures and Stratification Sequences of the Main Hibernia Zone

Table 2 summarizes the occurrences of sedimentary structures and stratification sequences in the Hibernia member and their association with different lithofacies.

6.2.1 M-Sandstone Facies

The M.H.Z. is characterized by its relatively thick sandstones which are generally moderately well- to well-sorted, usually containing very little fine matrix (Figs. 16a, 16b, 16c and 16d). Abundant large- and small- scale, high- and low-angle, trough and planar cross-bedding and horizontal bedding are present in these sandstones (Plates 9c and 9d). Rip-up mudclasts, normal graded-bedding, and truncations of the underlying laminae are commonly associated with the cross-bedded sandstones. The horizontal bedding is also closely associated with sets of cross-bedded sandstones and where observed, are well-sorted with little matrix, suggesting upper flow regime deposition (Visher, 1972).

Asymmetric and climbing ripple cross-laminations are especially abundant in the finer grained sandstones occurring in the upper parts of the M-sandstone lithofacies. These ripple cross-laminations also occur locally with cross-bedded sandstones. Thin beds of siltstone and mudstone are rarely incorporated within the sandstones (usually <10cm thick).

Basal scoured contacts and intrastratal scours are common features of the sandstones. Thin beds of intraformational conglomerates, with clasts consisting of siderite, quartzite, chert, and rip-up mudchips, locally occur directly above these scoured contacts (Fig. 14: well K-14, core #6; well B-08, core #6).

Abundant carbonaceous stringers and fragments (carbonized branches, leaves, and comminuted plant detritus) are also associated with these sandstones (Plates 8b and 8c), suggesting proximity to a terrestrial source.

The gamma-ray downhole log motifs of the M-sandstone facies are typically serrated and barrel-shaped (blocky), generally with abrupt basal contacts and abrupt to gradational upper contacts (Figs. 13 and 14).

Fining-upward trends from medium-, coarse-, or very coarse-grained sandstones into finer grained sandstones are common in these sandstones. These fining-upward trends can be gradational (Fig. 14: well K-18, cores #4 and #3; well B-08, core #6), or they can occur rapidly in the upper parts of the sandstone bodies (Fig. 14: well K-14, cores #10, and #14 & #13). The fining-upward trends normally show a gradational transition from the sandstone

facies into the "sandstone - mudstone facies".

The lack of fossilized shell material is characteristic of the M-sandstone facies. This lack of shell material could be attributed to post-depositional leaching. However, molds of shell material resulting from dissolution by diagenetic solvent pore-fluids have been observed in the U-sandstone facies of the U.H.Z. in well K-14 (3863m and 3877m) at approximately equal depths to the M-sandstone facies in well K-18. Since moldic porosity of this type has not been observed in the M-sandstone facies, it is likely that shell material was not deposited in this facies.

6.2.2 Sandstone - Mudstone Lithofacies

Individual sandstone bodies of the sandstone-mudstone lithofacies are thinner (<2m) and finer grained relative to the M-sandstone facies, with grain sizes ranging from medium- to very fine, with fine- and very fine-grained sandstone beds being the most prevalent. The larger sandstone interbeds are usually moderately well- to well-sorted, containing little fine matrix in most cases. Some of the thinner sandstone interbeds are more matrix rich. The sandstone interbeds usually display gradational and rapid transitional basal and upper contacts. Rarely, abrupt upper contacts of sandstone beds are present (Appendix 1: Well B-08, core #6; well K-18, core #5).

Locally, rootlets have been preserved in the very fine-grained sandstones and siltstone beds of this facies (e.g. Fig. 14: well B-08, core #4; well K-14, cores #10, #12 and #14; well

B-27, cores #7 and #10). Coal beds are also rarely associated with this facies. The only significant accumulation of coal observed is in well K-14, core #10, where a 15cm thick black, lignitic coal bed directly overlies a rootlet-rich siltstone unit. Other coal beds and laminae are inferred to be present at depths of 4037m and 3972m in well K-14, and 3958m and at the top of the M.H.Z. in well B-27, based on the Mobil well history logs.

Horizontal bedding is commonly present in the sandstone beds of this facies and trough and planar cross-bedding occur locally. Abundant asymmetric cross-laminations and rare climbing ripples are also present in the sandstone beds.

Abundant comminuted carbonaceous material and common carbonaceous stringers occur within the sandstone, siltstone, and mudstone beds of this facies. Rip-up mudclasts are locally present in the sandstone beds.

Soft-sediment deformation is common in this facies, including load casts, flame structures, disturbed (slumped) bedding, and sedimentary boudinage.

The light- to medium-gray mudstone interbeds rarely reach 5m in thickness. Thinly bedded (<0.2m) and laminated very fine- to fine-grained sandstones commonly occur within the mudstones. The laminated sandstones exhibit delicate parallel, lenticular and wavy bedding. Abundant asymmetric and rare starved ripple cross-laminations occur in lenticular and wavy bedded units.

Slight to moderate degrees of bioturbation (<10% of the sediment is churned), is more prevalent in the mudstone and siltstone beds. Pelecypod shell fragments are rarely preserved in

the mudstone beds (Fig. 14: well B-08, core #4).

Thin (<10cm), para-conglomerate beds are rarely present in the mudstone and siltstone interbeds (Plate 9b: Fig 14; well B-27, core #7; well K-18, core #3). The conglomerate clasts observed in these beds consist of equant quartzite and prolate siderite clasts.

Common siderite concretions and local sphaerosiderite microconcretions are also present, being more abundant in the interbedded mudstone.

Near the base of units assigned to this facies, where it grades into the M-sandstone facies, local low dips (approximately 5°), resulting from either post-depositional structuring or possibly depositional slopes, are observed.

The silt and sand content of this facies generally increases towards the M-sandstone facies.

Gamma-ray log motifs of this facies are very serrated, with deflections recording the sandstone beds.

The sandstone - mudstone facies units are commonly abruptly overlain by the M-sandstone facies (Fig. 14: well B-27, cores #9 and #10; well K-18, core #6; well B-08, cores #6, #5 and #4; well K-14, cores #14, #12 and #10).

6.2.3 M-Mudstone Lithofacies

This distinctive, relatively thick sequence of bioturbated, fossiliferous, well indurated, gray mudstone and siltstone, was observed in wells B-27 and K-14 (where core was collected), and is inferred to be present in wells O-35, P-15 and C-96, based on

gamma-ray log motifs (Fig. 14). It is uncertain as to whether this facies is present in well K-18 and B-08 since the characteristic log motif of this interval is not as well developed in the B-08 well and not recognizable in the K-18 well.

This facies exhibits more bioturbation and is more fossiliferous than the mudstone and siltstone beds of the sandstone and mudstone facies. Ichnofossils tentatively identified as Chondrites, Skolithos, Teichichnus, Diplocraterion, Arenicolites, and Asterosoma, are present in this mudstone facies, and do not appear to vary in abundance up section. The burrows in the K-14 well are calcareous, and therefore they are lighter in color compared to the surrounding sediment. Shell fragments, including those of pelecypods, gastropods, and ostracods, are common in the mudstone facies.

Siderite nodules, carbonaceous detritus (including stringers, and comminuted detritus), and disrupted bedding, are commonly associated in this facies.

The M-mudstone facies is abruptly overlain by units of the sandstone beds of variable thicknesses. For instance, in the K-14 well, 12m of homogeneous, medium-grained, quartz arenite directly overlies the M-mudstone facies, whereas in the B-27 well, a relatively thin (approximately 1m), medium-grained sandstone bed occurs in this position.

6.3 Sedimentary Structures and Stratification Sequences of the Upper Hibernia Zone

As stated in section 2, the M.H.Z. grades into the Upper Hibernia Zone.

The gamma-ray log signature of the zone is characteristically serrated, exhibiting "spike-like" deflections, indicating the presence of sandstone beds.

6.3.1 U-Sandstone Lithofacies

The moderately well- to well-sorted sandstones of the U.H.Z. are characteristically thinner and finer grained relative to the M-sandstone facies of the M.H.Z.. A single conglomerate bed is present in well K-14, core #9 (Fig. 14).

Common small-scale (<10cm), low-angle and high-angle planar cross-bedding and rare trough cross-bedding were observed in these sandstones. Asymmetric ripple cross-laminations are also common, usually in close association with cross-bedding. Climbing and starved ripple cross-laminations however, were not observed.

Abundant comminuted carbonaceous detritus and rare carbonaceous stringers are present within the sandstones. Rip-up mudclasts occur locally within the sandstones as well.

Soft sediment deformation is abundant, including disrupted bedding, load casts and flame structures.

Thinly bedded and laminated siltstone and mudstone beds occur locally within the sandstones.

Pelecypod and gastropod shell fragments and molds occur in local accumulations within the U-sandstone facies (Plate 10d). As

previously stated (section 5.3) the moldic porosity is the result of diagenetic leaching.

Bioturbation occurs locally in this facies and is more common in the U.H.Z. relative to the M-sandstone. Ichnofossils tentatively identified as Skolithos and Asterosoma, are present in the sandstones.

Minor amounts of siderite concretions and rare sphaerosiderite microconcretions occur in these sandstones. Trace amounts of glauconite are present in one of the sandstone bodies in the B-08 well, according to the Mobil well history report. The sandstones commonly exhibit scoured basal contacts and abrupt transitional upper contacts. Gradational coarsening-upward basal contacts from mudstones into overlying very fine- to fine-grained sandstones are locally present (Plate 10d; Appendix 1: well K-14, cores #7, #8 and #9).

Locally, fining-upward sequences have been observed, where coarse-, fine- or very fine-grained sandstones grade upwards into the mudstone facies (Appendix 1: well B-08, core #2; well K-14, cores #7 and #9).

6.3.2 U-Mudstone Lithofacies

This facies consists of light to dark gray mudstone and siltstone. Laminated and thinly bedded very fine- to fine-grained sandstone units are locally present within this facies (Appendix 1; well K-14, cores #7 and #8; well B-08, core #2). Asymmetric ripple cross-lamination is common where these units occur.

Soft-sediment deformation, including disturbed bedding, load

casts and flame structures, is abundant in this facies.

Carbonaceous comminuted detritus is common, and stringers are rare. Rootlets have been observed rarely in well K-14, core #12 (Fig. 14).

These mudstones are typically bioturbated to a greater degree than the mudstone interbeds of the sandstone - mudstone facies of the M.H.Z.. Ichnofossils tentatively identified as Rhizocorallium, Skolithos, Asterosoma, and Chondrites, are present in these mudstones. Fossilized shell material is also more abundant in the U.H.Z. mudstone facies than in the mudstone interbeds of the interbedded sandstone and mudstone facies of the M.H.Z. and includes pelecypods, gastropods, ostracods and bioclasts.

Siderite and local accumulations of sphaerosiderite microconcretions are present in this facies. Glauconite is also reported to be present in this facies (AGAT-K-14 consulting report, 1984).

A unique, 3.5 meter-thick sequence of brick-red, oxidized, hematite-rich mudstone, occurs in well K-14, core #9 (Appendix 1), at approximate depths of 3888-3893m. Rootlets are present rarely below this oxidized unit. Sphaerosiderite microconcretions appear to have altered to limonite in this zone.

6.4 Isopach Trends of the Hibernia Member

An isopach map of the complete Hibernia member (Fig. 19), illustrates a general northeastward thinning. Isopachs for the M.H.Z. alone, also show a general thinning towards the northeast

Figure 19: Contour interval is 25m. Position of Murre fault when extrapolated to depths of Hibernia member, (Morrel, pers. comm.).

Figure 20: Contour interval is 25m.

Figure 21: Contour interval is 25m.

Figure 22: Sandstone:shale contour interval is 0.25.

Figure 23: Sandstone:shale contour interval is 0.5.

Figure 24: Sandstone:shale contour interval is 0.1.

(Fig. 20). Isopachs of the U.H.Z. (Fig. 21) however, illustrate a more easterly thinning trend. It should be noted that the 0-35 well is adjacent to the Murre fault. The anomalous thickness of the member in the 0-35 well is possibly attributable to growth-faulting during deposition of the Hibernia sediments.

In essence, the Hibernia member is wedge-like in its mapped extent, with the wedge thickening southwestward.

6.5 Sandstone : Shale Ratios of the Hibernia Member

Sandstone : shale ratios were derived using a shale scale based on methods described by Dresser Atlas (1975). A calculated 50% sand content was used as the lower limit for sandstone. Mudstone, siltstone and some laminated sandstones are included in the shale sections (<50% sand).

The sandstone : shale ratio contour map of the Hibernia member (Fig. 22) illustrates a decrease in sandstone towards the northwest. Well B-27 has the lowest ratio (0.3 : 1), and K-14 on the other hand, is characterized by the highest ratio (1.9 : 1).

Sandstone : shale ratios of the M.H.Z. (Fig. 23), also show an increase in sand content towards the south; however, an anomalous high ratio is present in the K-18 well. The B-27 well is marked by the lowest ratio (0.4 : 1) and the K-14 well by the highest (2.3 : 1).

Sandstone : shale ratios of the U.H.Z. (Fig. 24), also show a general increase in sandstone towards the south. The ratio is greatest in the C-96 well (0.7 : 1), and lowest in the B-27 and K-18 wells (0.2 : 1).

6.6 Depositional Environments of the Hibernia Member

Despite the rich and varied suite of sedimentary structures in the Hibernia sandstones, most of the observed structures are not diagnostic of one environment (refer to Table 2). Hence, paleoenvironmental recognition must be based on associations of sedimentary features and on vertical and lateral facies relationships. It is probable that a variety of subenvironments related to one depositional model is represented in the Hibernia member.

As previously stated in section 1.2.3, the Hibernia member overlies marine Verrill Canyon shale and underlies marine mudstones and thinly bedded limestones of the Missisauga Formation. Therefore, the Hibernia member was most likely deposited in either a paralic or transitional environment. Paralic and transitional environments containing significant sand accumulations include; a/ regressive shorelines, b/ barrier islands and strandplains, c/ estuaries, d/ tidal flats and e/ deltas.

The siltstone and sandstone content of the underlying Verrill Canyon shale increases upwards towards the base of the Hibernia member. This general upward-coarsening is expressed by the gamma-ray downhole logs in Figure 12 and Appendix 2, especially in the C-96 and P-15 wells, where coarsening-upward sandstone bodies are also locally present. Coarsening-upward sequences are characteristic of prograding pro-delta and delta-front sequences, prograding barrier bar sequences (McCubbin, 1982), and regressive shoreline sand deposits (Spearing, 1971).

The environmental setting envisaged for the Hibernia member is that of a marine delta, whose northward progradation was followed by a marine transgression.

6.6.1 Depositional Environments of the Main Hibernia Zone

The coarsening-upward Verrill Canyon shales are overlain by the sandstone-rich, M.H.Z.. What is immediately striking about the internal stratigraphy of the M.H.Z. is the lack of laterally continuous facies. Adjacent wells typically contain no beds or markers that can confidently be correlated (Fig 14). The occurrence of rootlets and rare coal beds indicates that the conditions were favourable for terrestrial vegetation. The environmental setting envisaged for the M.H.Z. is that of a deltaic plain (Fig. 25). From sedimentary structures and stratification sequences, summarized in section 6.2, most of the M-sandstone facies are interpreted to represent distributary channels. However, the basal sandstone units in well B-08 (3634 - 3648m) exhibit a few coarsening-upward sequences and may reflect distributary mouth bars or barrier bar deposits, but a lack of sedimentological information from cores in this area prevents a conclusive interpretation. The sandstone - mudstone facies is interpreted as representing floodplain with associated overbank flood deposits. The mudstone facies probably represents either interdistributary bay or lake deposits. Micropaleontological studies by Williamson (pers. comm.) are consistent with this interpretation (refer to section 5.1).

Supporting criteria suggesting that the M-sandstone facies

are representative of distributary channel deposits are summarized below:

- a/- scoured basal contacts of the sandstone facies (Visser, 1972);
- b/- fining-upward sequences of the sandstone facies resulting from channel migration and the development of point bars (Cant, 1982);
- c/- range in grain sizes from very coarse- to fine-grained sand and local accumulations of conglomerates;
- d/- association of low- and high-angle, trough and planar cross-bedding, horizontal bedding, and current ripple cross-laminations;
- e/- well sorted sandstones, with cumulative size frequency curves similar to those of the point bars in Harms et al., (1963);
- f/- abundant carbonaceous stringers and detritus; locally the sandstones can be classified as coaly gravels;
- g/- abundant rip-up mudclasts, most probably derived from an adjacent floodplain;
- h/- lack of matrix in most sandstone facies (Cant, 1982);
- i/- lack of shell material and burrowing occurring only rarely in the sandstone facies;
- j/- gamma-ray log motifs similar to those of channel sandstones illustrated in Flach and Mossop (1985).

Evidence supporting a floodplain depositional environment for the sandstone - mudstone facies includes the following

Figure 25: Channel sandstones (M-sandstone lithofacies) and associated overbank deposits of postulated delta plain environment.

Depositional Model: Main Hibernia Zone

criteria:

- a/- occurrence of rootlets and rare coal beds;
- b/- in situ concretions of siderite, suggesting formation in a reducing environment of organic rich muds, particularly common in fluvial or coastal swamp environments (Miall, 1984, p.159);
- c/- only rare occurrences of shell material;
- d/- micropaleontological studies of Williamson (pers. comm.) suggesting a brackish water environment;
- e/- lack of glauconite, also consistent with a non-marine depositional environment.

Most of the sandstone interbeds of the sandstone - mudstone facies are interpreted as overbank flood deposits, such as crevasse splays, crevasse channel fills, and natural levees, which developed as flood waters flowed into the interdistributary floodplain area (Elliot, 1978). Supporting evidence substantiating overbank deposition for these sandstone interbeds includes the following criteria:

- a/- local occurrence of rootlets;
- b/- laminated very fine-grained sandstones and siltstones exhibiting wavy and lenticular bedding, similar to crevasse splay features illustrated in Ethridge et al., (1981, p.200);
- c/- coarsening-upward sequences from siltstones into very fine- and fine-grained sandstones are common;
- d/- sedimentary structures including small-scale sets of

cross-bedding, and abundant asymmetric and rare climbing-ripple cross-laminations, which are consistent with overbank deposits observed in present day environments (Cant, 1982; Coleman, 1976).

The M-mudstone facies is interpreted as representing either an interdistributary bay or a lacustrine environment because of its mud-rich composition, severe bioturbation in most parts (15-20% of sediment is churned), and the local accumulation of shell material. This distinctive mudstone facies may extend throughout most of the field as one laterally continuous unit. It is also possible to interpret from the available data, several discontinuous mudstone units.

6.6.2 Depositional Environments of the Upper Hibernia Zone

The U.H.Z. was most probably deposited during a time of increased marine influence relative to the M.H.Z.. As summarized in section 6.3, it is characterized by smaller scale and finer-grained sandstones than in the M.H.Z.. Most of the U.H.Z. is interpreted as representing deposits of a shallow, upper delta-front environment, on the seaward sloping margin, adjacent to a lower deltaic plain (Coleman, 1976; Coleman and Prior, 1982).

Evidence supporting this interpretation includes the following criteria:

- a/- a greater amount of bioturbation in the U.H.Z. than in the M.H.Z.;
- b/- scattered shell fragment accumulations (gastropods and pelecypods) in both the sandstone and mudstone facies;

c/- a wide variety of sedimentary structures associated with current and wave processes which have been documented by Coleman (1976), Elliot (1978), and Coleman and Prior (1982), including small scale cross-bedding, asymmetric ripple cross-laminations, and erosional truncations;

d/- sandstones commonly with abrupt basal contacts and sharply defined upper contacts, as documented by Elliot (1978);

e/- sandstones locally displaying gradational basal contacts with a coarsening-upward sequence, probably representing distributary mouth bars;

f/- occurrence of trace amounts of glauconite, consistent with a shallow marine depositional environment.

The 3.5m oxidized mudstone sequence, at the base of the U.H.Z. in the most southerly well (K-14, core #9) probably represents a subaerially exposed interdistributary floodplain, which preceded the inferred marine transgression over this area.

6.7 Discussion of Depositional Environments

The sedimentary structures and stratification sequences observed in the M-sandstone facies are not representative of regressive shoreline and barrier island deposits because they:

- are characterized by abrupt basal contacts and fining-upward sequences, which would not be expected in either a regressive shoreline or prograding barrier island deposit.

- generally lack shell material and bioturbation, which are usually associated with regressive shorelines and barrier islands;

- are coarser grained than present-day barrier islands [e.g. Galveston Island, Texas, where the modal grain size is fine sand (McCubbin, 1982)].

It is possible that the Hibernia member represents tidal flat and/or estuarine environments, where tidal effects tend to dominate the pattern of sedimentation (Clifton, 1982). These environments are characterized by channel-fill sandstones, intertidal mixed sandstone and mudstone flats, and marsh deposits (Weimer et al, 1982), displaying sedimentary structures and stratification sequences similar to those observed in the Hibernia member. However, these environments are usually characterized by abundant bioturbation and frequent accumulations of shell material, as well as the presence of local herringbone cross-bedding. As summarized in section 6.2, the M.H.Z. is not heavily bioturbated, shell material is essentially lacking, and herringbone cross-bedding has not been observed, thus limiting, but not completely precluding, the likelihood of a tidal-flat or estuarine environment for the M.H.Z.. Further paleontological studies are necessary for more critical analysis of the possible depositional environments.

The high degree of compositional and textural maturity of the M.H.Z. sandstone facies is probably partly attributable to the recycling of sedimentary rocks. Evidence for recycling is

documented in section 3.1.1 and illustrated in Plates 4a and 4b. This factor, together with marine sorting processes are responsible for the maturity of the sandstones in the U.H.Z. (Elliot, 1978).

Evidence of well-developed beach and barrier island deposits (common expressions of transitional environments during a marine transgression), have not been observed in the U.H.Z.. A possible reason for their apparent absence could be the influence of moderate or severe tidal activity which can not be precluded (e.g. Ord River and Klang River deltas, Coleman 1970).

The isopach trends discussed in section 6.4 (Figs. 19, 20 and 21), indicate that the Hibernia member thickens in a southwesterly direction, consistent with the interpretation of a northerly prograding delta, with probable concomitant growth faulting along the Murre fault, especially in the O-35 area. The most southerly well, K-14, contains the thickest M.H.Z. section (besides the O-35 well) (Fig. 20), indicating that the inferred marine transgression (during the deposition of the U.H.Z. sediments) was probably initiated in the northern portions of the Jeanne d'Arc Basin and advanced southwards through time, as would be expected in a deltaic complex whose source is toward the south. The thickest coal observed in core, and the oxidized mudstone sequence, are also located in the K-14 well, suggesting that this area was subjected to the greatest amount of terrestrial influences within the field area. This is in accordance with the proposed depositional environments.

Isopachs show a thickening of the U.H.Z. towards the Murre

fault. This can be interpreted as representing increased growth fault activity along the Murre fault zone during the deposition of the U.H.Z..

Sandstone:shale trends discussed in section 6.5 (figs. 22, 23, 24), show a general increase in sandstone content towards the south, which is consistent with an envisaged northerly prograding delta. The anomalously high sandstone content of the M.H.Z. in the K-14 and B-08 wells is possibly due to their proximity to main discharge channels, where active channelling persisted throughout the deposition of the M.H.Z.. Highly variable sandstone : shale trends are commonly associated with deltaic plain environments as illustrated in Coleman and Prior (1982, figs. 3 and 4). The B-27 well, on the other hand, is characterized by the lowest sandstone:shale ratio in the M.H.Z. and probably was located in an area where vertical accretion was prevalent, with periodic deposition of crevasse splay sandstones and relatively thin channel-fill sandstones.

If one assumes that the palynological zone boundaries of Davies (pers.comm.) are reliable time-horizons (Fig 12), the data can be interpreted as suggesting that deposition of the Hibernia sandstones continued for a longer period in the southwestern parts of the field (wells O-35 and P-15) than in the northern parts. For example, the 5B boundary in Figure 12, occurs within the sandstones in well O-35, but occurs above the Hibernia member in the K-18 and B-08 wells. This is consistent with the envisaged depositional settings.

The stratigraphic behaviour of the 5A horizon presents some

difficulties in relation to the writer's proposed northerly prograding delta system. This horizon occurs at the top of the U.H.Z. in the B-08 well, whereas in the O-35 well it is located near the basal contact of the M.H.Z., indicating an earlier initiation of sand deposition in the northern well. This could be the result of several processes. It is possible to interpret more than one source area for the Hibernia sediments from these data: a northerly or northeasterly source which was active during the 4-5A interval; and a southerly or southeasterly source, which was less active during the 4-5A interval but continued longer (into the 5B-5C interval). However, the sandstone:shale and isopach contour maps do not clearly indicate a northerly source area within the area of well control.

It is also possible to interpret the lesser amount of sand deposition in the O-35 well area during the 4-5A interval, as the result of an inactive delta lobe during this interval.

It should also be noted that the 5A horizon in the B-08 well is in a cored-interval, whereas the other 5A horizon picks are based on chip samples.

In summary, characteristic features of the Hibernia member are similar to those of delta plain (M.H.Z.) and delta front (U.H.Z.) environments. The M.H.Z. represents an interval of northward deltaic progradation, followed by the deposition of the U.H.Z., representing a period of southward marine transgression. Growth faulting along the Murre fault was probably concomitant with the deposition of the Hibernia sediments.

7. DEPOSITIONAL MODEL FOR THE HIBERNIA MEMBER
IN THE JEANNE D'ARC BASIN

7.1 Dispersal Patterns of the Hibernia Sediments

The dominant transport direction of the Hibernia sediments is interpreted to have been north-northeasterly, along the structural strike of the Jeanne d'Arc Basin (Fig. 26), (Grant et al., in press). Evidence on which this is based comes partly from wells to the north and south of the Hibernia oil field (Fig. 4). The Egret N-46 and K-36 wells intersect a thicker, sandier and coarser grained Hibernia member than is found within the Hibernia oil field. The Nautilus C-92 well, north of Hibernia, has a thinner Hibernia section.

The Egret N-46 well is situated on the edge of a major salt structure (Fig. 4), and K-36 is located slightly east of the salt structure (Grant et al., in press). Seismic sections through this part of the basin do not show any significant thickness changes affecting the Hibernia member. Hence, it appears that major structural readjustments in the Egret area occurred after the deposition of the Hibernia sediments (McAlpine, pers. comm.; Morrell, pers. comm.).

The Hibernia member is not present in the Rankin well (Fig. 4; McAlpine, pers. comm.; Morrell, pers. comm.). Its absence is the result of either erosion during an episode of post-depositional step faulting, or non-deposition. If the latter case were correct, it would follow that Hibernia member sediments may have been deposited as separate deltaic complexes along the western edge of the basin and the apparent textural and facies

Figure 26: Postulated paleogeography of the Jeanne d'Arc Basin during deposition of the Hibernia member. The encircled area represents a depositional setting similar to that envisaged for the Hibernia field.

2

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

trends along the strike of the basin are spurious.

The isopach contour map of the Hibernia member in the Hibernia field (Fig. 19), does illustrate a general thinning towards the north as previously discussed. This isopach phenomenon is envisaged as part of a northward prograding deltaic complex as discussed in section 6.7. It is also possible that similar isopach patterns could result from a northeasterly lobe of a deltaic complex prograding eastward off the western edge of the basin. However, the sandstone : shale ratios for both the M.H.Z. and U.H.Z. (Figs. 23 and 24), are not consistent with a westward source area, since the sandstone content, increases towards the southeast on the basis of present information.

Dip-meter log data were examined as a possible source of paleocurrent information. Post-depositional structures in the field area, among other possible factors, made reliable azimuth determinations difficult to obtain. Detailed analysis of the dip-meter logs is beyond the scope of this project, and is proposed as a desirable future study.

7.2 Provenance

Arthur et al., (1982), and Grant et al., (in press), have proposed that the Upper Jurassic and Lower Cretaceous sandstones within the Jeanne d'Arc Basin were derived mainly from the Avalon Uplift to the south, but also from the outer ridge to the east and the craton to the west. Petrographic data, documented in section 3.1.1, indicate that the source area contributed igneous, metamorphic, and recycled sedimentary rocks. The Precambrian and

Paleozoic basement of the craton and Avalon Uplift was the probable source for the igneous and metamorphic grains. The recycled sediments were probably derived from both the Paleozoic Appalachians and the early Mesozoic sediments deposited within the Jeanne d'Arc Basin and surrounding Grand Banks area. Based on the compositional and textural maturity of the sandstones, it is probable that most of the sediment is of recycled sedimentary origin..

7.3 Relationships to Regional Tectonics and Stratigraphy

The deposition of the Hibernia member represents a time of significant sandstone deposition within the Jeanne d'Arc Basin resulting from an episode of major tectonic adjustments during the stages of continental break-up between Europe and North America.

The sediments were derived from the Avalon Uplift and other elevated areas surrounding the subsiding Jeanne d'Arc Basin. The coarser-grained sediments prograded basinward (dominantly north) over the marine Upper-Jurassic Verrill Canyon shale. This progradation was terminated by a marine transgression. This rise in sea level could have been either eustatic or the result of basinal subsidence.

8.1 Diagenetic History of the Hibernia Member - Paragenesis of Cements and Authigenic Minerals

The authigenic minerals described earlier form a paragenetic sequence reflecting the diagenetic history of the Hibernia sandstones. The following paragenetic sequence proposed is based upon the textural relationships of the observed diagenetic features and components (Fig. 27).

8.1.1 Pyrite and Siderite

Pyrite and siderite are interpreted as being mainly eogenetic, forming at or near the surface of sedimentation, under reducing and neutral to weakly acidic conditions (Wolf and Chilingarian, 1976; Miall, 1984, p. 159). Mesogenetic (late forming) pyrite is also present (Plates 2c and 2d), usually as framboids.

8.1.2 Quartz

The most pervasive cementation episode was the precipitation, of early syntaxial quartz overgrowths on the surfaces of detrital quartz grains. Plates 5e and 5f show that this cementation occurred before major carbonate cementation.

The precipitation of an authigenic mineral requires: a/- steady circulation of pore fluids through an open pore system, and b/- the pore fluids to be supersaturated with respect to an authigenic mineral (Hutcheon et al., 1983).

Silica-rich pore fluids could have been derived in the

FIGURE 27: Diagenetic Sequence of Hibernia Sandstones

FIG. 28 - Diagenesis cycle of sandstones.

(after Schmidt and McDonald, 1979a)

following ways, with the first two probably contributing the bulk of silica:

- from meteoric ground waters;
- from muds, dewatering at the time of initial burial;
- from shales, at greater depths when Si^{4+} bearing waters are released during smectite - illite transition which occurs in shales over a wide range of depths (usually 3-4 km) and temperatures (60-120°C) (Blatt, 1979; Boles and Franks, 1979; Hayes, 1979; Hutcheon et al., 1983; Franks and Forester, 1984). During this clay transition, Si^{4+} in tetrahedral layers is replaced by Al^{3+} and the missing positive charge is balanced by absorbed K^+ (Veizer, pers. comm.).
- dissolution of siliceous microflora and microfauna: diatoms, radiolaria, and sponge spicules (Hutcheon et al., 1983).
- from pressure solution.

Quartz is stable at low temperatures and under acidic (low pH) conditions, but becomes susceptible to solution with pH values of 9 and greater (Dapples, 1967; Hutcheon et al., 1983).

In some of the very fine-grained sandstones, early cementation combined with compaction greatly reduced primary porosities (Plate 6a), thus inhibiting future migration of pore fluids through these sandstones, and therefore limiting future diagenetic processes.

8.1.3 Carbonate

Cementation and replacement of framework grains by carbonate minerals ("carbonatization" of Schmidt and McDonald, 1979a) occurred after early quartz cementation (Plates 5e, 5f and 6b). As discussed earlier, E.D.X. analysis revealed that this carbonate is calcite containing trace amounts of iron.

This carbonatization event records a probable change to CaCO_3 -saturated pore fluids with higher pH and temperature. According to Franks and Forester (1984), there are two end member sources for carbonate ions: a/- early (shallow) marine calcite, including recycled shell material, and b/- later (deep) carbonate from organic reactions in the shales. Underlying limestone formations that are subjected to pressure solution may also supply carbonate-rich fluids for precipitation (Dunnington, 1967; Mimran, 1977; Blatt, 1979). Stable isotope data (Franks and Forester, 1984) suggest a recycling of carbonate through dissolution / reprecipitation reactions, somewhat similar to the processes of decarbonatization (dissolution of carbonate) at depth, followed by reprecipitation of carbonate up section, forming a "carbonate curtain" where conditions are favourable for carbonate precipitation (Schmidt and McDonald, 1979a).

Corrosion and replacement of silicates is commonly associated with carbonatization (Dapples, 1967; Schmidt and McDonald, 1979b; Hutcheon et al., 1983). In addition to quartz, carbonates also replace feldspars. Characteristic replacement textures (Hutcheon et al. 1983), observed in the Hibernia sandstones include: a/- irregular embayed ("corroded") contacts

between cement and detrital grains (Plates 3b, 5e and 5f), b/- "islets" (inclusions) of detrital quartz grains within carbonate cement (Plates 5f, 7c and 7d), and c/- ghosts of original detrital grains which are outlined by impurities (Plate 5e and 6b).

The carbonatization episode is interpreted to have been early mesogenetic (Fig. 28), because the observed carbonate-cemented sandstones exhibit intact to slightly disrupted packing (Plates 5e, 5f and 6b). Although the original (pre-carbonatization) packing of the grains may have been slightly disrupted by the forces associated with carbonate crystallization (Hutcheon et al., 1983), the lack of strong evidence for pressure solution and grain fracturing supports the interpretation of relatively early cementation.

Carbonatization was not ubiquitous in the Hibernia sandstones. In the tightly quartz-cemented sandstones, occlusion of primary porosities and reduction of permeabilities inhibited the migration of carbonate-rich pore fluids.

8.1.4 Decarbonatization

Decarbonatization is a general term for the dissolution of any textural and mineralogical type of carbonate from sandstones or other rocks (Schmidt and McDonald, 1979a).

Most Hibernia sandstones show effects of decarbonatization, which followed the carbonate cementation event. Textural criteria used to recognize porosity enhancement resulting from decarbonatization (Fig. 29; Schmidt and McDonald 1979b; and

FIG. 29 - Petrographic criteria for the recognition of secondary porosity

"Patches" of remnant cement

Elongate Pores

Moldic Porosity

Corroded grains and embayments

Inhomogeneity of packing

Honeycombed grain

Oversized pores

Dissolution front

Carbonate

Feldspar grain

Quartz grain

Porosity

-modified after Schmidt and McDonald, 1979a.

FIGURE 30-

(a)- shale transit times, and (b)- measured pressures in porous rocks, for Hibernia B-08, K-18, O-35, and P-15 wells.
(after Grant *et al.*, in press)

Figure 30: The above two figures illustrate the occurrence of an overpressured zone directly, below the Hibernia member, within the Verrill Canyon shales.

Hutcheon et al., 1983) and observed in the Hibernia sandstones include:

- corroded grain boundaries (Plates 3c, 5c, 6c, 7d and 7e);
- embayments (Plate 7e);
- elongated pores (Plate 7a);
- oversized pores (Plates 4e, 7a, 7b and 7d);
- moldic porosity resulting from the dissolution of calcareous shell material (Plate 10d);
- honeycombed grains (Plates 1b and 4f);
- inhomogeneity of packing (Plate 5d);
- “patches” of remnant carbonate cement, similar to the partly dissolved calcite illustrated in Walton (1984, p. 156) and Plate 3c, in this report, (Plates 3e, 3f, 5c, 7a, 7b, 7c and 7d);
- dissolution fronts, which are diagenetic contacts between extensive carbonate-cemented and carbonate depleted zones (Plates 6c, 8d and 10d).

Mesogenetic decarbonatization could have developed in the Hibernia sandstones as a result of one or more processes. Burial and thermal maturation can cause decarboxylation of organic material, generating carbon dioxide (CO_2), which may combine with subsurface water to form carbonic acid (H_2CO_3), hence lowering the pH of the pore fluids and increasing the potential for carbonate dissolution (Schmidt and McDonald, 1979a, 1979c; Blatt, 1979; Franks and Forester, 1984; Galloway, 1984; Siebert et al., 1984). Type III kerogen (terrigenous vitrinite kerogen) is

capable of producing high amounts of CO_2 because of its high oxygen content (Hunt, 1979; Franks and Forester, 1984). Type III kerogen is abundant throughout the Jurassic and Lower Cretaceous sections of the Jeanne d'Arc and Avalon Basins (Grant *et al.*, in press).

Interlayer waters released from clays during shale compaction will yield large volumes of water usually having low pH values (approximately 5-6, Franks and Forester, 1984). The composition of these waters is controlled by chemical reactions occurring within the shales. Thermal maturation of organic matter and clay mineral reactions (smectite - illite conversion) are the major influences on the geochemical evolution of these pore waters. These waters, combined with the products of decarboxylation, may contribute to undersaturation with respect to carbonate mineral phases, and the consequent dissolution of the latter (Schmidt and McDonald, 1979a; Franks and Forester, 1984).

Geopressured zones may be undersaturated with respect to carbonates since the pore fluids can be acidic and highly gas-charged (high CO_2 content), (Schmidt and McDonald, 1979a, 1979c; Galloway, 1984). Grant *et al.* (in press) document the presence of an overpressured zone below the Hibernia member (Fig. 30). Periodic breaks in the upper seal of this overpressured zone could have resulted in the upward migration of CaCO_3 -undersaturated, low pH-flux from the geopressured zone into the Hibernia sandstones, causing dissolution of carbonate minerals. Galloway (1984), noted that the mixing and interaction of pore

fluids at geopressured boundaries resulted in porosity enhancement of the Frio sandstone and other Tertiary formations of southern Texas.

Because leaching requires an initial permeability in sandstones for a solvent flux to remove solutes (Bjorlykke, 1984), those sandstones with the higher preserved primary porosities and permeabilities will be subjected to solvent pore fluids for longer durations.

Local thin (<1m thick) carbonate-cemented sandstones occur within the sandstones and laminated sandstones of the M.H.Z. and U.H.Z. (Appendix 1: well K-14, core #7 - 3863m, core #8 - 3873m, 3874m, core #12 - 3933m; well B-27, core #7 - 3894.5m, core #9 - 3899m, 3899.5m, 3900.0m, core #10 - 3910m; well B-08, core #4 - 3562.5m). These carbonate-cemented sandstones are adjacent to porous sandstones with only sporadic "patches" of carbonate cement, interpreted as decemented zones (from evidence in section 8.2). The diagenetic contacts between the carbonate-cemented and decemented zones in the sandstones are dissolution fronts (Schmidt and McDonald, 1979c), and vary from being sharp or abrupt (Plates 6c, 8d and 10d) to gradational or "patchy". Four possible reasons may explain why carbonate-cemented quartz arenites and portions of carbonate-cemented quartz arenites may escape decarbonatization:

a/- the subsurface environment did not generate chemical conditions for leaching;

b/- the leaching capacity of migratory waters was exhausted;

c/- the leaching formation waters did not have access to the the cemented arenites (Schmidt and McDonald, 1979c).

d/- dissolution was incomplete, leaving remnant zones of carbonate-cemented zones.

Only the last seems applicable in the Hibernia sandstones. Where complete cementation by carbonate occurred, the only place extensive leaching could occur was at the boundaries of these now relatively thin cemented zones (Fig. 31), where porosities and permeabilities permitted interstitial solvents to come in contact with the carbonate cemented zone.

8.1.5 Clays

Kaolinite, the dominant pore filling clay, is neither widespread nor pervasive enough to significantly hinder fluid migration. Illite occurs only sporadically in the sandstones. Most kaolinite and illite precipitated as intergranular cements after decarbonatization (Plates 2a, 2b, 3a and 6d), with minor amounts as replacements of altering feldspars (Plates 1a, 1c and 1d). Loucks et al. (1984), and Franks and Forester (1984), also noted that kaolinite precipitation was intimately related with decarbonatization in the Eocene Wilcox Group and other Lower Tertiary sandstones along the Gulf Coast.

Some of the excess Si^{4+} released by the smectite - illite transformation, and the dissolution of potassium feldspars (supplying aluminum and silica), are possible ion sources for the authigenic kaolinite (Boles and Franks, 1979). This clay transformation usually occurs between depths of 2.5 and 4 kms,

FIGURE 31 - Postulated Time Sequence, Illustrating the effects of Decarbonatization on Carbonate-Cemented Zones

• IN INTERCALATED SHALES

FIG. 32 Burial diagenesis of quartz arenites. (after Schmidt And McDonald, 1979a)

FIGURE 33 - Generalized Depth vs. Porosity Relationships of Medium-Grained Quartz Arenites with a 2.7°C per 100m Geothermal Gradient

Figure 33: Note that depths for the Hibernia member fall in the limits for secondary porosity.

within the depth interval characterized by decarboxylation and liquid hydrocarbon generation (Curtis, 1978).

8.1.6 Possible second generation of quartz cement

Based on the occurrence of uncorroded quartz overgrowths in sandstones exhibiting significant porosities, remnant "patches" of carbonate cement and inhomogeneity of packing, at relatively great depths, (e.g. Plate 6e, from sample B-27-5-691, with a porosity of 16.0%, and Plate 6f, from sample K-14-14-778, with a porosity of 7.0%), it is suggested that a second episode of quartz cementation may have occurred after decarbonatization. Schmidt and McDonald (1979a, 1979c), reported this as a common diagenetic process (Fig. 32). However, sufficient evidence to prove its occurrence in the Hibernia sandstones is presently lacking.

8.2 Porosity Development and Relationship to Hydrocarbon Generation

Observed porosities (determined by the writer) in the Hibernia sandstones range from <1% up to 23%. Most of the porosity, especially in the coarser grained sandstones, is interpreted as secondary. It would be very unlikely for primary porosities above approximately 3% (irreducible porosity), to exist at the 3.5 - 4 km depths of the Hibernia member, based on normal depth - porosity relationships (Fig. 33) of Schmidt and McDonald (1979a, 1979c) and many others.

8.2.1 Decarbonatization

Savkevich (1969) was the first to illustrate that porosity

could actually increase with depth due to the dissolution of early-formed cements (Shanmugam, 1985). Since leaching often enlarges primary pore space, it is difficult to estimate the exact percentage of pore space that is secondary (Bjorlykke, 1984). Through detailed petrographic examination of these sandstones, criteria have been documented to demonstrate a secondary origin for the excellent porosities observed within the Hibernia sandstones. Section 8.1.4 documents criteria that substantiate a decarbonatization event as having been partly responsible for the secondary (dissolution-enhanced) porosity in the Hibernia sandstones.

Most of the more porous sandstones examined exhibit at least a few of these criteria, and many show most or all of the criteria (e.g. sample K-14-13-1).

Schmidt and McDonald (1979a) and Galloway (1984), have documented that major hydrocarbon generation developed after decarboxylation and the creation of secondary porosity through decarbonatization (Fig. 32). Major hydrocarbon migration and accumulation in the Hibernia sandstones is interpreted to have occurred after decarbonatization because bitumen remnants have been observed in pore spaces enhanced by decarbonatization. The occurrence of high porosity and productivity of hydrocarbon reservoirs at such depths (drill stem test results of 2000 to 3631 barrels per day, Arthur et al., 1982), is also consistent with the above statement.

8.2.2 Framework Grain Dissolution

Framework grain dissolution (F.G.D.) is ubiquitous in sandstones occurring above the "hydrocarbon generation window" or in those having received fluids from such rocks, because the CO_2 released during kerogen maturation is believed to be the active agent of feldspar dissolution (Siebert et al., 1984; Shanmugam, 1985).

As previously stated, F.G.D. contributed to the enhancement of porosity within the Hibernia sandstones. It is difficult to document the proportion of secondary porosity attributable to F.G.D. because the best petrographic signature (i.e. insoluble rims, e.g. chlorite) is not present. However, observed oversized pores and honeycombed grains do suggest that the Hibernia sandstones were subjected to F.G.D..

Plates 1a, 1b, 1c, 4d, 4e and 6b, show varying degrees of feldspar and chert dissolution within the Hibernia sandstones. Plate 1b, illustrates an almost completely dissolved feldspar grain, resulting in moldic porosity.

Complete dissolution of selected framework grains alters the original composition, such that sandstones may owe their present enrichment in quartz to dissolution of unstable framework grains such as chert and feldspars (Shanmugam, 1985).

CONCLUSIONS

The Upper Jurassic - Lower Cretaceous, Hibernia member of the Missisauga Formation consists of quartz-rich arenites with interbedded mudstones and siltstones. It has been divided into two petrographically and stratigraphically distinct zones: the Main Hibernia zone and the Upper Hibernia zone. Most of the sandstones in the M.H.Z. represent distributary channels of a northward-prograding deltaic plain environment. The finer grained and thinner sandstones of the U.H.Z. are interpreted as deposits of a shallow offshore deltaic foreslope environment, during a marine transgression.

The M.H.Z. thickens towards the south and west. The westward thickening is probably the result of growth faulting along the Murre fault during Hibernia time. The southward thickening probably reflects increased proximity to a southern source.

Clastic components have compositions reflecting metamorphic, igneous and sedimentary Paleozoic and Precambrian source rocks, as well as recycled nearby Mesozoic sediments.

Porosity in the sandstones varies from 3% to 23%, and most is interpreted as secondary, resulting from the dissolution of carbonate cements and framework grains.

10.

RECOMMENDATIONS FOR FURTHER STUDY

The following research should greatly improve the geological understanding of the Hibernia oil field and the Jeanne d'Arc

Basin:

a/ A detailed macro-paleontological study of the Hibernia member to augment the physical evidence for depositional environments.

b/ A sedimentological study of the Hibernia member in other parts of the Jeanne d'Arc Basin, to develop a depositional model of the basin.

c/ A detailed investigation into the diagenetic history of the Hibernia oil field and other wells within the basin.

d/ A geochemical (stable isotopic) study of the carbonate cements within the Hibernia member to gain an insight into the diagenetic conditions.

e/ A detailed dip-meter log study of the Hibernia member to determine paleocurrent directions and help improve the general depositional model.

f/ Normal and abnormal pressure regimes in the Jeanne d'Arc Basin also warrant further investigation.

PLATES

PLATE 1a -Plagioclase feldspar (F) partly altered to kaolinite.
length of field=430 microns.

1b -Honeycombed plagioclase grain (F), with moldic
porosity in quartz-rich arenite. length of field=700
microns.

1c -Plagioclase grain (F), partly replaced by kaolinite
and sericite. length of field=360 microns.

1d -Close-up of 1c showing kaolinite (k) and sericite (s)
clays replacing plagioclase grain. length of field=90
microns.

1e -Authigenic kaolinite booklets (k) adjacent to quartz
grain (Q). length of field=70 microns.

1f -Authigenic kaolinite (k) precipitated after quartz
overgrowth (o). length of field=85 microns.

PLATE 2a -Intergranular pore-filling kaolinite (k) precipitated after formation of quartz overgrowths. length of field=700 microns.

2b -Illite (i) on euhedral quartz overgrowth. length of field=90 microns.

2c -Pyrite framboid (in center) formed after euhedral quartz overgrowths. length of field=70 microns.

2d -Pyrite framboid (in center) adjacent to euhedral quartz overgrowths. length of field=430 microns.

2e -Kaolinite booklets, precipitated on euhedral quartz overgrowth. length of field=90 microns.

2f -Euhedral quartz overgrowths. length of field=200 microns.

PLATE 3a -Corroded boundaries of quartz grains. Notice kaolinite booklets and remnant euhedral quartz overgrowth. length of field=390 microns.

3b -Severely corroded quartz grain boundaries within a carbonate-cemented sandstone. (Q)- quartz grain. (C)- intergranular carbonate cement. length of field=140 microns.

3c -Severely corroded quartz grain in porous sandstone. length of field=350 microns.

3d -Fractured chert grain (ch). Drilling muds are present within the fracture, and therefore it is probable that the fracture did not result from sample preparation. Notice the corroded quartz grain (Q). length of field=930 microns.

3e -Severely corroded quartz grains (Q) with intergranular carbonate cement (c) in state of dissolution. length of field=160 microns.

3f -Intergranular carbonate cement (c) in state of dissolution, located between two quartz grains (Q). length of field=150 microns.

PLATE 3:**a****b****c****d****e****f**

PLATE 4a -Inherited, rounded, quartz overgrowth (arrow points to inherited quartz overgrowth), (p)= porosity. K-14-12-769; 3927.0m; width of field=0.6mm; xpl.

4b -Inherited quartz overgrowth (arrow points to inherited overgrowth). B-08-6-7; 3628.5m; width of field=0.6mm; xpl.

4c -A quartz-cemented, very fine-grained sandstone clast. K-14-14-782; 3969.0m; width of field=0.6mm; ppl.

4d -Intragranular porosity (ip) within chert grain (ch). (Q)=quartz grain, (p)=porosity. K-14-12-773; 3934.5m; width of field=0.6mm; ppl

4e -Intragranular porosity within chert grain (ch). (p)=porosity. K-14-14-785; 3971.5m; width of field=1.7mm; ppl

4f -Honeycombed grain (H), result of partial feldspar dissolution. B-27-9-703; 3901.7m; width of field=0.6mm; ppl.

PLATE 4

A

B

C

D

E

F

- Plate 5a -Sphaerosiderite micro-concretion in siltstone. B-27-10-710; 3907.4m; width of field=1.7mm; xpl.
- 5b -Sphaerosiderite micro-concretion "engulfing" quartz grains. K-14-10-749; 3861.77m; width of field=0.6mm; xpl.
- 5c -Partially altered feldspar grain (F) in porous sandstone. Also notice patches of carbonate cement (c). B-27-9-703; 3901.7m; width of field=1.7mm; ppl.
- 5d -Inhomogeneity of packing exhibited in porous sandstone. Notice large siltstone clast (s). The opagues within the siltstone clast are pyrite. B-27-7-698; 3887.0m; width of field=1.7mm; ppl.
- 5e -Authigenic quartz overgrowth around detrital quartz grain (Q) within a carbonate cemented sandstone, (C)-carbonate cement. Note ghost rims (G), where carbonate cement is replacing quartz. K-14-12-7; 3933.5m; width of field=0.6mm; xpl.
- 5f -Intergranular carbonate cement (C) within a carbonate-cemented sandstone. Note the corroding quartz grains (q) and overgrowths (o). Note plagioclase grain (F), being replaced by clays and carbonate. K-14-12-7; 3933.5m; width of field=0.6mm; ppl.

Plate 6a -"Tight", very fine-grained sandstone. Compaction and quartz cementation occluded most of the original porosity. B-27-7-700; 3889.0m; width of field=0.6mm; xpl.

6b -Authigenic carbonate cement occurring as intergranular cement (c) and as an alteration product of plagioclase feldspar (F). (G)=ghost rim of detrital quartz grain. K-14-12-7; 3933.5m; width of field=0.6mm; xpl.

6a

6b

Plate 6c -Dissolution front between a carbonate-cemented zone (C) and a decemented zone, exhibiting good porosity (P). B-27-9-1; 3899m; width of field=0.6mm; ppl.

6d -Kaolinite (k) in intergranular pore space, probably formed after decarbonatization. Note corroded grain boundaries and irregular shape of quartz grain (Q). K-14-12-766; 3924.6m; width of field=0.25mm; xpl.

6c

6d

Plate 6e -Rounded grain boundaries of detrital quartz clasts (Q). Note the euhedral, syntaxial, quartz overgrowths(o). B-27-5-691; 3854.2m; width of field=0.6mm; ppl.

6f -Euhedral, syntaxial quartz overgrowths (o), in a porous sandstone. (Q)=quartz clast, (p)=porosity. K-14-14-778; 3961.2m; width of field=0.6mm;- ppl.

6e

6f

- Plate 7a -Oversized pore space (op) probably the result of framework grain dissolution. Note patch of remnant carbonate cement (C), and corroded quartz boundaries. Also note a partially dissolved framework grain (d). B-27-9-703; 3901.7m; width of field=1.7mm; ppl.
- 7b -"Patch" of probable remnant carbonate cement (C) in porous sandstone. (P) indicates porosity. K-14-12-773; 3934.5m; width of field=1.7mm; ppl.
- 7c -"Patch" of carbonate cement (C), appears to have "engulfed" a silicate grain. Note deformed mudstone clast (M). Also note corroded quartz grain boundaries. K-14-14-785; 3971.5m; width of field=1.7mm; ppl.
- 7d -Intact packing in porous sandstone. Note patch of probable remnant carbonate cement (c), and oversized pore spaces (P). K-14-14-8; 3971.6m; width of field=1.7mm; ppl.
- 7e -Embayment (e) in a quartz grain. Note corroded grain boundaries. Green indicates porosity. K-18-5-6; 3835.68m; width of field=0.6mm; ppl.
- 7f -Fragmented fossil accumulation in a fine unit of the M.H.Z.. well B-27; core #6; box #12; 3875.95m to 3876.18m.

Plate 8a -Deformed, rip-up mudclasts (m). Also notice the scoured basal contact of the sandstone body (arrow). well K-14; core #10; box #6; 3906.23m to 3907.52m.

8b -Carbonaceous stringers and fragments within quartz arenite. well K-18; core #4; box #1; 3817.0 to 3818.5m.

8c -Carbonaceous stringers and fragments. Also notice laminated very fine-grained sandstone and siltstone / mudstone. well K-14; core #14; box #10; 3968.24m to 3969.62m.

8d -Dissolution front between carbonate-cemented sandstone (c) and decemented sandstone. The arrows point to the limits of carbonate cement. well K-14; core #12; box #8; 3928.86m to 3929.43m.

PLATE 1

A

B

C

D

Plate 9a -Conglomerate units (C), deposited on scoured surfaces.
well K-14; core #14; box #5; 3961.14m to 3962.6m.

9b -Paraconglomeratic bed (C), in a fine unit of the
M.H.Z.. Quartzite and siderite pebbles, in a coarse-
grained sand matrix, quickly fines upward into mudstone
and shale. well K-18; core #3; box #5; 3788.0 to
3789.5m.

9a

9b

Plate 9c -Large scale trough cross-bedding: well K-14; core #13;
box #3; 3940.13m to 3941.51m.

9d -Probable trough cross-bedding. well K-14; core #12;
boxes #12 and #13; 3934.4m to 3936.0m.

9c

9d

Plate 10a -Rip-up mudclast (m) in U.H.Z. sandstone body. Also notice the carbonaceous stringers and scoured contacts (s) of the sandstone units. (Md)=mudstone bed. well B-27; core #5; boxes #4 and #5; 3851.33m to 3854.04m.

10b -Scoured contacts (s) of sandstone bodies. Notice rip-up mudclasts (m) in the sandstones, and intrastratal contortions in the fines. well B-27; core #5; boxes #6 and #7; 3854.04m to 3856.75m.

10a

10b

Plate 10c -Laminated very fine-grained sandstone and mudstone /
siltstone. well B-08; core #6; 3624.20 to 3624.40m.

10d -Moldic porosity (mp) due to leaching of shell
fragments. Notice calcite-cemented zone (c), with white
arrows pointing to the dissolution fronts. well K-14;
core #7; boxes #10 and #11; 3861.25m to 3864.38m.

10c

10d

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Appendix 1: Detailed Graphic Logs of Cores From Wells B-08, K-18, B-27, and K-14

LEGEND FOR APPENDIX I

- Low-Angle X-Bdg.
- High-Angle X-Bdg.
- Trough X-Bdg.
- Asymmetric Ripple Laminations
- Climbing Ripple Laminations
- Starved Ripple Laminations
- Graded Bedding (normal) (reverse)
- Laminated with Mudstones
- Silty
- Rip-Up Mudclasts
- Load Structures
- Flame Structures
- Sedimentary Boudinage
- Carbonaceous Stringers
- Rootlets
- Shell Fragments
- Fern Leaf
- Coal Bed
- Moldic Porosity
- Scoured Contact
- Abrupt (non-erosional)
Contact
- Siderite
- Sphaerosiderite
- Hematite (oxidized zone)
- Carbonate Cemented Zone

➤ sample location
(quantitative analysis)

> sample location

B-08, CORE 2

B-08, CORE 3

B-08, CORE 4

B-08, CORE 5

B-08, CORE 6

K-18, CORE 3

K-18, CORE 4

K-18, CORE 5

K-18, CORE 6

B-27, CORE 5

B-27 CORE 6

B-27, CORE 7

B-27, CORE 8

B-27, CORE 9

B-27, CORE 10

K-14, CORE 7

K-14, CORE 8

K-14, CORE 9

154

K-14, CORE 10

K-14, CORE 12

K-14, CORE 13

K-14, CORE 14

APPENDIX 3 - PROBABLE ERRORS WITH 350 POINT COUNTS (after Nentwich, 1980)

FIGURE 12: Biostratigraphic Correlations in the Hibernia Area

O-35, 46°44'54.92"N; 48°49'53.74"W

P-15, 46°44'58"

GAMMA RAY DEPTH(m)

GAMMA RAY

1
OF/DE

In the Hibok-Like Area

P-15, 46°44'58.98"N, 48°46'51.18"W

GAMMA RAY DEPTH(m)

K-18, 46°47'34.69"N, 48°47'17.05"W

GAMMA RAY DEPTH(m)

Datum - Petrol Limestone

2000

2500

2000

2500

3000

Cataloging m

2

OF/DE

3

OF/DE

44°56.96"N, 48°46'51.16"W

K-18, 46°47'34.69"N, 48°47'17.05"W

B-08, 46°47'06.36"N, 48°45'29.87"W

GAMMA RAY DEPTH(m)

GAMMA RAY DEPTH(m)

GAMMA RAY DEPTH(m)

Datum - Petrel Limestone

Cataloging mbr.

2500

3000

Catalina mbr.

Catalina mbr.

50

3500

Hibara mbr.

4

OF/DE

5
OF/DE

6
OF/DE

3000

Catalina mbr.

5C

3500

5B

5A

Hibernia mbr.

4

3000

5C

3500

5B

5A

4

Hibernia mbr.

3000

3500

4000

4000

Hibernia mbr.

Hibernia mbr.

4000

5B

5A

4

4500

(T.D. - 4788m)

Base of Berriasian, based on the "B"
Epistominia sp. 3 foraminifera Zone

Base of Berriasian, based on the

Palynological Zone boundaries

5C - Top of Muderangia Mc

5B - Top of Striatella #EJ 2

5A - Top of Amphorug #EA

4 - Top of Glosteridium d

7 05/05

Hibernia mbr.

5B

5A

4

4000

(T.D. - 4407m)

4000

4500

Base of Berriasian, based on the "*Epistomina minutereticulata* - *Epistomina* sp. 2 - *Epistomina* sp. 3 foraminifera Zone" (Ascoli, 1984)

Base of Berriasian, based on the "*Schuleridea juddi* ostracod Zone" (Ascoli, 1984)

Palynological Zone boundaries (Davies, pers. comm.)

5C - Top of *Muderangle McWhaei* Zone - Late Tithonian - Berriasian

5B - Top of *Striatella* - EJ Zone - Tithonian

5A - Top of *Amphorula* - EA Zone - Tithonian

4 - Top of *Glossadinium dimorphum* Zone - Late Kimmeridgian

5000

(T.D. - 5039m)

8

05/DE

the "Epistomina minuteteticulata - Epistomina sp. 2 - Zone" (Ascoli, 1984)

on the "Schularidea juddi ostracod Zone" (Ascoli, 1984)

ries (Davies, pers. comm.)

g. McWhorter Zone - Late Tithonian - Berriasian

g. E. Zone - Tithonian

g. A. Zone - Tithonian

g. dimorphum Zone - Late Kimmeridgian

9

OF/DE

9

1 OF/DE

FIGURE 13: GENERALIZE
COMPOSITE SECTION
HIBERNIA MEMBER

125

2 OF/DE

FIGURE 13: GENERALIZED

COMPOSITE SECTION

HIBERNIA MEMBER

FIGURE 13: GENERALIZED

COMPOSITE SECTION

HIBERNIA MEMBER

Low-angle x-bedding

High-angle x-bedding

Shell fragments

Scoured contact

Rootlets

Thk. GAMMA RAY
(m)

-SAND-

TOP

3 OF DE

K-14

K-18

75

125

100

FIGURE 13: GENERALIZED

COMPOSITE SECTION

HIBERNIA MEMBER

- Low-angle x-bedding
- High-angle x-bedding
- Shell fragments
- Ripples
- Scoured contact
- Coal bed
- Rootlets

Thk. GAMMA RAY -SAND-
(m)

TOP

4

05/DE

3

OF/DE

3

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Rootlets

Thk. GAMMA RAY
(m)

-SAND-

K-14

K-18

75

TOP

200

50

175

5

ON/DE

Rootlets

Thk. GAMMA RAY
(m)

SAND

TOP

200

175

6

OF/DE

25

BASE

Thk. GAMMA RAY
(m)

-SAND-

175

150

MA RAY

7

MA RAY | -SAND-

8 05/11 8

0-35
 40°46'54.82"N 40°46'03.14"W TD=4770m

DEPTH GAMMA RAY LOG
 (meters) 50 100

Top Hibernia sh.

3900

3850

3875

4000

4025

FIGURE 14A: HIBERNIA MEMBER; GAMMA RAY LOG RESPONSE AND
IN WELLS 0-35, B-27, P-15, AND C-96

B-27

40°46'02.64"N 40°46'27.94"W TD=4384m

DEPTH GAMMA RAY LOG
 (meters) 50 100

3775

Top Hibernia sh.

3800

3825

3950

SANDSTONE-MUDSTONE

P-15

40°46'58.00"N 40°46'51.0"W TD=4407m

DEPTH GAMMA RAY LOG
 (meters) 50 100

3750

Top Hibernia sh.

3775

3800

Core-1

B-27

40°46'02.64"N 40°46'27.94"W TD=4384m

DEPTH GAMMA RAY LOG
 (meters) 50 100

3775

Top Hibernia sh.

3800

3825

3950

AND **FIGURE 14A: HIBERNIA MEMBER; GAMMA RAY LOG RESPONSE AND LITHOLOGY**

-96 IN WELLS O-35, B-27, P-15, AND C-96

3

06/DE

STONE

THE DAY

22

M-MUDSTONE

M-MUDSTONE

MAIN HIBERNIA ZONE

LEGEND

- Compensate
- Very Coarse-Grained S.
- Coarse-Grained Sand
- Medium-Grained Sand
- Fine-Grained Sand
- Very Fine-Grained Sand
- Silt

HIGH ANGLE CROSS-BEDDING

4 OF DE

SHELL FRAGMENTS

M-SANDSTONE

N-MUDSTONE

4075

4000

4025

4050

4075

4100

base of Muddy sh.

0.0 100
GAMMA RAY

N-SANDSTONE

3900

3925

3950

base of Muddy sh.

GAMMA RAY

dry wt. / lb. c. wt.

Core-7

Core-8

Core-8

Core-8

3850

3875

3900

base of Muddy sh.

3925

0.0 100
GAMMA RAY

3900

3925

3950

base of Muddy sh.

GAMMA RAY

505/DE

LEGEND.

- Conglomerate	- HIGH ANGLE CROSS-BEDDING
- Very Coarse-Grained Sand	- LOW ANGLE CROSS-BEDDING
- Coarse-Grained Sand	- RIPPLE CROSS LAMINATIONS
- Medium-Grained Sand	- INTERLAMINATED SANDSTONE & MUDSTONE
- Fine-Grained Sand	- ROOT STRUCTURES
- Very Fine-Grained Sand	- SHELL FRAGMENTS
- Silt	- SCURED CONTACT
- Mud	
- Colours and Rugosity in Mudstone	
- Thin Interbeds of Sands and Fines	

6 N/A 6

1 OF DE

FIGURE 14B: HIBERNIA MEMBER; GAMMA RAY LOG RESPONSE AND LITHOLOGY
IN WELLS K-14, P-15, B-08, AND K-18

2 OF DE

A MEMBER; GAMMA RAY LOG RESPONSE AND LITHOLOGY
IN WELLS K-14, P-15, B-08, AND K-18

P-15

40°45'00"N 40°43'00"W TD=4407m

DEPTH GAMMA RAY (API)
INCHES 00 150

Top Hibernia sh

U-MUDSTONE

U-SANDSTONE

3770

3800

B-08

40°47'00"N 40°45'00"W TD=4435m

DEPTH GAMMA RAY (API)
INCHES 0 150

Top Hibernia sh

U-SANDSTONE

U-MUDSTONE

U-SANDSTONE

U-MUDSTONE

3800

3825

3900

K-18

40°47'00"N 40°47'00"W TD=5039m

DEPTH GAMMA RAY (API)
INCHES 00 150

Top Hibernia sh

3700

3725

3750

3775

3800

UPPER HIBERNIA ZONE

MAIN
HIBERNIA ZONE

Cora-2

K-14 40°43'28"N, 40°41'30"W TD=4280m

DEPTH GAMMA RAYTRAP
(meters)

DEPTH GAMMA RAYTRAP
(meters)

B-08 40°43'28"N, 40°41'30"W TD=4280m

DEPTH GAMMA RAYTRAP
(meters)

3

OW/DE

P-15

40°42'00"N 80°44'30"W TD=4407m

DEPTH (M) (FATHOMS)
150

B-08

40°42'00"N 80°44'30"W TD=4435m

DEPTH (M) (FATHOMS)
150

Top Hibernia zone

Top Hibernia zone

U-SANDSTONE

U-MUDSTONE

U-SANDSTONE

U-MUDSTONE

U-SANDSTONE

UPPER HIBERNIA ZONE

MAIN
HIBERNIA ZONE

4

OF/DE

M-SANDSTONE

SANDSTONE-MUDSTONE

M-SANDSTONE

M-SANDSTONE

SANDSTONE-MUDSTONE

M-SANDSTONE

SANDSTONE-MUDSTONE

M-SANDSTONE

SANDSTONE-MUDSTONE

M-SANDSTONE

M-SANDSTONE

Base Hibernia zone

M-SANDSTONE

M-MUDSTONE

M-SANDSTONE

Core-13

Core-14

4000

4025

4050

Sea Floor

Scale 0 100 200 Feet

3850

3875

3900

Sea Floor

3925

Scale 0 100 200 Feet

3875

M-SANDSTONE

3900

M-SANDSTONE

SANDSTONE-MUDSTONE

3925

M-SANDSTONE

Core-8

Core-9

Scale 0 100 200 Feet

LEGEND

- Conglomerate
- Very Coarse-Grained Sand
- Coarse-Grained Sand
- Medium-Grained Sand
- Fine-Grained Sand
- Very Fine-Grained Sand
- Silt
- Mud
- Calcareous Burrows in Mudstone
- Thin Interbeds of Sand and Fine
- HIGH ANGLE CROSS-BEDDING
- LOW ANGLE CROSS-BEDDING
- RIPPLE CROSS LAMINATION
- INTERLAMINATED SANDS & MUDSTONE
- ROOT STRUCTURES
- SHELL FRAGMENTS
- BEDDED CONTACT

5 05/11

LEGEND

- Conglomerate	- HIGH ANGLE CROSS-BEDDING
- Very Coarse-Grained Sand	- LOW ANGLE CROSS-BEDDING
- Coarse-Grained Sand	- RIPPLE CROSS LAMINATIONS
- Medium-Grained Sand	- INTERLAMINATED SANDSTONE & MUDSTONE
- Fine-Grained Sand	- ROOT STRUCTURES
- Very Fine-Grained Sand	- SHELL FRAGMENTS
- Silt	- SCURED CONTACT
- Mud	
- Coloursous Burrows in Mudstone	
- Thin Interbeds of Sand and Fine	

6 OF 6

1 OF/DE

1000 11 41 1000 11 41 1000 11 41

B-27, 46°46'10.24"N, 48°48'27.04"W

P-13, 46°44'39.98"N, 48°46'50.00"W

P-14, 46°46'10.24"N, 48°48'27.04"W

B-08, 46°47'05"N, 48°45'26"W

O-35, 46°46'54.92"N, 48°49'53.74"W

K-18, 46°47'34.8"N, 48°47'17.30"W

1000

1000

1000

C.M.

2 OF DE

46°43'58.98"N, 48°46'11.18"W
46°46'10.24"N, 48°48'17.04"W

P-18, 46°44'58.98"N, 48°46'11.18"W

B-08, 46°47'05"N, 48°45'26"W

C-96, 46°45'10.00"N, 48°47'17.11"W

K-18, 46°47'34.6"N, 48°47'17.30"W

PETREL LIMESTONE

3 W/DE

C.M.

C.M.

C.M.

3000

3000

2500

2500

2000

2000

2000

1500

1500

1000

1500

2000

2500

PETREL LIMESTONE

C.M.

C.M.

40/41

2500

3000

3500

4000

4500

5 OF DE

C.M.

H.M.

V.C.S.

C.M.

H.M.

V.C.S.

TD - 4394 m

3000

3500

4000

4500

C.M.

H.M.

V.C.S.

3000

3500

4000

TD - 4435 m

C.M.

H.M.

V.C.S.

3000

3500

4000

TD - 4407 m

C.M.

H.M.

V.C.S.

C.M.

H.M.

V.C.S.

TD - 4384 m

LEGEND

H.M. - HIBERNIA MEMBER

C.M. - CATALINA MEMBER

V.C.S. - VERRILL CANYON SHALE

LEGEND

- H.M. - HIBERNIA MEMBER
- C.M. - CATALINA MEMBER
- V.C.S. - VERRELL CANYON SHALE

6 OF DE

LEGEND

- H.M. - HIBERNIA MEMBER
- C.M. - CATALINA MEMBER
- V.C.S. - VERRILL CANYON SHALE

APPENDIX 2: HIBERNIA WELLS; GAMMA RAY AND ACO

70/0E

D-4394m

LEGEND

H.M. - HIBERNIA MEMBER

C.M. - CATALINA MEMBER

V.C.S. - VERRILL CANYON SHALE

APPENDIX 2: HIBERNIA WELLS; GAMMA RAY AND ACOUSTIC LOG RESPONSE

8 OF 8

END

08.06.87

FIN