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Abstract

The Jeanne d'Arc Basin, located at the northeastern part of the Grand Banks of Newfoundland, is a Mesozoic failed-rift basin containing in excess of 22 km of sedimentary fill. Despite a period of vigorous exploration activity initiated by the discovery of the giant-class Hibernia oil field in 1979, the lithostratigraphic nomenclature is not yet standard. This has led to a plethora of lithostratigraphies used by various industry groups, government agencies, and academia, a situation that has caused communication problems. A new lithostratigraphic nomenclature is proposed for the Mesozoic rocks older than the Late Cretaceous Dawson Canyon Formation. The nomenclature consists of 17 formations (14 new), 3 members (new), and 2 markers (new).

The sedimentary evolution of the Jeanne d'Arc Basin is a response to the structural framework of the basin and to regional tectonic episodes related to the breakup of Pangea. Two periods of rifting, the first dominated by deposition of evaporites and the second by coarse clastics, are separated by a tectonically quiet period characterized by the deposition of fine clastics and limestones. A two-stage transition to a passive continental margin followed when fine clastics and minor chalky limestones were deposited.

Major reserves of oil have been discovered in the basin. The oil was generated after continental breakup in shales deposited at the end of the tectonically quiet period and is now trapped mainly in stacked sandstone reservoirs deposited during the second period of rifting. Geological and geochemical data indicate that perhaps as little as 10 percent of potential recoverable reserves have been discovered.

Résumé

Le bassin Jeanne d'Arc, situé dans la partie nord-est des Grands bancs de Terre-Neuve, est un bassin de rift avorté du Mésozoïque contenant plus de 22 km de sédiments de remplissage. Malgré une période d'exploration intense, entreprise après la découverte de l'immense champ pétrolifère Hibernia en 1979, la nomenclature lithostratigraphique n'a pas encore été uniformisée. De nombreuses lithostratigraphies différentes sont utilisées par divers organismes privés, gouvernementaux et universitaires, ce qui a pour effet de causer des problèmes de communication. C'est pourquoi une nouvelle nomenclature lithostratigraphique est proposée pour désigner les roches mésozoïques plus anciennes que celles de la formation de Dawson Canyon du Crétacé supérieur. La nomenclature est composée de 17 formations (14 nouvelles), 3 membres et 2 marqueurs (nouveaux).

L'évolution sédimentaire du bassin Jeanne d'Arc est liée à la structure du bassin et aux épisodes tectoniques régionaux découlant de la fragmentation de la Pangée. Entre deux périodes d'effondrement dont la première est caractérisée par le dépôt d'évaporites et la seconde, par le dépôt de sédiments clastiques grossiers, il s'est écoulé une période tectoniquement calme marquée par le dépôt de sédiments clastiques et de calcaires fins. Une transition en deux étapes débouchant sur une marge continentale passive s'ensuivit lorsque des sédiments clastiques fins et des calcaires crayeux secondaires se sont déposés.

D'importantes réserves de pétrole ont été découvertes dans le bassin. La formation du pétrole a commencé après la fragmentation continentale dans des schistes argileux déposés à la fin d'une période tectoniquement calme ; le pétrole est principalement piégé dans des grès réservoirs empilés déposés durant la seconde période d'effondrement. Selon les données géologiques et géochimiques recueillies, on n'aurait découvert que 10 % des réserves récupérables possibles.

SUMMARY

The Grand Banks of Newfoundland form a broad continental shelf, the easternmost promontory of the North American continental plate. The most conspicuous subsurface elements of this region, revealed by over 20 years of petroleum exploration, are a series of five interconnected sedimentary basins — namely the South Whale Subbasin of the Scotian Basin and the Whale, Horseshoe, Carson, and Jeanne d'Arc basins — containing deformed rocks of Late Triassic through Early Cretaceous age. These Mesozoic basins and the Paleozoic and Precambrian rocks that underlie and surround them were subject to periods of deformation and erosion during the Late Jurassic and Early Cretaceous that produced a prominent peneplain, the Avalon Unconformity, over the central Grand Banks and thick clastic deposits on its flanks. Slow regional subsidence during the Late Cretaceous and Tertiary resulted in a relatively undisturbed and thin cover of fine grained marine shelf deposits.

Although all the Mesozoic basins have been targets of exploration, potentially commercial hydrocarbon reserves, including the giant Hibernia oil field, have been discovered only in the Jeanne d'Arc Basin. A new lithostratigraphic framework and nomenclature for pre-Late Cretaceous rock units in the Jeanne d'Arc Basin is proposed in order to standardize the current profusion of stratigraphic units and terminology. The stratigraphic column consists of:

Eurydice Formation, *extended range*, Carnian-Norian reddish clastics;

Osprey Formation, *new*, Carnian-Norian to early Hettangian salt containing common intercalated red shale;

Argo Formation, *extended range*, late Norian-early Hettangian to late Hettangian-early Sinemurian massive salt;

Iroquois Formation, *extended range*, late Hettangian-early Sinemurian to Pliensbachian carbonates and evaporites;

Downing Formation, *new*, Pliensbachian to Kimmeridgian monotonous grey shale containing interbedded limestone and minor sandstone;

Whale Member, *new*, Toarcian to Bajocian limestone;

Voyager Formation, *new*, late Bathonian to early Oxfordian interbedded sandstone, siltstone, shale, coal, and limestone;

Rankin Formation, *new*, early Oxfordian to Kimmeridgian limestone, marl, and fine grained clastics;

Egret Member, *new*, early Kimmeridgian thinly interbedded organic-rich shale, marl, and fine grained siliciclastics;

SOMMAIRE

Les Grands bancs de Terre-Neuve forment une large plate-forme continentale qui correspond à l'extrémité est de la plaque continentale de l'Amérique du Nord. Les éléments souterrains les plus évidents dans cette région, révélés par plus de 20 ans d'exploration pétrolière, sont une série de cinq bassins sédimentaires reliés entre eux et contenant des roches déformées du Trias supérieur et du Crétacé inférieur, soit le sous-bassin South Whale du bassin Scotian et les bassins Whale, Horseshoe, Carson et Jeanne d'Arc. Ces bassins mésozoïques et les roches paléozoïques et précambriennes sous-jacentes et environnantes ont été déformées et érodées durant le Jurassique supérieur et le Crétacé inférieur produisant une pénéplaine importante, la discordance d'Avalon, au-dessus du centre des Grands bancs, et d'épais dépôts de roches clastiques sur ses flancs. Une lente subsidence régionale durant le Crétacé supérieur et le Tertiaire s'est traduite par le dépôt d'une mince couverture relativement peu perturbée de sédiments de plate-forme sous-marine à grain fin.

Même si tous les bassins mésozoïques ont été des cibles pour l'exploration pétrolière, les réserves d'hydrocarbure à valeur potentiellement commerciale, notamment l'immense champ Hibernia, se limitent à ce jour au bassin Jeanne d'Arc. Une restructuration et une nouvelle nomenclature de la lithostratigraphie des unités rocheuses du bassin Jeanne d'Arc d'âge antérieur au Crétacé supérieur sont proposées afin d'uniformiser le foisonnement actuel d'unités et de termes stratigraphiques. La colonne stratigraphique proposée est composée des éléments suivants :

Formation d'Eurydice, *intervalle élargi*, roches clastiques rougeâtres carniennes-noriennes ;

Formation d'Osprey, *nouvelle*, sel du Carnien-Norien de l'Hettangien inférieur contenant des intercalations de schiste argileux rouge ;

Formation d'Argo, *intervalle élargi*, sel massif du Norien supérieur-Hettangien inférieur à l'Hettangien supérieur-Sinémurien inférieur ;

Formation d'Iroquois, *intervalle élargi*, carbonates et évaporites de l'Hettangien supérieur-Sinémurien inférieur au Pliensbachien ;

Formation de Downing, *nouvelle*, schiste argileux gris monotone du Pliensbachien au Kimméridgien contenant du calcaire et du grès secondaire interstratifiés ;

Membre de Whale, *nouveau*, calcaire du Toarcien au Bajocien ;

Formation de Voyager, *nouvelle*, grès, siltstone, schiste argileux, charbon et calcaire interstratifiés du Bathonien supérieur à l'Oxfordien inférieur ;

Formation de Rankin, *nouvelle*, calcaire, marne et roches clastiques à grain fin de l'Oxfordien inférieur au Kimméridgien ;

Membre d'Egret, *nouveau*, schiste argileux, marne et roches silicoclastiques à grain fin à haute teneur en matières organiques, finement interstratifiés, datant du Kimméridgien inférieur ;

Jeanne d'Arc Formation, *new*, Kimmeridgian to Tithonian interbedded sandstone, conglomerate, and shale ;

Fortune Bay Shale, *new*, Tithonian shale and siltstone ;

Hibernia Formation, *new*, Tithonian to Berriasian quartz sandstone and shale ;

Hebron Well Member, *new*, Berriasian quartz sandstone and minor shale ;

"B" marker, *new*, late Berriasian to Valanginian massive limestone ;

Catalina Formation, *new*, late Berriasian to Valanginian thinly bedded, fine grained siliciclastics and minor limestones ;

"A" marker, *new*, late Hauterivian to early Barremian thin limestone bed ;

Eastern Shoals Formation, *new*, Hauterivian to Barremian interbedded sandstone and siltstone or massive calcareous sandstone/oolitic limestone ;

Whiterose Shale, *new*, late Tithonian to Barremian shale, siltstone, and minor limestone ;

Avalon Formation, *new*, late Barremian to early Albian coarsening upward shale, siltstone, and sandstone sequence ;

Ben Nevis Formation, *new*, late Aptian to late Albian fining upward sandstone and siltstone sequence ;

Eider Formation, *new*, late Albian to late Cenomanian coarsening upward sequence of mudstone, sandstone, and lesser limestone and marl ;

Nautilus shale, *new*, late Barremian to late Albian-Cenomanian shale and mudstone.

The Mesozoic and Cenozoic stratigraphy of the Jeanne d'Arc Basin is intimately related to the tectonic development of the Grand Banks. Although the basin lies well inboard of the continent-ocean boundary, the sedimentary fill is composed of distinctive depositional sequences that are each interpreted to record a unique tectonic episode in the development of the North Atlantic Ocean and the Labrador Sea. In brief, six primary Mesozoic-Cenozoic sequences record two periods of rift subsidence, separated by a Middle Jurassic quiet period and followed by a two-phase transition to passive continental margin subsidence. The six sequences are, from oldest to youngest :

1. Aborted Rift — Late Triassic to Early Jurassic continental red beds and restricted marine evaporites and carbonates.
2. Epeiric Basin — Early to Late Jurassic normal marine shales and carbonates and minor, fine grained deltaic sediments.
3. Late Rift — Latest Jurassic and Neocomian sandstone-dominated deltaic and estuarine sediments.

Formation de Jeanne d'Arc, *nouvelle*, grès, conglomérat et schiste argileux interstratifiés du Kimméridgien au Tithonique ;

Schiste argileux de Fortune Bay, *nouveau*, schiste argileux et siltstone tithoniques ;

Formation d'Hibernia, *nouvelle*, grès et schiste argileux à quartz du Tithonique au Berriasien ;

Membre d'Hebron Well, *nouveau*, grès quartzique et schiste argileux secondaire du Berriasien ;

Marqueur " B ", *nouveau*, calcaire massif du Berriasien supérieur au Valanginien ;

Fromation de Catalina, *nouvelle*, roches silicoclastiques à grain fin finement interstratifiées et calcaires secondaires, du Berriasien supérieur au Valanginien ;

Marqueur " A ", *nouveau*, mince couche de calcaire de l'Hauterivien supérieur au Barrémien inférieur ;

Formation d'Eastern Shoals, *nouvelle*, grès et siltstone interstratifiés de l'Hauterivien au Barrémien ou grès calcaire/calcaire oolitique massif de l'Hauterivien au Barrémien ;

Schiste argileux Whiterose, *nouveau*, schiste argileux et siltstone et calcaire secondaire du Tithonique supérieur au Barrémien ;

Formation d'Avalon, *nouvelle*, séquence de schiste argileux, siltstone et grès à granulométrie négative du Barrémien supérieur à l'Albien inférieur ;

Formation de Ben Nevis, *nouvelle*, séquence de grès et de siltstone à granulométrie positive de l'Aptien supérieur à l'Albien supérieur ;

Formation d'Eider, *nouvelle*, séquence de mudstone, grès et, en moindre quantité, de calcaire et de marne, à granulométrie négative, de l'Albien supérieur au Cénomanien supérieur ;

Schiste argileux Nautilus, *nouveau*, schiste argileux et mudstone du Barrémien supérieur à l'Albien supérieur-Cénomanien.

La stratigraphie mésozoïque et cénozoïque du bassin Jeanne d'Arc est étroitement liée à l'évolution tectonique des Grands bancs. Bien que le bassin s'étende bien à l'intérieur de la limite continent-océan, les sédiments de remplissage sont formés de séquences distinctes qui correspondraient chacune à une épisode tectonique unique pendant la formation du nord de l'océan Atlantique et de la mer du Labrador. En résumé, six séquences mésozoïques-cénozoïques principales sont le reflet de deux périodes de subsidence par effondrement, séparées par une période calme au Jurassique moyen et suivies par une période transitoire à deux phases débouchant sur une subsidence de marge continentale passive. Ces six séquences sont, de la plus ancienne à la plus récente :

1. Rift avorté — couches rouges continentales et évaporites et carbonates de milieux marins restreints, du Trias supérieur au Jurassique inférieur.
2. Bassin épéirique — schistes argileux, et carbonates de milieux marins normaux et sédiments deltaïques secondaires à grain fin, du Jurassique inférieur au supérieur.

4. Transition to Drift: Phase I — Barremian to Cenomanian shallow to deep estuarine sandstones and shales.
5. Transition to Drift: Phase II — Late Cretaceous and Paleocene open-marine shelf, overlapping deltaic deposits and distal turbidites, and chalky limestones.
6. Passive Margin — Tertiary neritic shale, siliceous mudstone, and minor chalk.

Potentially commercial hydrocarbon reserves in the Jeanne d'Arc Basin reflect the uniquely favourable association of a mature, organic-rich, oil-prone source rock, good reservoir beds and trapping mechanisms, good migration pathways, and proper timing of trap formation. Geochemical data identify and characterize the primary source rock, the Egret Member of the Rankin Formation, and two minor hydrocarbon contributors. Oil accumulations in stacked sandstone reservoirs of the Late Rift sequence and the location of the source rock in the overpressured Epeiric Basin sequence implies predominantly vertical migration along faults. Organic maturation data show that most of the oil was generated in the Tertiary after the structural traps were in place.

A quantitative evaluation of the potential oil yield of the Egret Member indicates that the published current best estimate of potential recoverable oil reserves, 195.2 million cubic metres (1.2 billion barrels), may represent as little as 10 percent of the possible ultimate production of the Jeanne d'Arc Basin.

3. Rift tardif — sédiments deltaïques et estuariens à prédominance de grès de la toute fin du Jurassique et du Néocomien.
4. Transition vers des sédiments de dérive (première phase) — grès et schiste argileux estuariens d'eau peu profonde à profonde, du Barrémien au Cénomanien.
5. Transition vers des sédiments de dérive (deuxième phase) — plate-forme de milieu marin ouvert du Crétacé supérieur et du Paléocène recouvrant des sédiments deltaïques, des turbidites distales et des calcaires crayeux.
6. Marge passive — schiste argileux néritique, mudstone siliceux et craie secondaire du Tertiaire.

Les réserves d'hydrocarbure potentiellement commerciales qui se trouvent dans le bassin Jeanne d'Arc sont le résultat d'une association particulièrement favorable d'une roche mère mature, riche en matières organiques et propice à la formation de pétrole, de couches réservoirs, de mécanismes de piégeage et de parcours de migration appropriés ainsi que de pièges formés à l'étape propice. Les données géochimiques permettent d'identifier et de caractériser la roche mère principale, le membre d'Egret de la formation de Rankin, et deux sources secondaires d'hydrocarbures. L'accumulation de pétrole dans des roches réservoirs de grès empilées dans la séquence du rift tardif et l'emplacement de la roche mère dans la séquence du bassin épéirique en surpression laissent supposer une migration principalement verticale le long des failles. Les données sur la maturation organique indiquent que la grande partie du pétrole s'est formée pendant le Tertiaire après la mise en place de pièges structuraux.

Une évaluation quantitative de la production possible de pétrole par le membre d'Egret indique que les meilleures estimations publiées des réserves de pétrole récupérables, soit 195,2 millions de mètres cubes (1,2 milliard de barils) pourraient ne correspondre qu'à 10 % de la production éventuelle possible du bassin Jeanne d'Arc.

INTRODUCTION

The Grand Banks of Newfoundland comprise a broad late Cretaceous-Tertiary continental shelf on a basement of Paleozoic and Precambrian continental crust at the northern end of the Appalachian Orogen of eastern North America (Fig. 1). The outstanding subsurface geological elements of this region are a series of interconnected sedimentary basins that formed during the Mesozoic Era (Fig. 2). These basins and the intervening basement highs are truncated by a prominent peneplain, the Avalon Unconformity, and are buried beneath a relatively thin cover of undeformed Upper Cretaceous and Tertiary strata. None of the Mesozoic-Cenozoic sedimentary section outcrops onshore Newfoundland (Fig. 1).

The Mesozoic basins of the Grand Banks have been extensively explored by the petroleum industry for more than 20 years ; nevertheless, significant hydrocarbon accumulations have been discovered only in the Jeanne d'Arc Basin, a Mesozoic failed-rift basin containing in excess of 22 km of sedimentary fill (Fig. 3). Exploration activity has centred there since the discovery of a giant oil field at Hibernia in 1979, and several more potentially commercial oil and gas accumulations have been found. Despite the accumulated wealth of subsurface information, a standard lithostratigraphic nomenclature for this basin is not yet in use. The resulting profusion of lithostratigraphic names has caused communication problems between various industry groups, government agencies, and academia.

Accordingly, the objectives of this paper are :

1. To define with precision the Mesozoic lithostratigraphic units of the Jeanne d'Arc Basin and to propose formal names for them in accordance with the recommendations of the International Subcommission on Stratigraphic Classification (1976) and the North American Commission on Stratigraphic Nomenclature (1983).
2. To describe the sedimentary evolution of the Jeanne d'Arc Basin in the context of the proposed stratigraphic framework, emphasizing its response to the structural framework of the basin and to regional tectonic episodes related to the breakup of Pangea.
3. To briefly discuss the petroleum potential of the Jeanne d'Arc Basin, particularly as it relates to the tectonostratigraphic history of the Grand Banks.

The proposed lithostratigraphic framework and interpreted sedimentary evolution are the result of an integrated approach to basin analysis. Regionally correlatable seismic sequences were tied to extensive lithostratigraphic and biostratigraphic data bases from oil exploration wells, enabling the recognition of distinctive depositional sequences. These depositional sequences provided fundamental divisions for identifying and correlating lithostratigraphic units and yielded new insights into the evolution of the Grand Banks sedimentary basins.

As much as possible, the names proposed here have been retained from the heterogeneous informal nomenclature already in use. New names were derived from names of wells or nearby bathymetric features. Because well control in the Jeanne d'Arc Basin is still fairly dispersed, the lithostratigraphic units purposely have been kept broad ; nevertheless, the overall framework is believed to be sound. As more information becomes available, further refinement of facies distribution patterns will become possible, and the nomenclature will allow insertion of smaller or more restricted stratigraphic units. It will be seen that some of the proposed units may have widespread application to other Mesozoic basins of the Grand Banks.

The well data used in this study are those released to the public by the Canada Oil and Gas Lands Administration (COGLA) and the Canada-Newfoundland Offshore Petroleum Board (CNOPB) after a 2-year period of confidentiality for wildcat wells, or a 90-day period for delineation wells. Multichannel reflection records are held confidential for 5 years by COGLA and CNOPB. As of March 1989, results have been released for 58 out of 64 wells drilled or drilling in the Jeanne d'Arc Basin and released seismic coverage is in excess of 100 000 km. The biostratigraphic age assignments are a synthesis of ages from diverse sources and disciplines. Most reliance was placed on palynological assemblages after Barss et al. (1979), supplemented by extensive unpublished data provided by E.H. Davies and by the Bujak Davies Group under contract. Age interpretations from ostracods and foraminifers were also relied on for supporting evidence (Ascoli, 1988). A detailed synthesis of biostratigraphic (palynology) and lithostratigraphic correlation of seven wells from the Hibernia field by Davies (1986 ; see also Williams et al., in press) and Davies and McAlpine (unpublished results) was extended to several other wells in the Jeanne d'Arc Basin using various combinations of seismic, lithostratigraphic, and biostratigraphic techniques. The geochronology in this paper is based on the Decade of North American Geology time scale (Palmer, 1983).

Acknowledgments

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GSC

Figure 1. Bathymetric map showing the principal physiographic features of the continental margin of Eastern Canada and locations of exploratory wells (dots). Hatched shading indicates Precambrian Shield rocks; stippled shading covers area of the Appalachian Orogen. Unshaded area is underlain by Mesozoic-Cenozoic sediments.

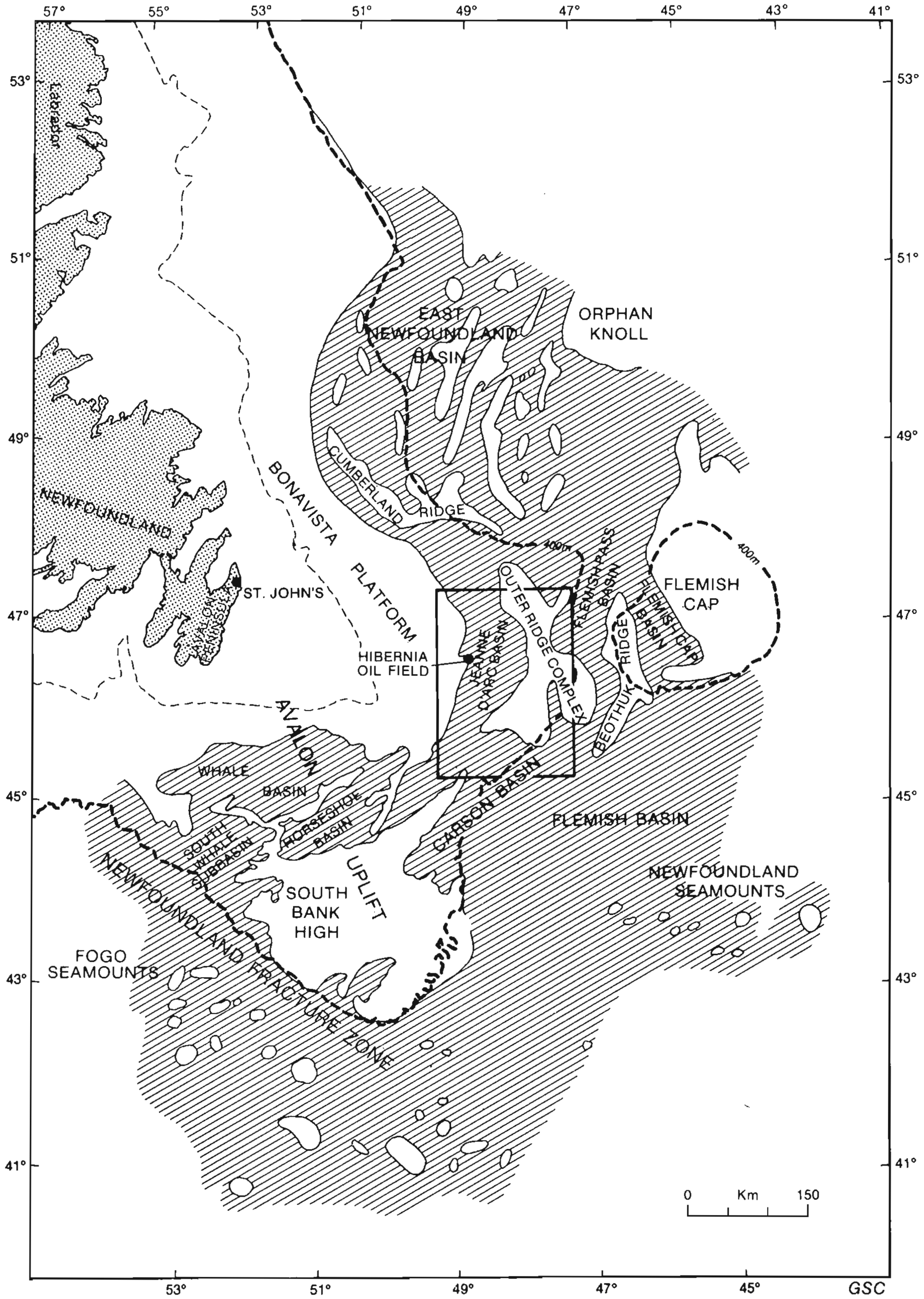

Figure 2. Simplified tectonic map showing the principal positive structural elements and Mesozoic basins (hatched) underlying the continental margin around Newfoundland. Light dashed line is landward edge of Upper Cretaceous-Tertiary sediments. Heavy dashed line is 400-m isobath. Rectangle outlines area of Figure 3.

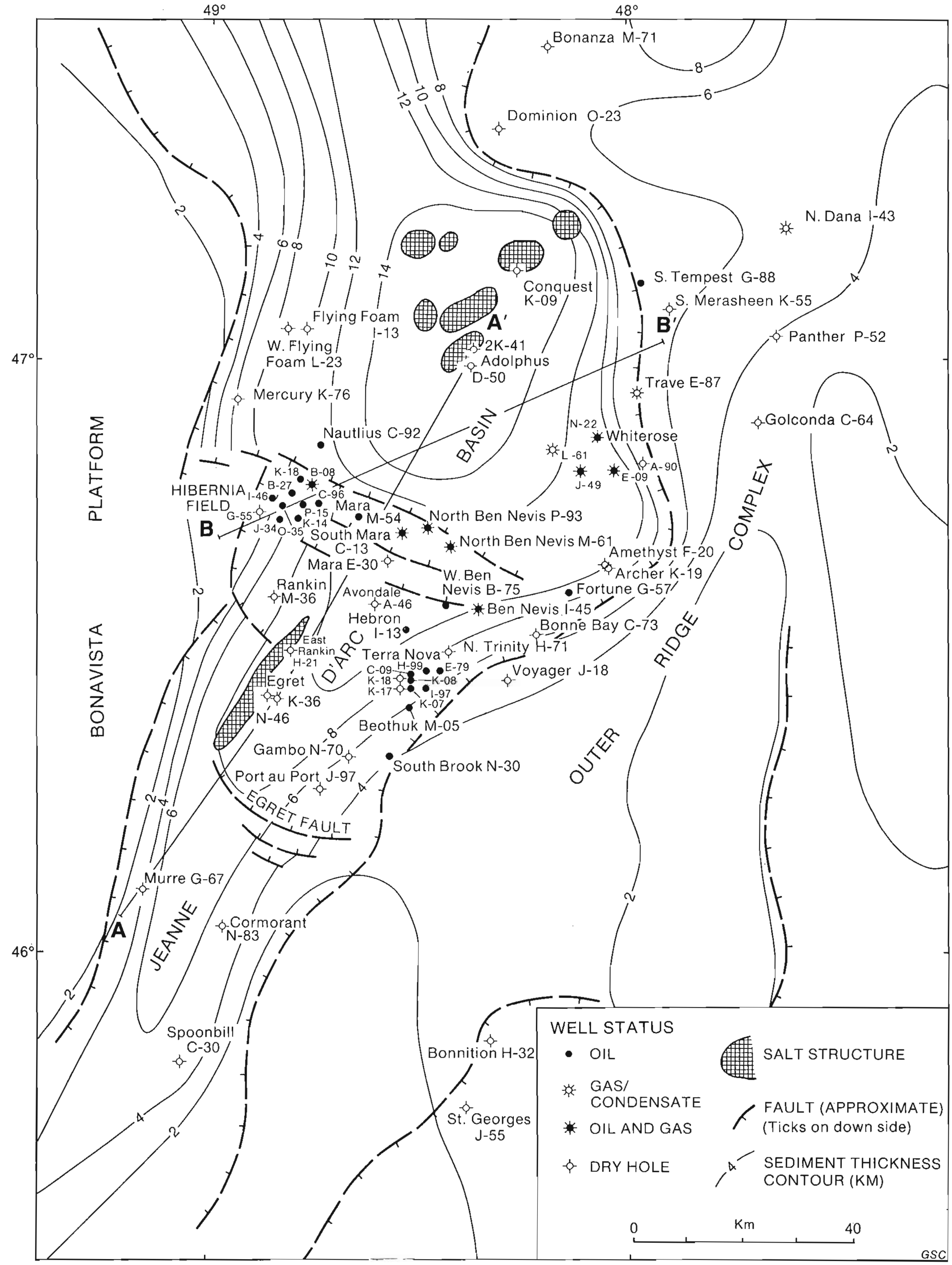

Figure 3. Diagrammatic tectonic element and sediment thickness map of the Jeanne d'Arc Basin (modified from Grant and McAlpine, in press). Sediment thickness is conservative in the basin depocentre because basement lies below the depths recorded by industry seismic records; deep multichannel seismic data recorded to 20 seconds show that the basin is over 20 km deep (Enachescu, 1986; Keen et al., 1987). Lines A and B are locations of seismic profiles in Figures 4 and 5.

REGIONAL SETTING

About 250 million years ago, at the close of the Paleozoic Era, the area that is now the continental margin of Newfoundland occupied a central position in the Pangea supercontinent. It was surrounded to the south, east, and north by areas that would become northwest Africa, Iberia, and the British Isles. Prior to that time the region had a long and complex history of construction, characterized by the opening and closing of the Iapetus Ocean, that began with rifting in the late Precambrian and ended with a series of accretionary events during the Paleozoic. The rocks of the Appalachian Orogen record three main Paleozoic tectonic episodes, the Taconian, the Acadian, and the Alleghanian orogenies that culminated in the Ordovician, the Devonian, and the Permian respectively (Williams, 1979). Subsequent fragmentation of Pangea during the Mesozoic Era led to the formation of the Atlantic Ocean and left the Grand Banks situated at the eastern corner of the North American continental plate between the northeast oriented Scotian margin and the northwest oriented Labrador margin (Fig. 1).

Various accounts of the Mesozoic-Cenozoic tectonostratigraphic evolution of the Grand Banks have been provided by Amoco and Imperial (1973), Sherwin (1973), Jansa and Wade (1975), Hubbard et al. (1985), Grant et al. (1986a, b), Enachescu (1987), Grant et al. (1988), Tankard and Welsink (1988), and Grant and McAlpine (in press) ; In summary, regional geological and geophysical evidence indicates that continental plate separation was a complex process which progressed sequentially from south to north around the Grand Banks : whereas the Atlantic south of the Grand Banks commenced opening in the Early Jurassic, seafloor spreading probably did not begin between the Grand Banks and Iberia until the middle Cretaceous and gradually propagated northeast and then northwest to the Labrador Sea by the end of the Cretaceous.

Although the Mesozoic rocks and the unconformities preserved beneath the Grand Banks were formed in an intra-cratonic setting, they provide a fragmentary record of the breakup of Pangea. The Grand Banks' geological framework is extremely complex ; it is a multifarious consequence of differential basement subsidence caused by diachronous opening of the Atlantic Ocean and attendant variously-aligned tensional regimes, inherited Paleozoic structural grain, and a late Mesozoic-Tertiary regional arch (the Avalon Uplift) that trends southeast from the Avalon Peninsula to the Newfoundland Ridge (Fig. 1 and 2). The salient geological features of the Grand Banks revealed by seismic data are a conspicuous peneplain (the Avalon Unconformity) overlain by a relatively thin cover of undisturbed Upper Cretaceous and Tertiary strata and a series of interconnected and structured Mesozoic basins and intervening basement highs truncated by the peneplain.

The oldest dated Mesozoic rocks are Late Triassic red clastics, probably deposited in a portion of a vast rift system that dissected Pangea before its breakup. Gradual marine encroachment from the Tethys Sea drowned the rifted topography and promoted the deposition of evaporites (predominantly salt) followed by marine carbonates. Early Jurassic breakup south of the Grand Banks coincided with establishment of a continental sea north of the Newfoundland Fracture Zone (Fig. 2) where environmental conditions led to the deposition of shales and carbonates and, eventually as the sea shallowed, minor fine grained clastics. Upwarping of the Avalon Uplift during the Kimmeridgian initiated the formation of the northeast-trending extensional basins and promoted regional peneplanation. The Whale, Horseshoe, and southern Jeanne d'Arc basins preserve beneath the peneplain only remnants of the Jurassic epeiric sea deposits that covered the Grand Banks. The South Whale, Carson, and northern Jeanne d'Arc basins flanking the axial high, however, contain onlapping uppermost Jurassic and Lower Cretaceous continental and shallow-marine clastics.

The Jeanne d'Arc Basin is the deepest of the Mesozoic basins and thus contains the most complete stratigraphic record of Grand Banks evolution. Figure 3 shows the major tectonic elements of the area : a stable basement high, the Bonavista Platform, flanking the basin to the west ; the north-northeast plunge of the basin toward the depocentre ; and the Outer Ridge Complex, a structural high composed of north- to northeast-trending basement ridges overlain in part by complexly deformed Triassic and Jurassic rocks stratigraphically equivalent to those in the basin. Salt underlies much of the Jeanne d'Arc Basin, and it has exerted a strong influence on the structural aspect of the sedimentary fill. Among the most spectacular products of salt flowage are the diapiric structures near the Adolphus wells and the salt wall in the vicinity of the Egret wells (Fig. 3 and 4). Much of the faulting in the basin may be the result of compensatory movement for salt withdrawal and flowage.

The pattern of faulting is dominated by three main sets of faults : listric-type faults parallel to the basin margins ; high-angle normal faults parallel to the basin margins ; and trans-basin faults orthogonal to the other two sets. The basin is divided into three structural-stratigraphic segments by trans-basin faults (Fig. 3 and 4). South of the Egret Fault (Enachescu, 1987) uppermost Jurassic and Lower Cretaceous rocks are virtually absent because of erosion and depositional thinning. Between the Egret Fault and the Hibernia to Ben Nevis trans-basin fault zone, this section thickens dramatically. North of the trans-basin fault zone a thickened middle Cretaceous section has been preserved. The sedimentary record of the Upper Jurassic and Lower Cretaceous in the basin is characterized by several unconformities that merge updip with the inter-basin peneplain, and collectively, they indicate that the Avalon Unconformity was formed during 50-60 million years (late Kimmeridgian to Albian-Cenomanian) of uplift, deformation, and erosion (Fig. 4, 5, and 6).

Since the end of the Early Cretaceous, the Grand Banks area, including the Jeanne d'Arc Basin, has subsided as a relatively intact structural block. During the Late Cretaceous, sediment supply was intermittent and produced overlapping deltaic sequences with distal turbidites and deep-water chalks. Cenozoic subsidence, although still influenced by the Avalon Uplift, was relatively uniform and uneventful except for a few salt structures and faults that remained active. Sedimentation was dominated by deep-water mudstones and shales.

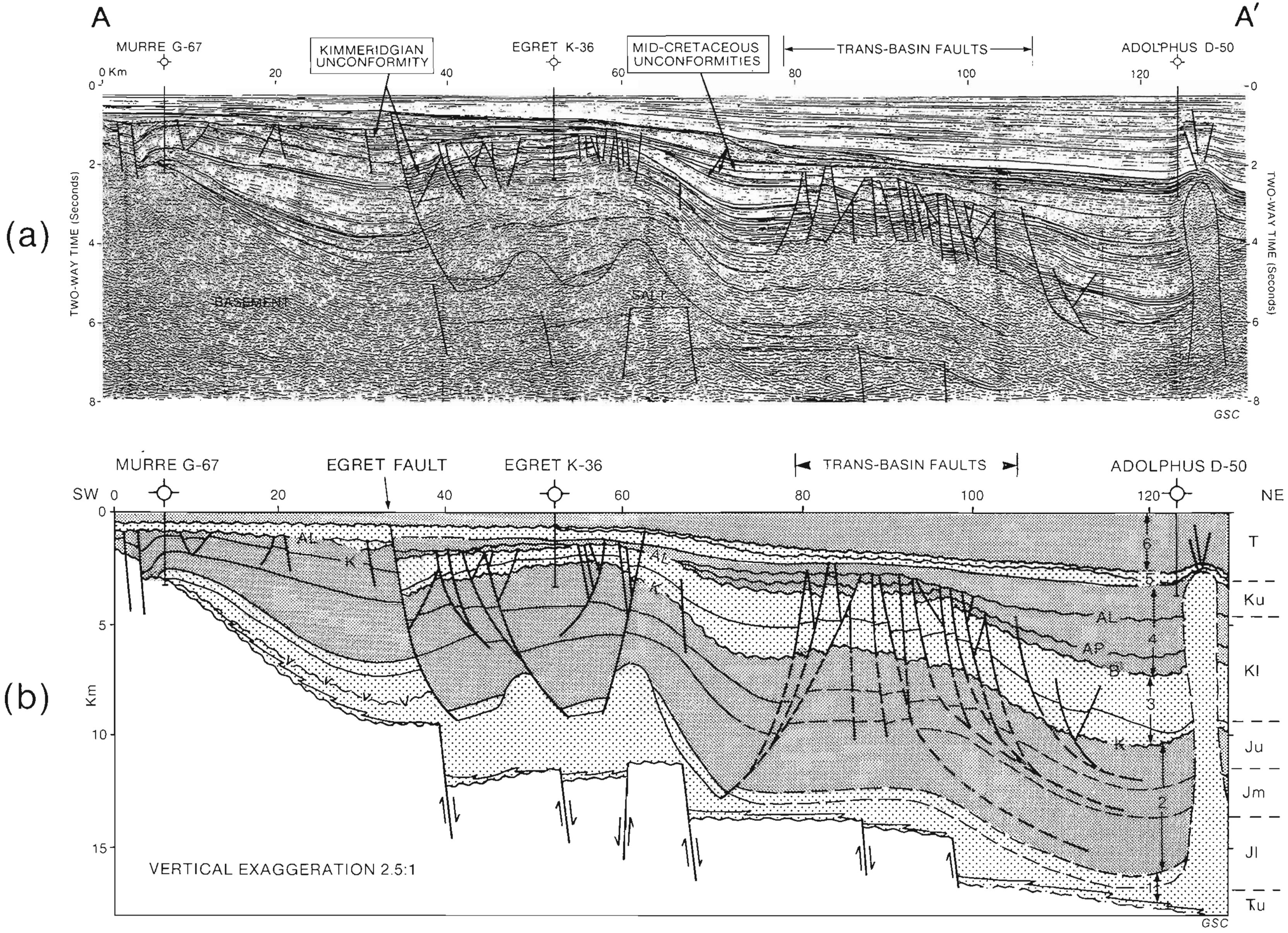

Figure 4. (a) North-northeast seismic profile approximately along the axis of the Jeanne d'Arc Basin. Line of section shown on Figure 3. Notable features discussed in the text are: the Kimmeridgian unconformity, which exhibits prominent channelling in the vicinity of the Egret K-36 well, the three mid-Cretaceous unconformities that bound two onlapping fill seismic sequences; the trans-basin fault zone extending from the Hibernia field to the Ben Nevis I-45 well; and the Egret Fault about 15 km south of Egret K-36 which offsets the Kimmeridgian unconformity about 1.2 seconds and overlies an important basement fault. (Seismic line NF 79-112, courtesy of Geophysical Service Incorporated).
(b) Geological interpretation of Figure 4a. The Mesozoic-Cenozoic stratigraphic record is divided into six depositional sequences (numbered 1 through 6) that can be related to unique tectonic periods in the evolution of the Newfoundland margin. Details of these sequences are given in the text; unconformities lettered K, B, AP, and AL are defined in Figure 6.

LITHOSTRATIGRAPHY

Previous stratigraphy

Over 100 wells have been drilled in the waters surrounding Newfoundland since the first hole (Tors Cove D-52 in the South Whale Subbasin) was abandoned in 1966. The Jeanne d'Arc Basin has been the site of nearly 60 of these wells (including 20 delineation wells). Murre G-67, the first attempt in that basin, was abandoned in 1971, but most wells were drilled during the last decade following the Hibernia P-15 wildcat discovery in 1979 (Fig. 3). Despite this vigorous exploration activity and extensive geological investigations by several petroleum companies and research groups, the lithostratigraphic nomenclature for the Jeanne d'Arc Basin has not been standardized. By contrast, formal lithostratigraphic schemes were proposed for the Scotian Shelf (McIver, 1972) and the Labrador Shelf (Umpleby, 1979) within a decade of the first wells being drilled. This reflects not only the complex geological history of the Grand Banks, on account of its pivotal position between the comparatively simple passive margins to the southwest and the northwest, but also reflects the fact that nearly all the early wells were drilled on or near the axis of the Avalon Uplift and on diapiric salt structures where much of the section is missing.

Stratigraphies published before the Hibernia discovery extended Scotian Shelf terminology across the Grand Banks to the Jeanne d'Arc Basin. Although homotaxial equivalency of gross units was demonstrable in many cases, several informal rock units needed to be introduced to describe the more detailed stratigraphy. Figure 7 shows the chronological development of stratigraphic nomenclature applied to this area. Earlier descriptions of the stratigraphic record can be found in Bartlett and Smith (1971) and Sherwin (1973).

Wells drilled after Hibernia in the Jeanne d'Arc Basin penetrated a more complete stratigraphic record, particularly a more fully developed Cretaceous section. Arthur et al. (1982) introduced four new informal lithostratigraphic units for the productive reservoirs units at Hibernia field. Grant et al. (1986a, b) synthesized previous stratigraphies with unpublished biostratigraphic analyses, but did not introduce any new units. More recent accounts were given by Boudreau et al. (1986), McAlpine and Grant (1986), Tankard and Welsink (1987), McAlpine and Edwards (1988), and Sinclair (1988). In addition, several unpublished schemes are currently in use by petroleum companies.

Proposed stratigraphy

The new lithostratigraphy proposed here is summarized in Figure 8 and Table 1. The Mesozoic rocks older than the Late Cretaceous Dawson Canyon Formation are divided into 17 formations (14 new), 3 members (new), and 2 markers (new). The Late Cretaceous and younger section was not included in this study ; however, R.R. Boudreau (pers. comm.,1985) and Boudreau et al. (1986) appear to have satisfactorily correlated two deltaic sandstone units (Otter Bay formation, Coniacian to Santonian and Fox Cove formation, Santonian to late Maastrichtian) which they regard as lateral equivalents of the Dawson Canyon Formation. Sinclair (1988) considers these units to be members of the Dawson Canyon Formation. The South Mara unit sandstone (Fig. 8) is described as a member of the Banquereau Formation by Sinclair (1988).

Two correlation sections illustrating gamma-ray/sonic log and lithological characteristics of the proposed units in several key wells are provided for reference (Fig. 9 and 10). Figures 11 to 27 illustrate all well type sections and well reference sections. An attempt has been made in the text to specify the boundaries of each unit in enough wells that no doubt remains about the unit's interpreted distribution and intended usage. The depths recorded in Figures 11 to 27 and all depths in the text are unmodified gamma-ray/sonic log depths.

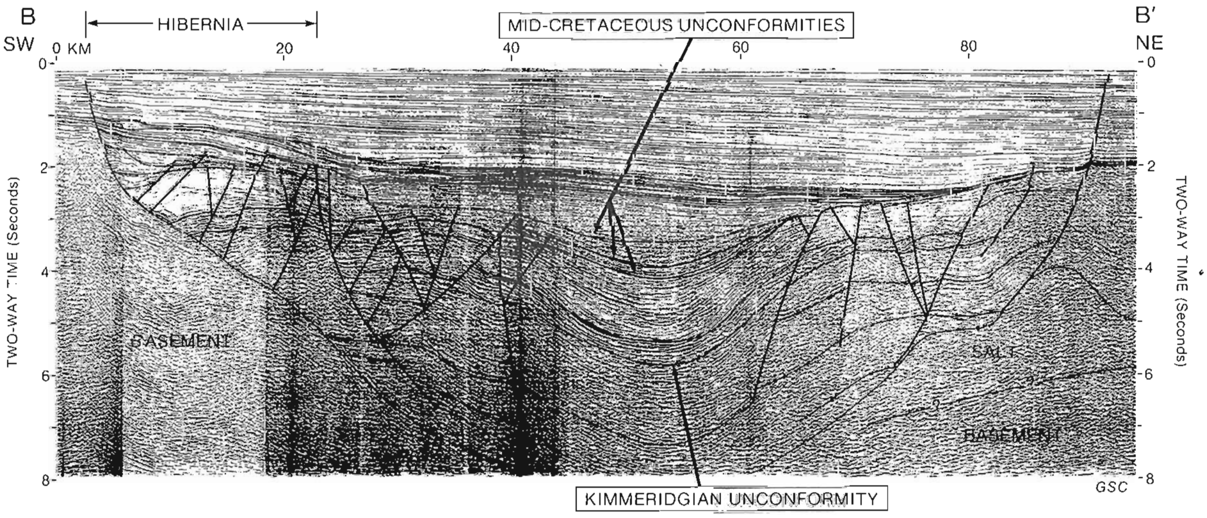

Figure 5. East-northeast seismic profile across the Jeanne d'Arc Basin. Line of section shown on Figure 3. (Seismic line NF 79-114, courtesy of Geophysical Service Incorporated).

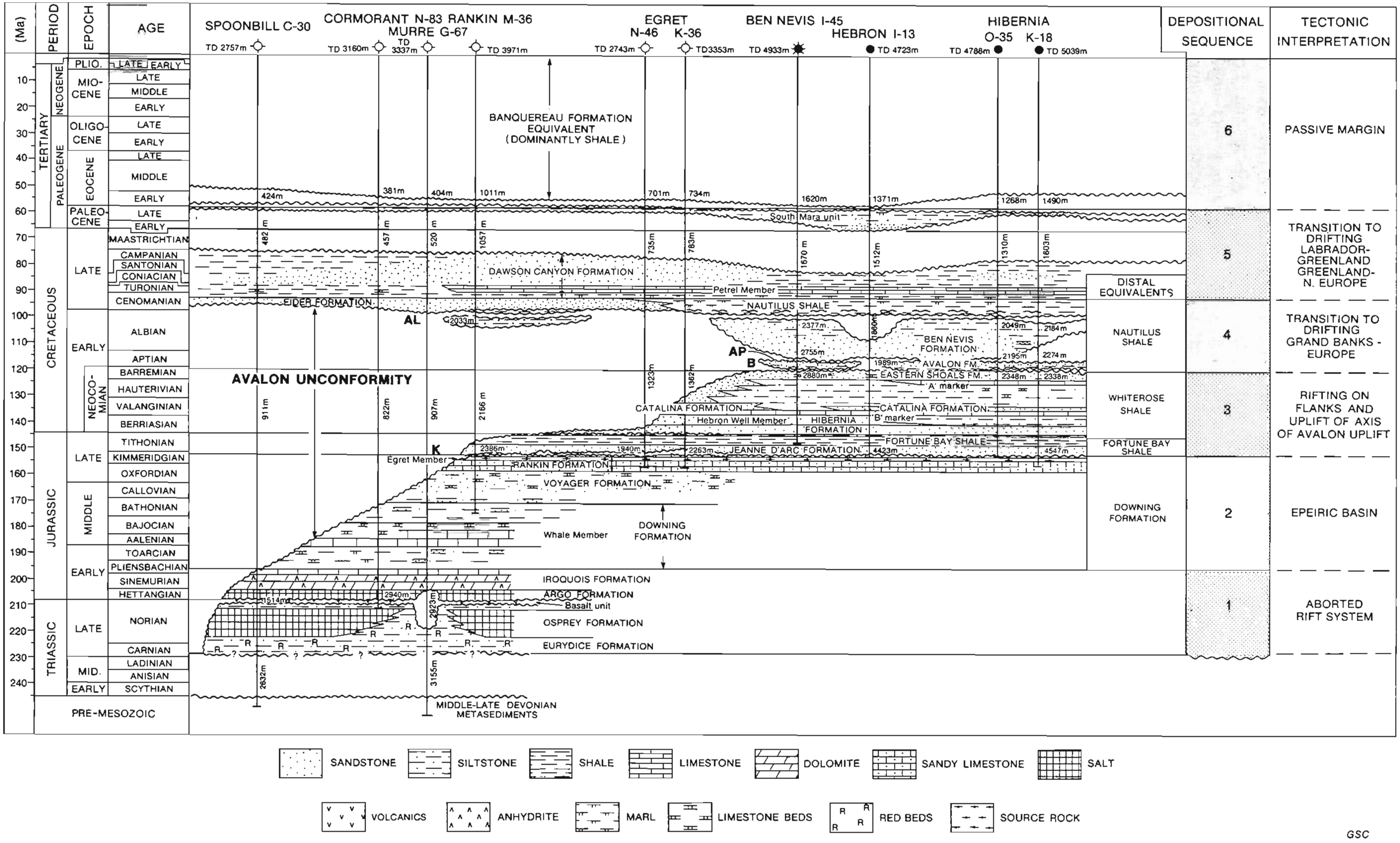

Figure 6. Time-stratigraphic section of the Jeanne d'Arc Basin showing lithostratigraphic framework and major depositional sequences. Well locations in Figure 3. The numbers beneath wells at stratigraphic hiatuses are depths in metres where these breaks were encountered. The Avalon Unconformity, a prominent peneplain buried beneath the central Grand Banks, records the net effect of at least four erosional events that are identified by well and seismic data. The ages of these events are Kimmeridgian(K), late Barremian(B), late Aptian(AP), and late Albian-Cenomanian(AL).

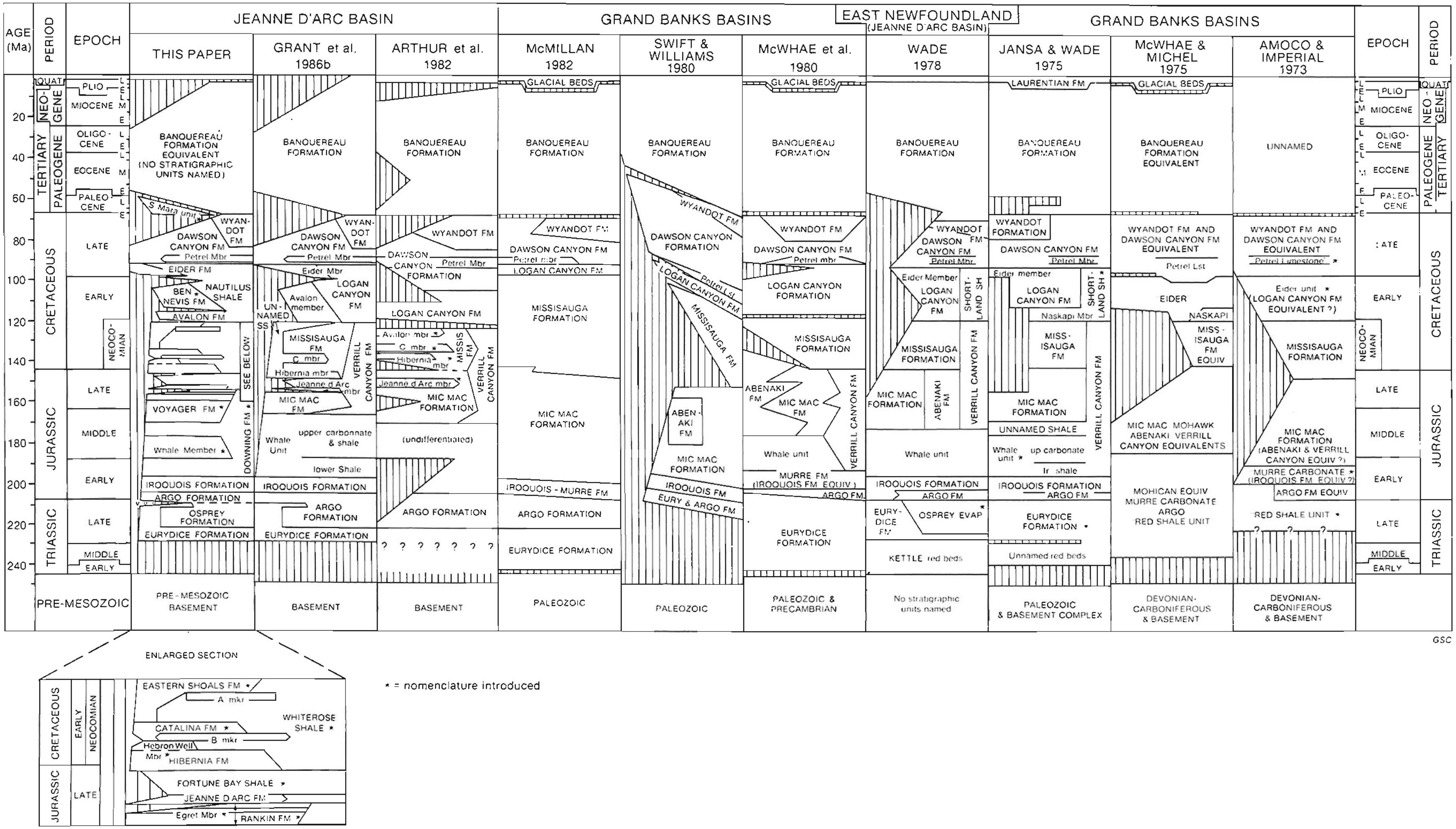

Figure 7. Comparison of stratigraphic terminology applied to the Mesozoic-Cenozoic section on the Grand Banks by various authors. See Figure 8 for details of stratigraphy proposed in this paper.

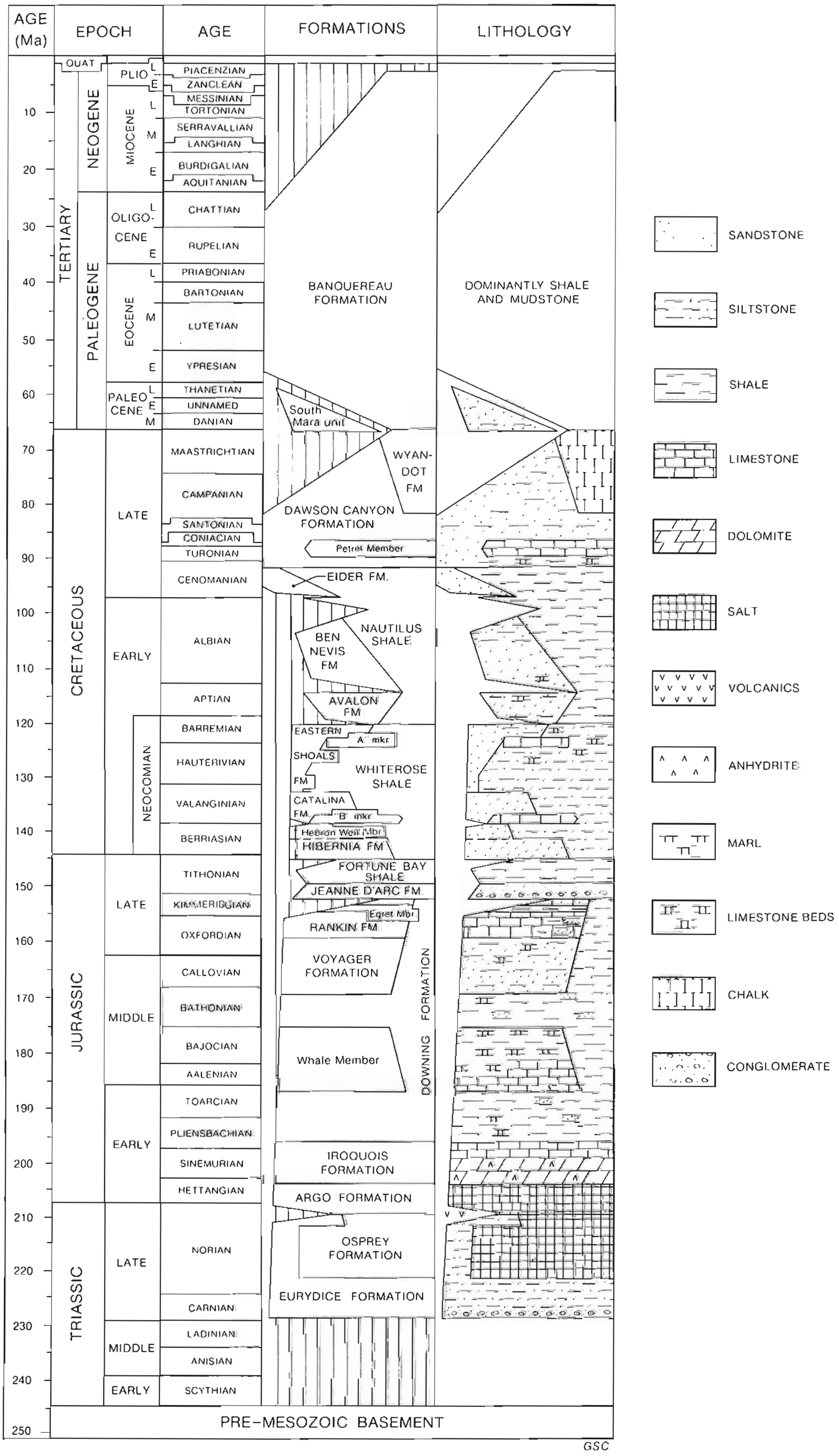

Figure 8. Lithostratigraphic chart for the Jeanne d'Arc Basin.

Table 1. Well type sections and well reference sections defined in this paper and technical details of the relevant wells.

Lithostratigraphic Unit	Type Section	Reference Section
Nautilus Shale	Mobil et al. Nautilus C-92 2668-3285 m	
Eider Formation	Amoco-IOE A-1 Eider M-75 708-830 m	Mobil et al. Rankin M-36 1582-1730 m
Ben Nevis Formation	Mobil et al. Ben Nevis I-45 2377-2755 m	
Avalon Formation	Mobil et al. Ben Nevis I-45 2755-2880 m	
Whiterose Shale	Husky-Bow Valley et al. Whiterose N-22 2728-3357 m	
Eastern Shoals Formation	Mobil et al. Ben Nevis I-45 2880-2981 m	Mobil et al. Hibernia G-55 2574-3389 m
"A" Marker	Chevron et al. Hibernia P-15 2506-2514 m	
Catalina Formation	Chevron et al. Hibernia P-15 3211-3418 m	Mobil et al. Hibernia O-35 3130-3300 m Petro-Canada et al. Terra Nova K-08 2264-2385 m
"B" Marker	Mobil et al. Ben Nevis I-45 3804-3909 m	
Hebron Well Member	Mobil et al. Hebron I-13 2887-3098 m	
Hibernia Formation	Mobil et al. Hibernia K-14 3839-4062 m	Mobil et al. Hebron I-13 2887-3490 m
Fortune Bay Shale	Petro-Canada et al. Terra Nova K-18 2840-3050 m	
Jeanne d'Arc Formation	Petro-Canada et al. Terra Nova K-18 3050-3413 m	
Egret Member	Mobil et al. Rankin M-36 2436-2491 m	Husky-Bow Valley et al. Trave E-87 3046-3120 m
Rankin Formation	Mobil et al. Rankin M-36 2386-3144 m	Husky-Bow Valley et al. Trave E-87 2844-3775 m
Voyager Formation	Mobil et al. Rankin M-36 3144-3752 m	Husky-Bow Valley et al. Voyager J-18 3246-3743 m (T.D.)
Whale Member	Amoco-IOE A-1 Murre G-67 1817-2008 m	
Downing Formation	Amoco-IOE A-1 Murre G-67 1245-2586 m	
Iroquois Formation		Amoco-IOE A-1 Murre G-67 2586-2923 m
Argo Formation		Amoco Imperial Skelly Spoonbill C-30 1263-1514 m
Osprey Formation	Amoco Imperial Skelly Osprey H-84 1692-3306 m	Amoco Imperial Skelly Spoonbill C-30 1652-2534 m
Eurydice Formation		Amoco-IOE A-1 Murre G-67 2923-3155 m

Well Name	Latitude (North)	Longitude (West)	Date of Rig Release	Rotary Table (m)	Water Depth (m)	Total Depth (m)
Ben Nevis I-45	46°34'39.74"	48°21'09.84"	09/10/1980	26.82	101.18	4932.00
Eider M-75	45°34'54.97"	51°56'41.52"	07/09/1971	29.90	77.70	3530.20
Hebron I-13	46°32'33.95"	48°31'45.47"	09/13/1981	27.30	94.00	4723.00
Hibernia G-55	46°44'17.07"	48°53'10.75"	02/24/1981	29.70	76.50	3460.00
Hibernia K-14	46°43'39.83"	48°47'36.18"	01/15/1984	32.90	78.90	4462.00
Hibernia O-35	46°44'54.92"	48°49'53.74"	07/13/1980	24.00	80.00	4788.00
Hibernia P-15	46°44'58.98"	48°46'51.18"	01/07/1980	11.30	80.20	4407.00
Murre G-67	46°06'20.40"	49°09'38.20"	09/20/1971	29.90	64.60	3337.30
Nautilus C-92	46°51'03.55"	48°44'20.64"	07/16/1982	27.40	84.40	5115.00
Osprey H-84	44°43'28.79"	49°27'22.92"	08/16/1973	25.90	61.30	3473.80
Rankin M-36	46°35'46.58"	48°50'56.26"	08/06/1983	26.80	72.40	3971.00
Spoonbill C-30	45°49'06.47"	49°04'06.18"	10/15/1973	29.90	65.20	2757.20
Terra Nova K-08	46°27'31.60"	48°30'59.60"	06/11/1984	25.00	94.50	4500.00
Terra Nova K-18	46°27'44.05"	48°32'31.58"	11/25/1984	24.30	91.40	3925.00
Trave E-87	46°56'17.56"	47°58'09.74"	06/26/1984	25.00	138.00	3988.00
Voyager J-18	46°27'32.50"	48°17'00.49"	06/12/1984	27.40	101.00	3744.30
Whiterose N-22	46°51'47.99"	48°03'56.51"	01/05/1985	27.40	122.00	4633.50

All unit boundaries provided in this table and throughout the text are gamma-ray/sonic log depths related to Rotary Table datum.

Well sample materials are stored at the:
Canada-Newfoundland Offshore Petroleum Board
Core Storage and Research Centre
St. John's, Newfoundland

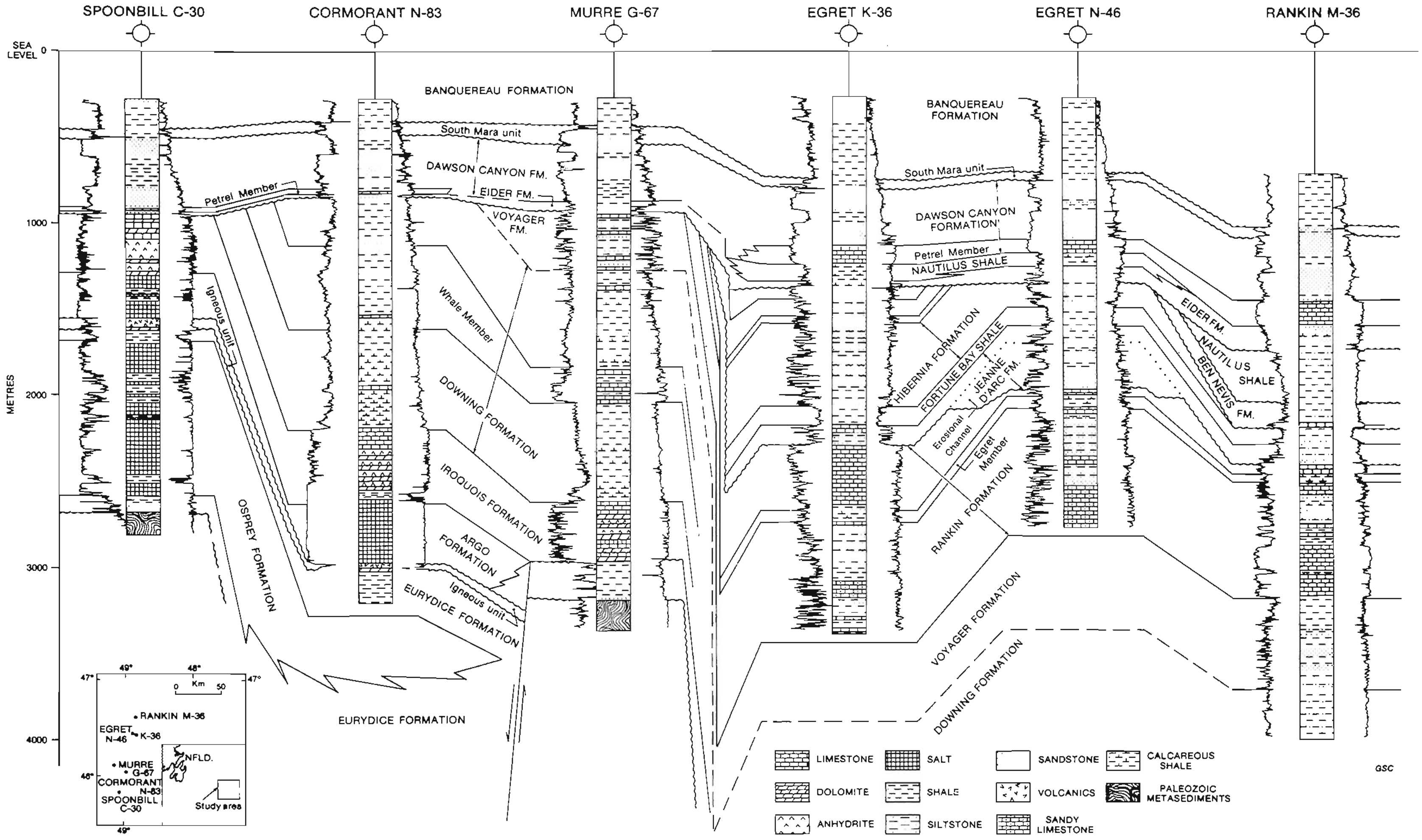

Figure 9. Gamma-ray/sonic log and lithostratigraphic correlation from Spoonbill C-30 to Rankin M-36. The Egret Fault between Murre G-67 and Egret K-36 has an actual throw of over 2 km (see Fig. 4).

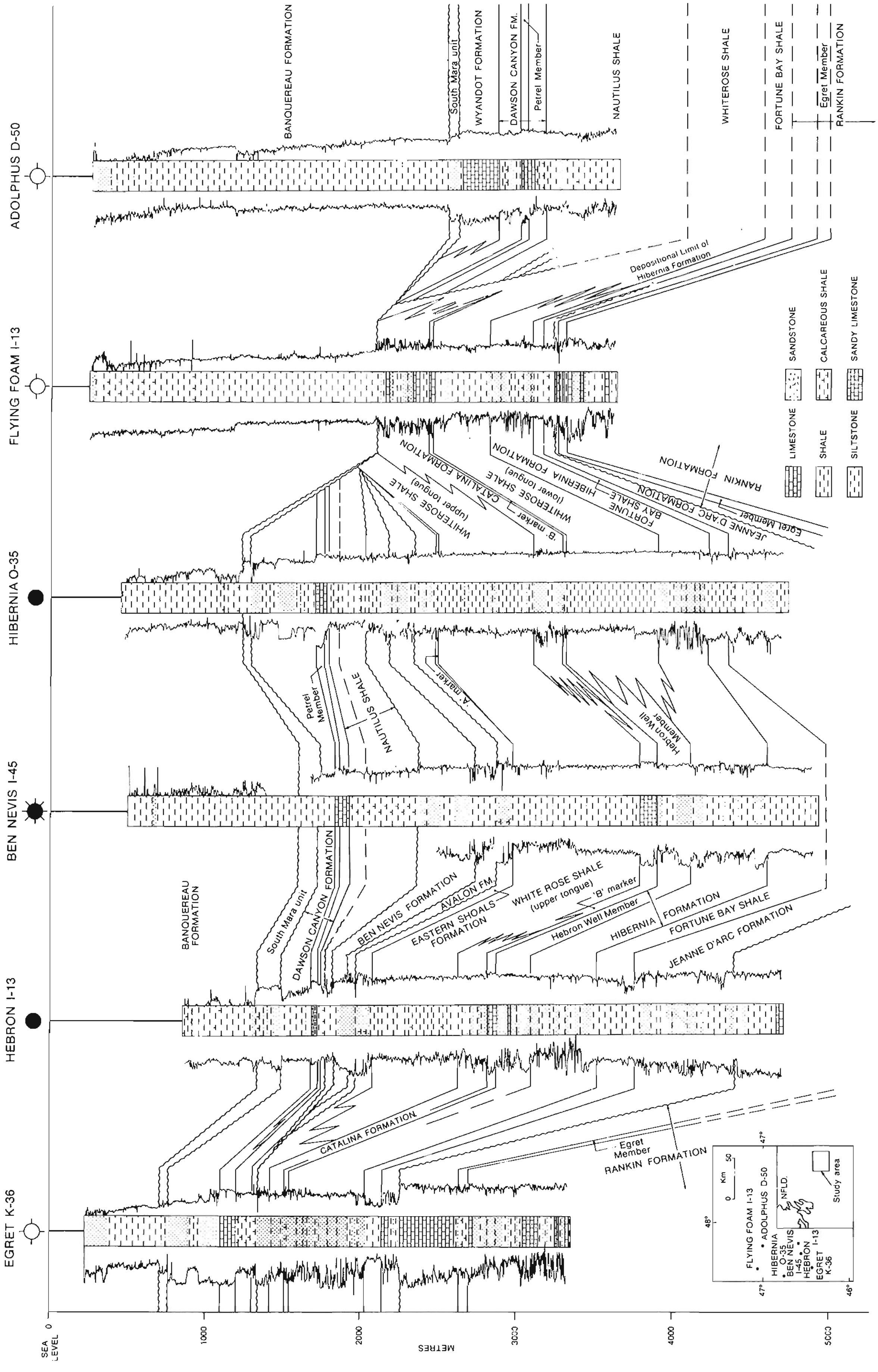

Figure 10. Gamma-ray/sonic log and lithostratigraphic correlation from Egret K-36 to Adolphus D-50.

Eurydice Formation, range extended from Jansa and Wade (1975)

FIGURE 11

Name — Jansa and Wade (1975) formally named this base Mesozoic red clastic sequence after its type section at the Shell Eurydice P-36 well location in the Orpheus Graben on the Scotian Shelf. It is proposed here to extend the range of the formation to the Jeanne d'Arc Basin.

Well type section — Shell Eurydice P-36 from 2393 to 2965 m (T.D.), more than 572 m thick, was proposed as the type section by Jansa and Wade (1975).

Well reference section — Amoco and Imperial (1973) and Jansa and Wade (1975) recognized a lithologically similar unit in the Amoco-IOE A-1 Murre G-67 well from 2923 to 3155 m, 232 m thick. It is here designated the reference section for the Jeanne d'Arc Basin (Fig. 11, Table 1).

Lithology — The type section was described by Jansa and Wade (1975). There, it is dominated by reddish siltstones and shales containing scattered anhydrite nodules and rare feldspathic sandstones. In the reference section, a thin basal conglomerate contains pebbles derived from older sedimentary and low-grade metamorphic rocks. The remainder of the section consists of reddish-brown silty shales and argillaceous siltstones. The upper 90 m contains anhydrite, probably in nodules and veins, and becomes calcareous toward the top.

Boundaries — The Eurydice Formation marks the base of the Mesozoic section in the Jeanne d'Arc Basin. At the Murre G-67 well the Eurydice Formation overlies metasediments of Middle to Late Devonian age (Barss et al., 1979) with a marked unconformity. Regionally, the Eurydice Formation interfingers with salt of the overlying Osprey and Argo formations (Fig. 9). In wells, the top of the formation is taken as the base of the lowest massive salt of the Osprey or Argo. Salt is absent at Murre G-67 due to withdrawal or nondeposition, and the formation is abruptly overlain by a carbonate-evaporite sequence, the Iroquois Formation.

Distribution — Only two other wells have encountered the Eurydice Formation in the Jeanne d'Arc Basin. Spoonbill C-30 penetrated a 98 m thick (2534-2632 m) mixed sequence of red siltstones, shales, and sandstones overlying low-grade metasediments of undetermined age. An 87 m thick red shale unit (1565-1652 m) within the salt sequence at Spoonbill is assigned also to the Eurydice Formation and correlated to a 185 m thick (2975-3160 m T.D.) red shale unit at the bottom of the Cormorant N-83 well (Fig. 9).

Age — Carnian-Norian to Rhaetian based on rare palynomorphs that have been recovered from the red beds at Cormorant N-83 and Spoonbill C-30 (Barss et al., 1979). The Rhaetian stage is incorporated within the upper part of the Norian stage in the chronostratigraphic scale used here (Palmer, 1983).

Depositional environment — The Eurydice Formation contains traces of anhydrite, exhibits hematite matrix pigmentation, and lacks marine fossils. Accordingly, it was probably deposited under arid climatic conditions in a continental environment. The generally fine grained nature of the clastics at the reference section suggests little depositional relief.

Remarks — Red clastics of similar age and lithostratigraphic position were encountered in several wells drilled in other Grand Banks basins as well as the Scotian Basin. Because these red beds are thought to represent the initial sedimentary deposits in a large and formerly contiguous Triassic rift system, and although their mappability cannot be demonstrated now, the name Eurydice Formation is extended to the Grand Banks in preference to a proliferation of stratigraphic terms, e.g. the Kettle red beds of Jansa et al. (1977) and Jansa et al. (1980).

Osprey Formation, new and restricted from Jansa et al. (1977)

FIGURES 12 AND 13

Name — Osprey evaporites was an informal name given by Jansa et al. (1977) to a 2054 m thick (1252-3306 m) halite-rich evaporite sequence in the Amoco Imperial Skelly Osprey H-84 well in the Carson Basin. The unit is here given formation rank and restricted to the lower three subunits of the four-part subdivision of Jansa et al. (1977). The upper subdivision is assigned to the Argo Formation.

Well type section — Amoco Imperial Skelly Osprey H-84 from 1692 to 3306 m, 1614 m thick, is designated the type section (Fig. 12, Table 1).

Well reference section — Amoco Imperial Skelly Spoonbill C-30 from 1652 to 2534 m, 882 m thick, is designated the reference section for the Jeanne d'Arc Basin (Fig. 13, Table 1).

Lithology — At the type section the formation consists of halite (approximately 70 percent) interbedded with reddish shale (approximately 30 percent). Minor dolomitic mudstone, siltstone, and rare sandstone beds also occur. Traces of anhydrite are present as small nodules. The halite is often pinkish due to the presence of argillaceous impurities. The reference section comprises similar lithologies in almost identical ratios. Preliminary geochemical evidence suggests that the Osprey salt has a distinctively low bromide concentration (Jansa et al., 1980; Holser et al., 1988). The bromide content varies from <20 to 90 ppm and the higher values occur near the top of the formation. By contrast, the bromide concentration of the overlying Argo Formation salt shows cyclicity and values oscillate between 50 and 240 ppm (ibid.).

Boundaries — The base of the formation is taken as the base of the lowest massive salt that is in abrupt contact with underlying Eurydice Formation clastics. Red shales are commonly intercalated with the salt and indicate that the lower contact is conformable. The Osprey Formation is unconformably overlain by the Argo Formation at the type section, based on seismic evidence, and is probably in intercalated contact with a tongue of the Eurydice Formation at the reference section (Fig. 6 and 9).

Distribution — The Osprey Formation is known only in the Grand Banks Mesozoic basins. The regional extent of the formation is difficult to establish because most Grand Banks wells encountered salt in salt flowage structures that have disrupted internal relationships. This causes problems in separating the Osprey salt from overlying Argo salt. Although both the Osprey and Argo formations are halite-rich, the Osprey generally contains more argillaceous interbeds and the halite tends to be darker coloured due to impurities. Bedded anhydrite and dolomite are much less common in the Osprey Formation. The low bromide content of the Osprey salts is a distinctive geochemical characteristic. Based on lithology, age, geochemistry, and seismic evidence, the Osprey Formation has been identified in only four wells on the Grand Banks : Coot K-56 (3258-3507 m) and Sandpiper 2J-77 (2513-2946 m) in the Whale Basin, Osprey H-84 in the Carson Basin, and Spoonbill C-30 in the Jeanne d'Arc Basin. While these widely distri-

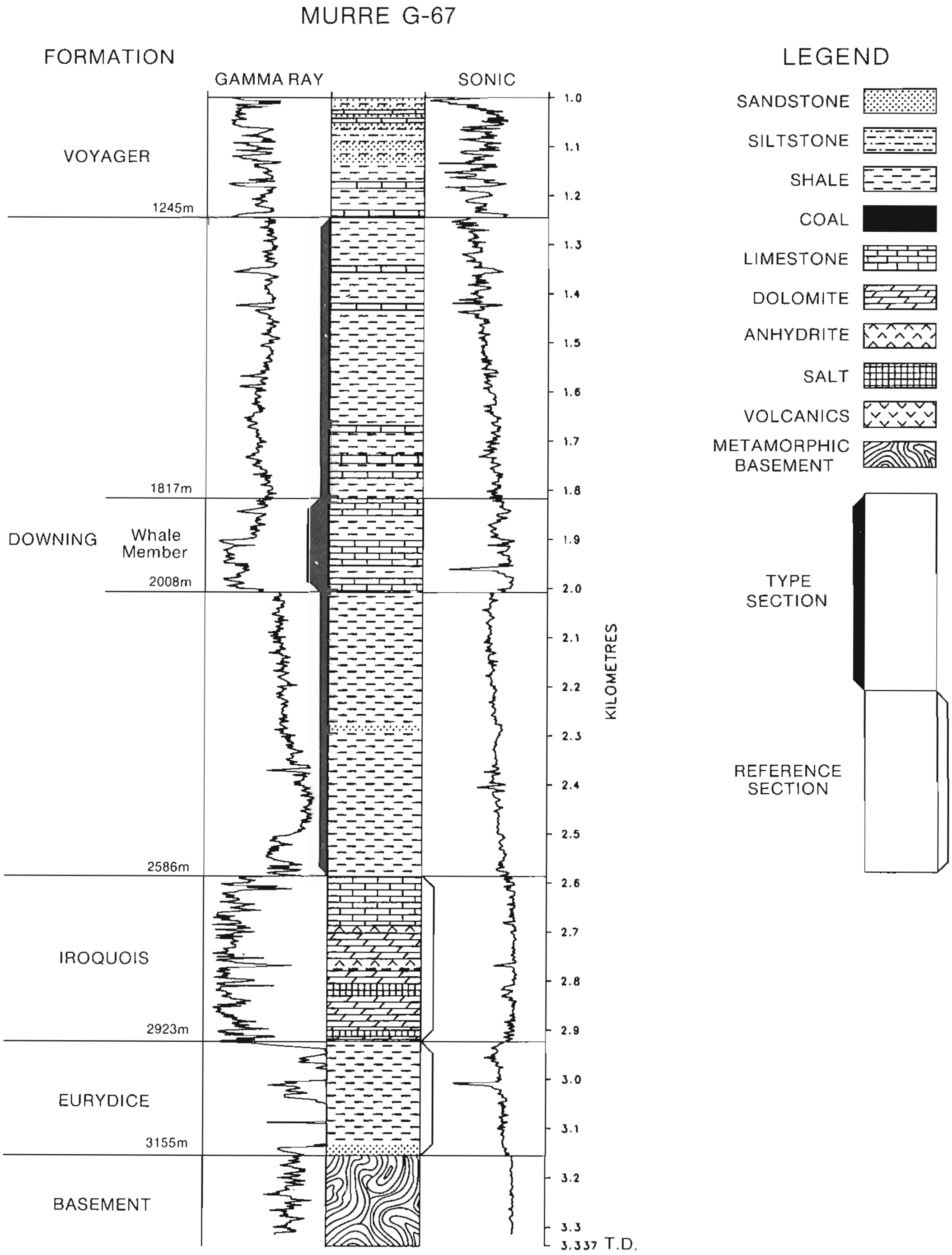

Figure 11. Gamma-ray/sonic log and lithostratigraphy of Murre G-67 well. Well type section for Downing Formation and Whale Member. Well reference section for Eurydice and Iroquois formations. Legend applies also to Figures 12 through 27.

buted occurrences cannot be correlated with certainty between diapiric structures and between basins, the evidence suggests they may have been deposited in a large, formerly contiguous depositional basin. In the southern part of the Jeanne d'Arc Basin, the Osprey evaporites can be differentiated seismically from the younger Argo evaporites by an intervening thin, highly-reflective sequence taken to be a series of subaerial basalt flows. The basalts were encountered in the Cormorant N-83 and Spoonbill C-30 wells (Fig. 9). In the northern part of the basin, seismic definition is precluded because of limitations on seismic penetration caused by great depth and salt flowage.

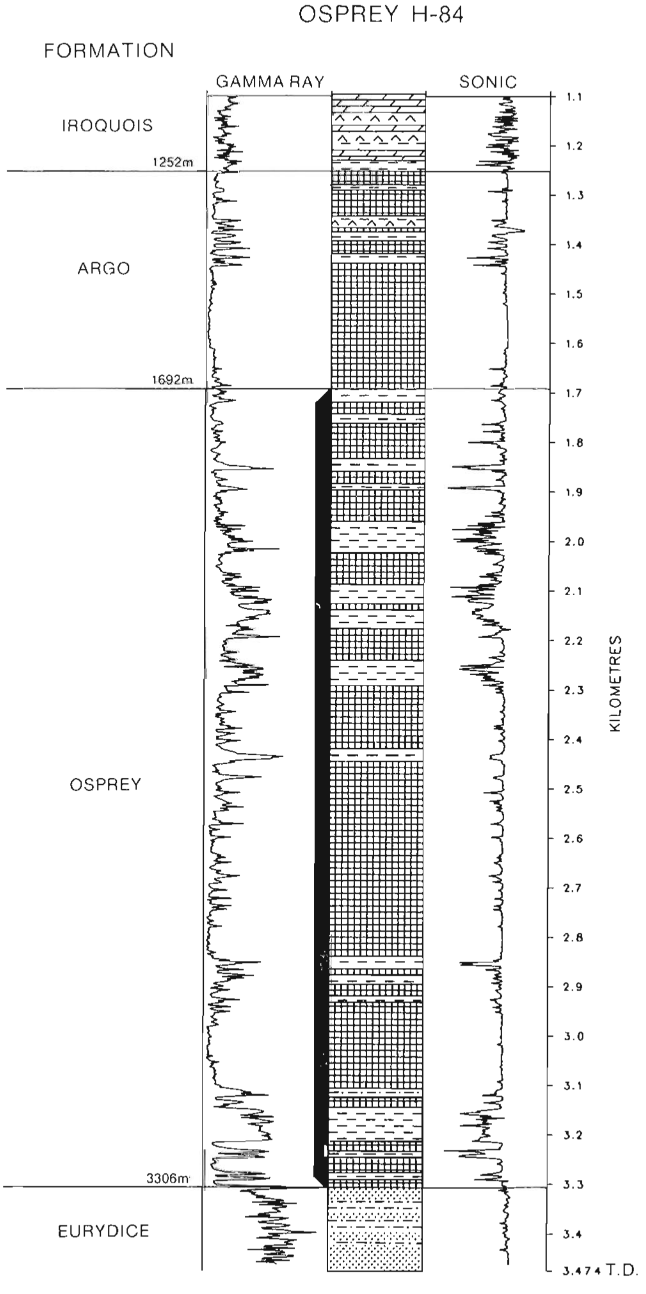

Figure 12. Gamma-ray/sonic log and lithostratigraphy of Osprey H-84 well. Well type section for Osprey Formation. Legend as in Figure 11.

Age — Carnian-Norian to Rhaetian-early Hettangian, based on palynomorphs that have been identified in the intercalated shales in all recognized occurrences of the Osprey salt (Barss et al., 1979). The Rhaetian stage is incorporated within the upper part of the Norian stage in the chronostratigraphic scale used here (Palmer, 1983).

Depositional environment — The environmental conditions that lead to the deposition of thick salt sequences are not well understood because of the lack of modern analogues. Important environmental indicators for the Osprey salt are the paucity of marine palynomorphs, the presence of intercalated reddish nonmarine shales, the deficiency of bedded anhydrite and carbonates, and the very low bromide concentrations. Jansa et al. (1980) proposed a lateral-fractionation depositional model to explain the lack of sulphates in the Osprey Formation evaporite sequence. They postulated that a system of carbonate shoals separated the site of halite deposition from the Tethys Sea to the west and that only brine already depleted in calcium ions and sulphates reached the Grand Banks area. Holser et al. (1988) suggested a dominantly nonmarine input and conclu-

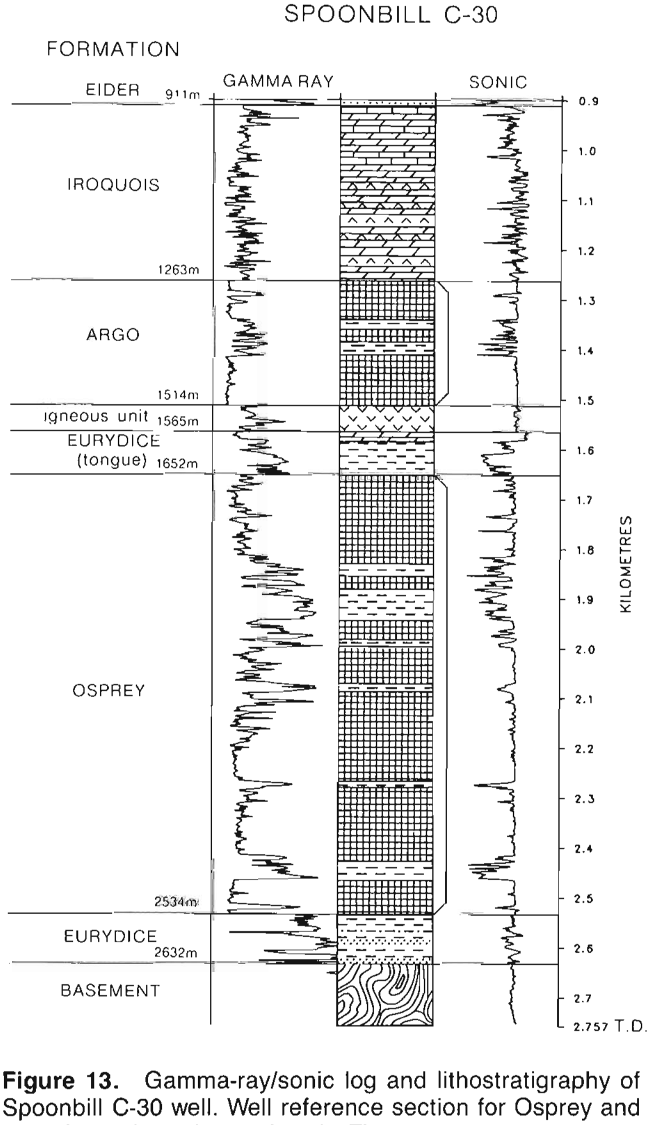

Figure 13. Gamma-ray/sonic log and lithostratigraphy of Spoonbill C-30 well. Well reference section for Osprey and Argo formations. Legend as in Figure 11.

ded that access to the Tethys Sea must have been minimal. In addition, they suggested that second-cycle salt from Paleozoic evaporites must be considered as a possible source for the halite.

Argo Formation, range extended from McIver (1972)

FIGURE 13

Name — McIver (1972) named the thick sequence of mobile salt in the Scotian Basin after the Shell Argo F-38 well. Amoco and Imperial (1973), Jansa and Wade (1975), Arthur et al. (1982), and several other authors have used this name for the entire Mesozoic salt sequence in the Grand Banks. It is proposed here that the name be restricted to the upper part of the thick salt sequence in the Jeanne d'Arc Basin.

Well type section — Shell Argo F-38 from 2305 to 3085 m, 780 m thick, was designated the type section by Wade (1976).

Well reference section — Amoco Imperial Skelly Spoonbill C-30 from 1263 to 1514 m, 251 m thick, is here designated the reference section for the Jeanne d'Arc Basin (Fig. 13, Table 1).

Lithology — At the type section the Argo Formation consists of massive beds of coarsely crystalline halite separated by thinner beds of impure salt and reddish dolomitic or anhydritic shale and beds of argillaceous microcrystalline dolomite. At the Spoonbill C-30 and Cormorant N-83 wells (Fig. 6 and 9), the formation is mostly massive salt, colourless to light pink, but includes minor thin intercalations of grey, green, and red shale and anhydritic dolomite. The Argo Formation is generally distinguishable from the underlying Osprey Formation by overall lithological aspect. The Argo Formation tends to be of lighter colour due to less argillaceous impurities and to contain fewer and thinner shale intercalations, but more dolomite beds. Where geochemical analyses are available, the Argo Formation shows higher and more cyclic bromide concentrations than the Osprey Formation (Holser et al., 1988).

Boundaries — In the Jeanne d'Arc Basin, the base of the Argo Formation is placed at the base of the first massive salt that overlies abruptly and probably unconformably a thin igneous unit in the Spoonbill C-30 and Cormorant N-83 wells. The Argo Formation is overlain conformably and gradationally by the carbonate-dominated Iroquois Formation. The top is placed at the top of the uppermost massive salt.

Distribution — The Argo Formation is more widespread than the Osprey evaporites. Its known range extends from the southern Scotian Shelf to the northern Grand Banks. In the Jeanne d'Arc Basin the Spoonbill C-30 and Cormorant N-83 were the only wells that encountered relatively undisturbed Argo salt; however, a fault sliver at the base of the Hibernia I-46 well contained thin beds of salt in a red bed and dolomite sequence that has been dated palynologically as Sinemurian (E.H. Davies, pers. comm., 1984). This age indicates that these beds may belong to the Argo Formation or, possibly, to the lower part of the Iroquois Formation which also may contain thin salt beds. Undated diapiric salt encountered by the Adolphus 2K-41 well may also be part of the Argo Formation (Fig. 3).

Seismic data indicate that salt is widespread at the base of the Mesozoic section in the Jeanne d'Arc Basin and underlies much of the Outer Ridge Complex (Fig. 4 and 5). Nevertheless, the great depth of the salt and the consequent paucity of well data and poor seismic definition does not permit differentiation between the Argo and Osprey salts over much of the area.

Age — The palynological age of the Argo Formation is late Hettangian to early Sinemurian at the type section, and Rhaetian-early Hettangian to late Hettangian-early Sinemurian at the reference section (Barss et al., 1979). The Rhaetian stage is incorporated within the upper part of the Norian stage in the chronostratigraphic scale used here (Palmer, 1983).

Depositional environment — By lithological and geochemical comparison to the Osprey salt, the Argo salt was deposited in slightly deeper water, farther from terrestrial input, and more often interrupted by normal marine conditions. The Argo's wide regional distribution suggests that it extended beyond the range of the Osprey salts which were probably deposited in the axial areas of developing graben.

Iroquois Formation, range extended from McIver (1972)

FIGURE 11

Name — Amoco and Imperial (1973) gave the informal name Murre carbonate to a widespread, Lower Jurassic carbonate-evaporite sequence on the Grand Banks, encountered at the Murre G-67 well between about 2586 and 2923 m; they tentatively correlated it to the Iroquois Formation (McIver, 1972) on the Scotian Shelf because of its similar age and lithology. Jansa and Wade (1975) considered the Murre carbonate to be an extension of the Iroquois Formation and retained the Scotian Shelf name. The carbonate-evaporite sequence on the Grand Banks is certainly homotaxial to the Iroquois Formation, although biostratigraphic data indicate that it may be one or two stages older in the Jeanne d'Arc Basin (late Hettangian-early Pliensbachian) than in the western Grand Banks or Scotian Shelf (Pliensbachian-Toarcian). Nevertheless, the name Iroquois Formation is retained here.

Well type section — Shell Iroquois J-17 from 1805 to 2044 m, 239 m thick, was designated the type section of the Iroquois Formation by McIver (1972).

Well reference section — Amoco-IOE A-1 Murre G-67 from 2586 to 2923 m, 337 m thick, is here designated the reference section for the Jeanne d'Arc Basin (Fig. 11, Table 1).

Lithology — Generally the Iroquois Formation exhibits a typical stratigraphic succession of interbedded evaporites and dolomite, overlain by dolomite which is overlain by limestone. At the reference section the Iroquois Formation can be divided into three subunits (Jansa et al., 1976). The lower subunit (2810-2923 m) consists of locally anhydritic, microcrystalline dolomite, rare beds of dolomitized pelloidal wackestone, oolitic grainstone and dark grey shale, and several halite beds. The middle subunit (2687-2810 m) is similar in composition to the lower one but lacks halite. The upper subunit (2586-2687 m) consists of micritic limestone, skeletal and oolitic limestone, and pelloidal lime packstone.

Boundaries — The base of the Iroquois Formation is placed at the top of the uppermost massive salt of the Argo Formation which it overlies gradationally and conformably. At the type section it is in sharp basal contact with the Eurydice Formation, probably because of salt withdrawal. The boundary with the overlying Downing Formation shale is apparently gradational and conformable at the Murre G-67 and Cormorant N-83 wells. The contact is picked on mechanical logs at the top of the clean massive limestone section. Regional seismic profiles show that the upper contact is locally unconformable as a result of early salt movement.

Distribution — The Iroquois Formation has been encountered in numerous wells from Georges Bank (COST G-2 well), across the Scotian Shelf to the Grand Banks basins (see Fig. 1). Well data and seismic evidence indicate it is virtually ubiquitous above the salt sequence on the Grand Banks. The lithological composition varies according to position in the originally contiguous depositional system. For instance, at the Coot K-56 well in the Whale Basin, a thin unit (2253-2281 m) of anhydritic dolomite overlies Argo salt, whereas at the Bittern M-62 well in the Horseshoe Basin, thick (3467-4697 m) massive microcrystalline argillaceous limestone with minor dolomite and a few basal anhydrite beds overlies Osprey salt. In the Jeanne d'Arc Basin, only the Spoonbill C-30 (911-1263 m, top eroded), Cormorant N-83 (2161-2590 m), and Murre G-67 (reference section) wells encountered a normally stratified sequence of the Iroquois Formation (Fig. 6 and 9). The Hibernia I-46 well may have bottomed in an Iroquois equivalent that underlies with abrupt unconformable or faulted contact a Lower Cretaceous clastic sequence.

Age — Pliensbachian to Toarcian in the Scotian Basin according to Wade and MacLean (in press). The palynological age at the reference section is late Hettangian-early Sinemurian to Pliensbachian (Barss et al., 1979).

Depositional environment — The sequence of dolomite-halite-anhydrite, succeeded by dolomite-anhydrite and finally limestone, encountered at the reference section, is typical of the vertical and lateral lithofacies variations observed regionally in the Iroquois Formation. These rocks indicate a succession of environments which are interpreted to record a gradual marine transgression over the Grand Banks. According to Jansa and Wade (1975), these environments are hypersaline, semi-restricted lagoons and tidal flats followed by shallow-marine lagoons to inner-shelf conditions and, finally, a shallow to moderately deep epicontinental sea. Algal-laminated anhydrites displaying "chicken wire" structure and algal-laminated dolomites, observed in a conventional core taken at the Cormorant N-83 well, were probably deposited in a tidal flat environment.

Downing Formation, new

FIGURE 11

Name — From the Downing Basin, a prominent bathymetric depression on the northwestern Grand Banks. The Downing Formation corresponds to the informal Whale unit plus an unnamed upper Middle Jurassic shale (Fig. 7) both defined by Jansa and Wade (1975), and is equivalent to the Whale unit of Jansa et al. (1976). The Whale unit (sensu Jansa et al., 1976) is here given formation rank and renamed the Downing Formation. The name Whale is retained for a carbonate member within the formation.

Well type section — Amoco-IOE A-1 Murre G-67 from 1245 to 2586 m, 1341 m thick, is here designated the type section (Fig. 11, Table 1).

Lithology — The Downing Formation is a thick monotonous unit dominated by silty and marly grey shale with interbedded limestone and minor fine grained sandstone. Overall, it exhibits a gross lithofacies pattern consisting of a lower shale, a middle limestone, and an upper shale. The relative development of these facies varies regionally, and lithostratigraphic boundaries are probably diachronous within the formation.

The type section is described by Jansa et al. (1976) although with slightly different boundaries (1140-2577 m). The lower shale unit (2008-2586 m) consists predominantly of medium to dark grey, calcareous and silty shale with local thin beds of calcareous glauconitic siltstone and micritic limestone. Macrofossil and coalified plant fragments and siderite nodules are common minor constituents. The basal 80 m of the interval is composed of interbedded argillaceous skeletal packstone, marlstone, and shale and is a zone of transition from the underlying limestones of the Iroquois Formation.

The middle limestone unit (1817-2008 m), later defined as the Whale Member, is dominated by light grey to white, skeletal-pelletoidal grainstones and wackestones and thinner beds of oolitic grainstones and intraclast-bioclast packstones. The limestones are interbedded with light grey, light brownish-grey, and locally reddish-brown calcareous shale, light grey siltstone, and locally fine grained calcareous sandstone. The contact between this unit and the upper shale unit is sharp and is marked by a breccia of reworked oolitic grainstone intraclasts in an argillaceous matrix.

The upper shale unit (1245-1817 m) consists of massive grey calcareous shale containing local beds of grey marlstone, calcareous siltstone, and fine grained argillaceous and calcareous sandstone. A few beds of light brown sandy and argillaceous algal oncolite-intraclast grainstone/wackestone and skeletal-pelletoidal packstone/wackestone occur within the sequence.

At the nearby Cormorant N-83 well the Downing Formation (822-2161 m; top eroded) does not contain well-developed limestones, and the middle limestone unit (1103-1516 m) is represented by grey to reddish-brown calcareous and silty shale with subordinate calcareous siltstone, very fine grained calcareous sandstone and marlstone, and rare pelletoidal wackestone (Fig. 9).

Boundaries — The lower contact with the Iroquois Formation is discussed above with that formation's boundaries. The upper contact is gradational and conformable with the overlying Voyager Formation. The boundary is often identified on the sonic log as a break between the overall fining upward, upper shale unit of the Downing Formation and the higher velocity interbedded sandstone, shale, and limestone of the Voyager Formation. The upper shale unit of the Downing Formation is considered to be the lateral distal equivalent of both the Voyager and Rankin formations, but this has not yet been observed in wells.

Distribution — The formation has been penetrated by only four wells in the Jeanne d'Arc Basin area : Murre G-67 (type section), Cormorant N-83, Golconda C-64 from 3055 to 4451 m (T.D.), and Rankin M-36 from 3752 to 3967 m (T.D.). Nevertheless, it is a widespread deposit, occurring throughout the Grand Banks ; for example, Carson Basin in Skua E-41 from 2338 to 3239 m (T.D.), Horseshoe Basin in Bittern M-62 from 1897 to 3467 m, and Whale Basin in Eider M-75 from 1932 to 3530 m (T.D.).

Age — The palynological age has been reported as Pliensbachian to Oxfordian-early Kimmeridgian at the type section (Barss et al., 1979). Regional seismic data, however, indicate that the formation may range no younger than Middle Jurassic at that location. It is interpreted to be generally Pliensbachian to Bathonian in age (except where it becomes the basinal facies equivalent of the Voyager and Rankin formations) and may range as young as Kimmeridgian.

Depositional environment — Paleoenvironmental data indicate that the Downing Formation was deposited during a prolonged marine transgression over the Grand Banks area (Jansa and Wade, 1975 ; Jansa et al.,1976 ; Barss et al.,1979). Generally progressive deepening of the marine environment was interrupted by periods of shallowing recorded by the presence of skeletal and oolitic limestones, especially in the middle limestone unit (Whale Member). The absence of coarse clastics suggests a period of tectonic quiescence when a distant shoreline bordered a low-lying hinterland. It is not clear whether the Avalon Uplift was a positive feature during this time. The presence of thick, limestone-rich Early and Middle Jurassic intervals at Heron H-73 and Bittern M-62, in the South Whale and Horseshoe basins, and the absence of equivalent age strata at Twillick G-49 and Jaeger A-49 suggest that a land mass or a shallower region may have existed in the area of the present South Bank High (Fig. 2).

Subdivisions — As noted above, the formation can be subdivided into three lithological units. Only the middle limestone unit, the Whale Member, is named here.

Whale Member, new and restricted from Jansa and Wade (1975)

FIGURE 11

Name — From the informal Whale unit introduced by Jansa and Wade (1975) and modified by Jansa et al. (1976) to designate the Early and Middle Jurassic shale-limestone sequence (Downing Formation) penetrated at Murre G-67. The middle limestone-rich unit of the Downing Formation is here designated the Whale Member.

Well type section — Amoco-IOE Murre G-67 from 1817 to 2008 m, 191 m thick, is designated the type section (Fig. 11, Table 1).

Lithology — As described above for the middle limestone unit of the Downing Formation.

Boundaries — The lower and upper contacts with more argillaceous units of the Downing Formation are generally gradational and conformable. They are easily picked on the gamma-ray and sonic logs when adjacent units are dominantly shale (e.g. Murre G-67, Skua E-41, 2814-2832 m, and Eider M-75, 2624-3005 m) or may be difficult to pick when adjacent units are more limy (e.g. Bittern M-62, 2646-2679 m).

Distribution — Similar to that of the entire Downing Formation. In the Jeanne d'Arc Basin, the Whale Member has been penetrated as a well-developed limestone unit only at the type section and at Golconda C-64 from 3707 to 3802 m. Nevertheless, the top of the Whale Member provides a good regional seismic marker within the Downing Formation showing that the member has wide distribution, not only in the Jeanne d'Arc Basin, but throughout the Grand Banks.

Age — Toarcian to Bajocian, by palynology, at the type section (Barss et al., 1979).

Depositional environment — As described above for the middle limestone unit of the Downing Formation.

Voyager Formation, new

FIGURES 14 and 15

Name — From the Husky-Bow Valley et al. Voyager J-18 well where the formation is well developed, but not fully penetrated. The Voyager Formation corresponds to the lower part of the Mic Mac Formation as applied by previous authors to the Jeanne d'Arc Basin (e.g. Jansa and Wade, 1975 ; Arthur et al., 1982 ; Fig. 7). The name Voyager appears in the Offshore Schedule of Wells 1966-1986 (Canada Oil and Gas Lands Administration, 1987) to designate an interbedded clastic/carbonate sequence encountered between 4333 and 4500 m (T.D.) in the Petro-Canada et al. Terra Nova K-08 well and between 4283 and 4628 m (T.D.) in the Husky-Bow Valley et al. Whiterose N-22 well. That application is the same as proposed here. The Voyager Formation overlies the Downing Formation and underlies the Rankin Formation in a normally stratified section.

Well type section — Mobil et al. Rankin M-36 from 3144 to 3752 m, 608 m thick, is here designated the type section (Fig. 14, Table 1).

Well reference section — Husky-Bow Valley et al. Voyager J-18 from 3246 to 3743 m (T.D.), more than 497 m thick (Fig. 15, Table 1).

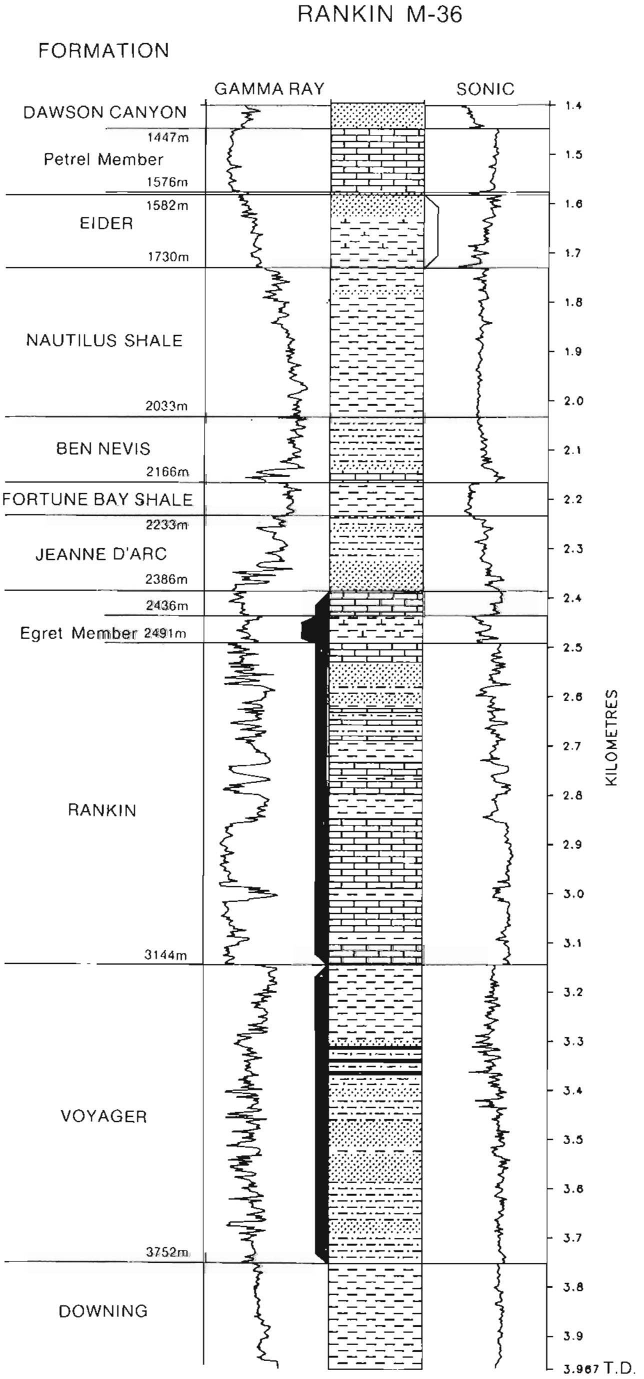

Figure 14. Gamma-ray/sonic log and lithostratigraphy of Rankin M-36 well. Well type section for Voyager and Rankin formations and Egret Member. Well reference section for Eider Formation. Legend as in Figure 11.

Lithology — The Voyager Formation is an interbedded sandstone, shale, and limestone sequence with shale dominant toward the top. At the well type section, the lower part of the formation (3305-3752 m) is an interbedded sandstone, siltstone, and shale sequence containing a few thin limestone beds and thin coal seams in the top 80 m (Fig. 14). The sandstones are light grey to white, quartzose, very fine to fine grained, and generally well cemented with calcite and locally silica. A few sands exhibit poor to fair porosity. Quartz grains are subrounded and well sorted. The siltstones are light grey, calcareous, and argillaceous. The shales are medium grey to dark grey, carbonaceous, and variably calcareous. The limestones are white to light brown, oolitic and sandy, and locally bioclastic.

The upper part of the formation (3144-3305 m) is predominantly shale containing minor limestone and siltstone interbeds (Fig. 14). The shales are medium to dark grey, silty, and slightly calcareous and carbonaceous. Limestones are white to grey, microcrystalline to very finely crystalline, slightly to very argillaceous, and probably occur as stringers. Very rare siltstones are grey, calcareous, and argillaceous.

The lithofacies present at the well reference section are similar, but the relative proportions of rock types are different (Fig. 15). The lower part of the formation (3367-3743 m, T.D.) contains a higher percentage of sandstones and limestones and the beds are thicker. Coal seams are not present although the sandstones contain common carbonaceous material. The shaly upper part of the formation (3246-3367 m) contains fewer limestone interbeds.

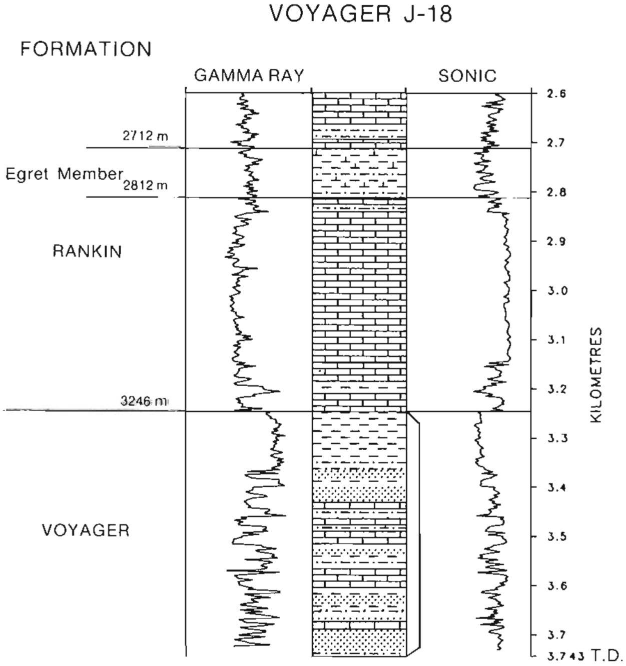

Figure 15. Gamma-ray/sonic log and lithostratigraphy of Voyager J-18 well. Well reference section for Voyager Formation. Legend as in Figure 11.

Boundaries — The lower contact with the Downing Formation has been penetrated by only three wells in the Jeanne d'Arc Basin area; Murre G-67 at 1245 m, Golconda C-64 at 3707 m, and Rankin M-36 at 3752 m. In those wells, the contact is apparently conformable and fairly abrupt on well logs. Regional seismic data support this interpretation. The top of the formation has been penetrated by several other wells in the southern Jeanne d'Arc Basin where it is marked by clear log breaks between the upper shaly interval of the Voyager Formation and massive limestones of the overlying Rankin Formation. The upper contact is not as distinctive in the most northerly wells that are known to have encountered the formation, Whiterose N-22 (4284 m), Trave E-87 (3775 m), South Tempest G-88 (4305 m), and Panther P-52 (3790 m) because, there, the Rankin Formation consists predominantly of fine grained sandstones and shales.

Distribution — North of its updip erosional limit, which occurs between the Murre G-67 and Cormorant N-83 wells, the Voyager Formation is known throughout the Jeanne d'Arc Basin and on the Outer Ridge Complex.

Age — Late Bathonian to early Oxfordian at both the type section and the reference section (Bujak Davies Group, 1988a, b).

Depositional environment — Fine grained sandstones, shales, and coals, and subordinate oolitic limestones of the Voyager Formation prograded over neritic shales of the upper Downing Formation during a period of widespread regression on the Grand Banks. A shallow- to marginal-marine deltaic environment is interpreted for these sediments in the Jeanne d'Arc Basin. The upper shaly unit probably represents either a change in the regional sediment dispersal pattern or deepening marine conditions.

Subdivisions — Two subdivisions are recognized, a lower interbedded sandstone, shale, and limestone unit and an upper shale unit, although neither is accorded formal status at present.

Rankin Formation, new

FIGURES 14 and 16

Name — From the Mobil et al. Rankin M-36 well in the Jeanne d'Arc Basin. The Rankin Formation is defined as the lithostratigraphic unit underlain by the Voyager Formation and overlain by the Jeanne d'Arc Formation. The Rankin Formation is probably equivalent to the upper part of the Mic Mac Formation or to the Abenaki Formation (Scotian Shelf names) as applied by previous authors to the Grand Banks (Fig. 7). The name has been used informally by Boudreau et al. (1986) to designate the sandstone, limestone, and shale sequence of Bathonian to Kimmeridgian age lying between the top of the Whale unit (sensu Jansa and Wade, 1975; equivalent to the top of the Whale Member of the Downing Formation) and the base of an organic-rich shale member (Egret Member) within the Rankin Formation, as it is defined here.

Well type section — Mobil et al. Rankin M-36 from 2386 to 3144 m, 758 m thick, is here designated the type section (Fig. 14, Table 1).

Well reference section — Husky-Bow Valley et al. Trave E-87 from 2844 to 3775 m, 931 m thick (Fig. 16, Table 1).

Lithology — The Rankin Formation is a lithologically heterogeneous unit. Rankin M-36 illustrates the typical development of the formation in the southern part of the Jeanne d'Arc Basin where it comprises three broad units (Fig. 14). The basal massive limestones (2856-3144 m) are mainly white to brown, oolitic and skeletal wackestones, packstones, and grainstones with no porosity development. In the middle unit (2533-2856 m), fine clastics predominate with minor lime mudstones and oolitic and skeletal wackestones. Sandstones are white to grey, very fine to fine grained, quartzose, subrounded, and well sorted, and exhibit poor porosity due to carbonate cementation. Intercalated shales are grey to green and variably calcareous, grading to marls. Siltstones are light grey, calcareous, argillaceous, and locally sandy. The upper unit (2386-2533 m) is a sequence of thinly interbedded limestone, marl, and shale. The limestone is white to grey lime mudstone, hard and dense, and variably argillaceous, grading to marl. The intercalated shale is dark brown to grey, calcareous, and carbonaceous. The upper limy unit can be distinguished from the lower massive limestone unit by the former's "spiky" acoustic log signature which is caused by the thinly interbedded nature of the unit.

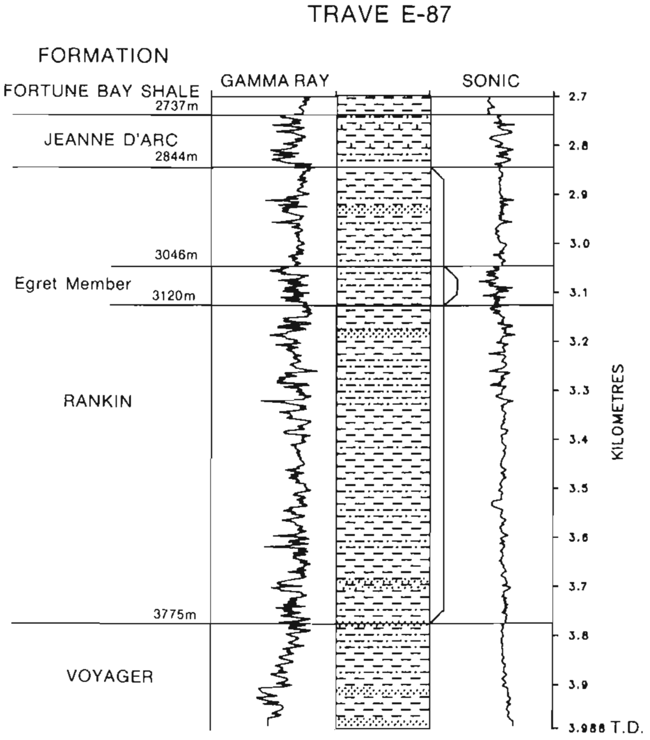

Figure 16. Gamma-ray/sonic log and lithostratigraphy of Trave E-87 well. Well reference section for Rankin Formation and Egret Member. Legend as in Figure 11.

In more northerly wells, the Rankin Formation is dominated by fine grained siliciclastics, exemplified in the Trave E-87 well where the formation consists of a monotonous sequence of interbedded sandstone, siltstone, shale, and rare limestone. Nevertheless, the overall vertical gamma-ray and acoustic log pattern observed at Rankin M-36 is still recognizable at Trave E-87. One noteworthy correlative log signature is the low velocity section between 2436 and 2491 m at Rankin M-36 and between 3046 and 3120 m at Trave E-87. This interval is defined later as the Egret Member of the Rankin Formation. The sandstones encountered at Trave E-87 are white to light grey, very fine to fine grained, quartzose, subangular to subrounded, and moderately well sorted. Porosity is generally poor due to calcite cementation but locally fair in friable beds. Siltstones are grey, calcareous, and argillaceous. The shales are light grey to light brown (reddish-brown in the Egret Member), firm to hard, blocky to subfissile, and calcareous, and locally grade to siltstone. Minor thin limestones are grey to light brown, microcrystalline to cryptocrystalline, hard, and slightly argillaceous and silty.

Boundaries — The lower boundary is the contact between the massive limestones or interbedded fine clastics of the lower unit of the Rankin Formation and the upper massive shale unit of the Voyager Formation, and is marked by clear changes in log character. The upper boundary is marked by a regional unconformity of Kimmeridgian age at the contact with the overlying Jeanne d'Arc Formation (Fig. 4, 5, and 6). The upper contact may be easy to recognize where the Jeanne d'Arc Formation is developed as a medium to coarse clastic facies (e.g. Rankin M-36) or more difficult to pick where fine clastics or limestones predominate in the overlying section (e.g. Trave E-87). The upper contact is commonly recognizable on seismic profiles which may show erosional channelling or angular relationships at the Kimmeridgian unconformity, especially over basin margin structures (Fig. 9). This surface becomes paraconformable in the basin centre.

Distribution — The original regional distribution of the Rankin Formation cannot be reconstructed due to erosion at the Kimmeridgian unconformity and a suite of middle Cretaceous unconformities (Fig. 6). The formation has not been encountered by wells south of the Egret Fault (Fig. 3), but seismic data indicate that its erosional limit is nearby (Fig. 4 and 6). North of the Egret Fault the formation is widespread and probably ubiquitous. It is known from more than seventeen wells, including Egret K-36 (2263-3353 m, T.D.), Port au Port J-97 (1643-2498 m), Terra Nova K-08 (3548-4286 m), Hibernia K-18 (4547-5039 m, T.D.), Voyager J-18 (2598-3247 m), and Archer K-19 (3172-4299 m, T.D.).

Age — Early Oxfordian to early Kimmeridgian at the type section (Bujak Davies Group, 1988a) where the top is eroded, but may extend as young as middle Kimmeridgian in the basin centre.

Depositional environment — The lithological heterogeneity and the relative lack of subsurface control for the Rankin Formation present difficulties for interpreting its regional depositional environment. In the southern Jeanne d'Arc Basin the massive oolitic and skeletal limestone sequence in the lower part of the formation suggest a high energy, shallow-marine shelf environment deprived of clastic input. Subsequent transgression followed by regression are indicated by the fine clastics and thinly intercalated limestones and shales of the middle and upper units respectively. Northward in the basin and on the Outer Ridge Complex the formation is less calcareous, and fine clastics predominate. Regional well control (e.g. Baccalieu I-78, 3648-4561 m, and Lancaster G-70, 3877-5194 m, in the Flemish Pass Basin) suggests a northeastern source for the sandstones that are interpreted to be starved shelf and deep-marine turbiditic deposits.

Subdivisions — As noted above, the formation is a heterogeneous unit. Although several vertical and lateral lithostratigraphic units can be recognized, only one basin-wide shale unit, the Egret Member, is accorded formal status at present.

Egret Member, new

FIGURE 14

Name — From the Amoco-Imp-Skelly B-1 Egret K-36 well, where this unit was first recognized and interpreted to be an organic-rich potential oil source rock for the Jeanne d'Arc Basin (Bujak et al., 1977a, b; Swift and Williams, 1980). Boudreau et al. (1986) defined the Egret formation as the limestone and shale sequence between the base of the Egret Member and the top of the Rankin Formation, both as defined here. They called the Egret Member the Argentia member. Tankard and Welsink (1987) applied the name Egret sequence to at least 1300 m of oolitic limestones, organic-rich shales, siltstones, and very fine grained sandstones underlying the Jeanne d'Arc sequence. Their Egret sequence probably includes both the Voyager and Rankin formations defined here, although this is not clear.

Well type section — Mobil et al. Rankin M-36 from 2436 to 2491 m, 55 m thick, is here designated the type section (Fig. 14, Table 1).

Well reference section — Husky-Bow Valley et al. Trave E-87 from 3046 to 3120 m, 74 m thick (Fig. 16, Table 1).

Lithology — Around the southern perimeter of the Jeanne d'Arc Basin, north of the Egret Fault, the Egret Member consists of thinly interbedded and laminated brown marls and calcareous shales and claystones, and brown and grey lime mudstones as exemplified by the type section. Basinward and to the northeast (e.g. reference section and South Tempest G-88), slightly calcareous grey shale and siltstone progressively become the dominant lithofacies. Minor thin sandstones are very fine to fine grained and argillaceous.

Boundaries — The Egret Member is characterized by its lower sonic velocity, lower bulk density, and higher resistivity compared to adjacent units (Grant and McAlpine, in press). These anomalous log values result from its high organic carbon content (up to 9 percent) and from indigenous hydrocarbons generated within this oil-prone source rock (see Petroleum Potential section). Gamma-ray readings are not diagnostic of the member. Both the lower and upper contacts, with either limestones in the south or fine clastics in the north, are abrupt but apparently conformable and are easily picked on the sonic log.

Distribution — The distribution appears to be the same as that of the entire Rankin Formation. Key wells that have penetrated the member are Port au Port J-97 (1833-1912 m), Egret K-36 (2642-2703 m), Hibernia K-18 (4819-4907 m), Flying Foam I-13 (3281-3353 m), Panther P-52 (3219-3291 m), South Tempest G-88 (3730-3814 m), and North Dana I-43 (3883-4000 m).

Age — Early Kimmeridgian at both the type section and the reference section (Bujak Davies Group, 1988a, b).

Depositional environment — The fine grained and laminated nature of the Egret Member and its high organic carbon content suggest a low energy, restricted depositional environment. Isopachs show thickest occurrences in the present day axis of the Jeanne d'Arc Basin and on the northeastern Outer Ridge Complex. A narrow zone of thin deposition between these two areas suggests a sill that could have acted as a barrier to circulation (McAlpine et al., 1988). Oolitic and skeletal packstones and grainstones, often encountered both below and above the unit in the south, suggest proximity to a carbonate shelf or bank. The environment was probably a fairly deep-water anoxic basin or, less likely, a shallow restricted platform. Farther north, a deeper water siliciclastic environment prevailed where density currents probably played a significant depositional role. Terrestrial organic matter content is low (F. Goodarzi, pers. comm., 1988) suggesting low continental runoff at the time of deposition. High planktonic productivity, coupled with oxygen depletion due to carbonate deposition and restricted circulation in a silled basin, resulted in high accumulation and preservation of organic material.

Jeanne d'Arc Formation, new from McKenzie (1980)

FIGURE 17

Name — From the Jeanne d'Arc Basin. McKenzie (1980) used the term Jeanne d'Arc sand zone to refer to the lowest hydrocarbon-bearing reservoir at the Hibernia field. Arthur et al. (1982) called these sandstones the Jeanne d'Arc member of the Mic Mac Formation (e.g. Hibernia P-15, 4113-4245 m). The Jeanne d'Arc Formation is defined here as a broader, fining upward clastic unit that includes the Jeanne d'Arc member (cf. Arthur et al., 1982) and that is underlain by the Rankin Formation and overlain by the Fortune Bay Shale.

Well type section — Petro-Canada et al. Terra Nova K-18 from 3050 to 3413 m, 363 m thick, is here designated the type section (Fig. 17, Table 1).

Lithology — The Jeanne d'Arc Formation is characterized by an overall fining upward sequence of sandstone-dominated deposits. Lithofacies are highly variable within the formation and several locally correlatable units can be recognized, although none are given member status at this time.

At the type section the formation can be broadly described within a threefold subdivision : a lower shale, a middle sandstone, and an upper shale.

The lower shale unit (3385-3413 m) consists of grey to grey-brown, fissile, calcareous, and silty shale containing a few thin interbeds of brown argillaceous lime mudstones.

The middle sandstone unit (3203-3385 m) is dominated by sandstones grading to conglomerates with minor interbedded shales and siltstones. Almost 117 m of conventional core were cut in this interval and they show the presence of four major lithofacies. (a) A pebbly sandstone and conglomerate lithofacies composes over 80 percent of the unit. This lithofacies is present in four massive sequences up to 27 m thick composed of stacked, fining upward, 0.2 to >1.0 m thick, sandstone and pebble/cobble conglomerate beds. The sandstones are pale grey and brownish grey, fine to very coarse grained, poorly to moderately sorted, and subangular to subrounded. Sedimentary structures include erosion surfaces, internal horizontal lamination, and low-angle cross-bedding. Common conglomeratic horizons occur as basal lags, composed of clast-supported, well-rounded pebbles and cobbles of sandstone, limestone, granite, and quartz/quartzite/chert lithologies. (b) A cross-bedded sandstone lithofacies is characterized by overall fining upward sequences, composed of pale grey to brownish-grey and greyish-orange (siderite cemented), very fine to coarse grained, thin to thickly bedded sandstones containing current ripples, cross-bedding, horizontal lamination, erosion surfaces, intraformational rip-up mudclasts, and carbonaceous wood fragments. These sandstones are interbedded with medium to dark grey laminated siltstones and silty shales. (c) A current-rippled sandstone and shale lithofacies is characterized by thinly interbedded, buff to pale grey, very fine to medium grained, moderately well-sorted sandstones and medium and dark grey shales and siltstones.

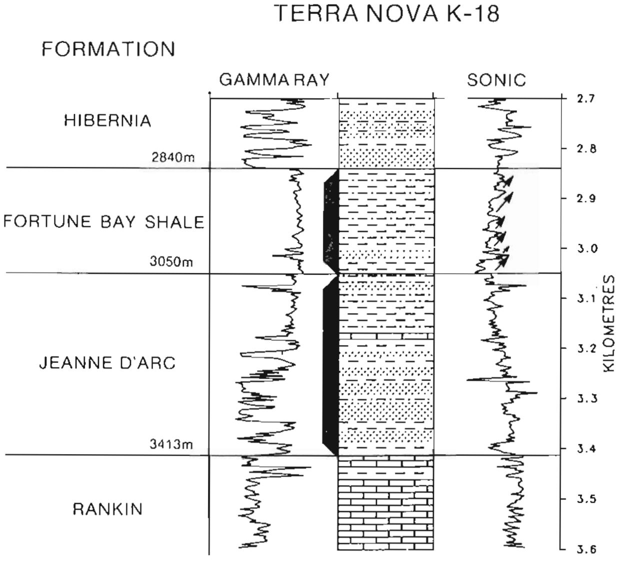

Figure 17. Gamma-ray/sonic log and lithostratigraphy of Terra Nova K-18 well. Well type section for Jeanne d'Arc Formation and Fortune Bay Shale. Legend as in Figure 11.

Sedimentary structures in the sandstones include current ripples, horizontal lamination, slump structures, and intraformational mudclasts. (d) A grey shale with rare sandstone lithofacies is characterized by medium to dark grey and greenish-grey silty and calcareous shales containing scattered carbonaceous wood fragments and thin pale grey to brownish-grey, siderite and calcite cemented, very fine and fine grained sandstones exhibiting slump structures, current ripples, intraformational mudclasts, and possible fossilized roots.

The upper shale unit (3050-3203 m) at the Terra Nova K-18 well consists mainly of shales and siltstones with several thin sandstone interbeds and rare thin limestones. The shales are light to medium grey, fissile, slightly carbonaceous, and locally calcareous and silty. Siltstones are grey to brown, argillaceous, calcareous, and sandy. Sandstones are light grey to brown, very fine to fine grained, quartzose, moderately well sorted, subangular to subrounded, and calcite cemented. A 7 m thick limestone bed at 3176 m is a grey to brown argillaceous mudstone.

Boundaries — The upper boundary is usually easily picked on well logs and is placed at the abrupt contact between the overall fining upward Jeanne d'Arc Formation and the coarsening upward Fortune Bay Shale. The contact with the underlying Rankin Formation is commonly an unconformity and is easily recognized in samples and on well logs where the Rankin Formation is developed as a limestone facies. Where the Jeanne d'Arc and Rankin formations have similar clastic lithofacies development (e.g. South Tempest G-88), correlations are tenuous and the contact is difficult to determine using present well control. It is loosely defined as the base of the first clastic-dominated sequence that fines upward overall and which underlies the Fortune Bay Shale.

Distribution — The Jeanne d'Arc Formation can be recognized throughout the basin from Port au Port J-97 (1575-1643 m) northeast to North Dana I-43 (3578-3775 m). The formation has not been penetrated south of the Egret Fault where seismic data indicate it is absent, except for a few erosional remnants, due to erosion and/or nondeposition. Wells that have encountered the Jeanne d'Arc Formation include Egret N-46 (1567-1940 m), Egret K-36 (2149-2263 m), Hibernia K-18 (4055-4547 m), South Mara C-13 (4814-5034 m, T.D.), Archer K-19 (3000-3172 m), Trave E-87 (2737-2844 m), and South Tempest G-88 (3237-3529 m).

Age — According to Bujak Davies Group (1988d), who use a three-part Kimmeridgian stage followed by a Portlandian stage, the formation, in several wells, is consistently Kimmeridgian in age. However, if their middle and upper divisions of the Kimmeridgian are correlated as Tithonian (cf. Harland et al., 1982), then the formation is Kimmeridgian to Tithonian in age. The latter interpretation, which conforms with the time scale of Palmer (1983), is favoured here.

Depositional environment — The Jeanne d'Arc Formation records the first major period of coarse clastic sedimentation in the Jeanne d'Arc Basin. The lithofacies represent a suite of associated environments that, overall, are interpreted to characterize fluvially dominated fan-delta sedimentation into a rapidly subsiding basin. Individual fans probably advanced into the basin via point entries (e.g. Hibernia and Terra Nova) initiated by periodic movement on marginal growth faults. Older sedimentary and igneous rocks were eroded from the southern perimeter of the basin and transported axially to the northeast as indicated by prominent erosional channels seen on multichannel seismic lines in the area of the Egret wells (Fig. 4 and 10). Fan-deltas represented by the middle sandstone unit at the type section intertongue with marginal-marine outer fan and fan abandonment shales exemplified by the lower and upper shale units respectively. The overall fining upward nature of the formation and its ultimate transgression by the Fortune Bay Shale may be the result of eustatic overprint by the well-documented Late Jurassic global rise of sea level (e.g. Vail et al., 1977).

Fortune Bay Shale, new

FIGURE 17

Name — From Fortune Bay, a prominent coastal inlet on the southern coast of Newfoundland. The Fortune Bay formation was introduced informally by Boudreau et al. (1986) to designate the predominantly shale and siltstone interval overlying the Jeanne d'Arc Formation and underlying the Hibernia Formation. This unit is here given formation rank and designated the Fortune Bay Shale.

Well type section — Petro-Canada et al. Terra Nova K-18 from 2840 to 3050 m, 210 m thick, is here designated the type section (Fig. 17, Table 1).

Lithology — The Fortune Bay Shale is a generally upward coarsening shale and siltstone unit that locally contains thinly interbedded sandstones.

The type section displays six stacked sequences of shale grading upward to siltstone (Fig. 17). The two oldest sequences exhibit sandstone development at their upper boundaries. This pattern of stacked coarsening upward sequences within an overall coarsening upward unit characterizes the Fortune Bay Shale regionally. Only the number of sequences and the presence or absence of sandstones and their stratigraphic position within this remarkably homogeneous formation vary between wells (Fig. 9 and 10). The sandstones may be locally important as reservoirs since they flowed oil at a daily rate of 385 m^3 during a drillstem test of a 10 m thick interval at the Mobil et al. Hibernia B-08 well. There, they are known as the Hibernia stray sandstones by the operator.

Shale is the major lithology for the formation. It is generally light grey to grey, fissile to blocky (splintery where overpressured), slightly calcareous in part, carbonaceous, and fossiliferous. Thin horizons or concretions of orange-brown siderite are common. Siltstones are grey to brown, argillaceous, slightly calcareous, carbonaceous, and sandy. Rarely the siltstones grade to sandstones that are grey, quartzose, fine grained, subangular, well sorted, argillaceous, and calcite cemented.

Boundaries — The formation is characterized by its high gamma-ray values and relatively low sonic velocity compared to adjacent formations. The lower contact with the Jeanne d'Arc Formation is abrupt and is probably a depositional unconformity. It is easily picked on well logs, although this may be difficult in samples. The upper contact with the Hibernia Formation is gradational and conformable. It is defined as the base of the basal coarsening upward delta-front sequence of the Hibernia Formation (described later) or alternatively, when this sequence is not present, the base of the first massive Hibernia Formation sandstone. Where the Hibernia Formation is absent, the Fortune Bay Shale can be distinguished from the overlying Whiterose Shale by its lower sonic velocity as seen on the sonic log.

Distribution — The Fortune Bay Shale is a ubiquitous lithostratigraphic unit within the Jeanne d'Arc Basin north of the Egret Fault. South of the Egret Fault it is probably absent due to erosion (Fig. 6 and 9).

Virtually all wells with sufficient stratigraphic penetration have encountered the formation including Egret K-36 (2042-2149 m), Gambo N-70 (1910-1966 m), Hebron I-13 (3490-3770 m), Hibernia K-18 (3859-4055 m), South Mara C-13 (4609-4814 m), Archer K-19 (2609-3000 m), Trave E-87 (2520-2737 m), and South Tempest G-88 (3143-3232 m).

Age — Interpreted to be middle to late Kimmeridgian in several wells by Bujak Davies Group (1988d). But, for reasons stated with the age of the Jeanne d'Arc Formation, the Fortune Bay Shale is considered here to be of Tithonian age.

Depositional environment — Seismic data show evidence of internal prograding and overlapping clinoforms which indicates that the Fortune Bay Shale is the delta front and prodelta facies of the overlying Hibernia Formation. Paleoenvironmental data from ostracod assemblages (P. Ascoli, pers. comm., 1983) suggest marginal-marine to shallow neritic depositional environments, which is supported by the occurrence of carbonaceous material, siderite nodules, pelecypod shell fragments, and the generally non-calcareous nature of the shales.

Hibernia Formation, new from McKenzie (1980)

FIGURES 18 and 19

Name — From the Chevron Hibernia P-15 well, the discovery well for the Hibernia oil field. McKenzie (1980) referred to the middle hydrocarbon-bearing reservoir at the Hibernia field as the Hibernia sand zone. Arthur et al. (1982) called these sandstones the Hibernia member of the Missisauga Formation (e.g. Hibernia P-15, 3744-3924 m). This sandstone unit is here designated the Hibernia Formation. It is defined as the sandstone-dominated unit occurring between the underlying Fortune Bay Shale and the overlying Whiterose Shale or alternatively the overlying "B" marker.

Well type section — Mobil et al. Hibernia K-14 from 3839 to 4062 m, 223 m thick, is here designated the type section (Fig. 18, Table 1).

Well reference section — Mobil et al. Hebron I-13 from 2887 to 3490 m, 603 m thick, is the reference section and also the type section for the Hebron Well Member (2887-3098 m) of the Hibernia Formation (Fig. 19, Table 1).

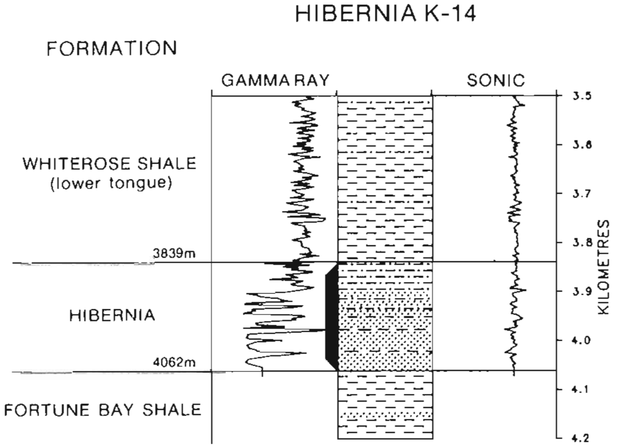

Figure 18. Gamma-ray/sonic log and lithostratigraphy of Hibernia K-14 well. Well type section for Hibernia Formation. Legend as in Figure 11.

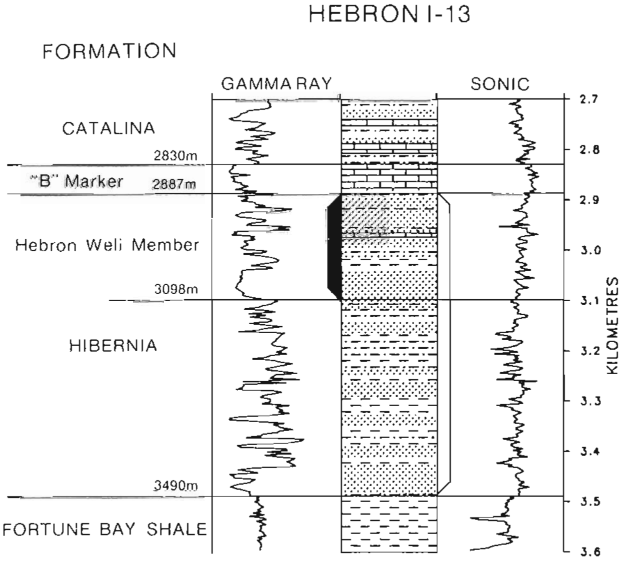

Figure 19. Gamma-ray/sonic log and lithostratigraphy of Hebron I-13 well. Well type section for Hebron Well Member. Well reference section for Hibernia Formation. Legend as in Figure 11.

Lithology — The Hibernia Formation is composed of alternating thick sandstones and thinner interbedded shales. At the type section it is possible to subdivide the formation into two units (Brown et al., 1989). The lower unit (3901-4062 m) consists of thick (up to 25 m), stacked, fining upward sequences of pale grey to buff, moderate to well sorted, fine to very coarse grained quartz arenites. The sandstones contain abundant carbonaceous stringers and fragments (carbonized branches, leaves, and comminuted plant detritus) and common basal lags consisting of siderite, quartzite, chert, and rip-up mudclasts. Sedimentary structures are dominated by sharp erosive bases, cross-bedding (dipping up to 25 degrees), planar horizontal lamination, and current ripples. Thin beds of siltstone and mudstone are rarely incorporated within the sandstones.

Sequences of thinly interbedded shales, siltstones, sandstones, and rare coals separate the more massive sandstones. Individual sandstone beds in these sequences are less than 2 m thick, predominantly very fine and fine grained, and moderately to poorly sorted. Sedimentary structures are dominated by horizontal lamination, current and wave ripples, abundant burrows (locally bioturbated), and very common rootlets. Abundant comminuted carbonaceous material, common carbonaceous stringers, intraformational mudclasts, and local concentrations of bivalve and indeterminate fossil debris are present in this lithofacies.

The upper unit at the type section (3839-3901 m) consists of interbedded sandstones, silty shales, and siltstones. The sandstones are characteristically thinner and finer grained than those of the lower unit. This sequence contains common small scale low- and high-angle planar cross-bedding and asymmetrical ripple cross-laminations. Abundant comminuted carbonaceous detritus, rare carbonaceous stringers, and local rip-up mudclasts are present. Bioturbation is common and local concentrations of shell material include pelecypods, gastropods, ostracods, and unidentified bioclasts. A unique bed of brick-red, hematite-rich mudstone occurs near the base of the unit (3889-3993 m). Carbonized rootlet impressions are present below this oxidized bed.

Elsewhere in the Jeanne d'Arc Basin, the base of the Hibernia Formation usually consists of a persistent coarsening upward sequence of sandstones or sandstones interbedded with siltstones and shales ; in the southeast, the top consists of a thick sequence of massive sandstones. The lower sequence is unnamed and the upper sequence is designated the Hebron Well Member of the Hibernia Formation.

The unnamed lower sequence at the well reference section (3430-3490 m, not cored) consists of white to light grey, clean quartz sandstones. The sandstones are fine grained at the base, grading to medium to coarse grained at the top. The grains are angular, medium to well sorted, and variably cemented by silica. In other wells the sequence is a mixture of interbedded sandstones, siltstones, and shales. This latter sequence was cored at the Mobil et al. South Mara C-13 well (4581.4-4599.6 m) where it consists of very fine grained argillaceous and bioturbated, locally fine grained and laminated sandstones containing carbonaceous wood debris and mudclasts, overlying bioturbated and carbonaceous silty shales.

The Hebron Well Member at the well reference section (2887-3098 m) consists of a 62 m thick basal sandstone overlain by a sequence of 5 to 20 m thick sandstones separated by thinner shales and siltstones. The basal sandstone fines upward from medium to coarse grained at the base to fine grained at the top. It is white to light grey, generally moderate to well sorted, subrounded to subangular, and calcareous cemented in the upper fine grained part. A core at 2944 to 2961.5 m recovered a stacked sequence of thin (up to 1.5 m thick) sandstones containing a few limestone and siltstone interbeds. The sandstones are pale brownish grey (argillaceous) and pale grey (calcite cemented), very fine to medium grained, subangular, and moderately sorted. Cores exhibit planar horizontal lamination, wavy discontinuous bedding, and burrows. Accessories include carbonaceous debris, intraformational mudclasts, ooids, and bivalve, gastropod, and echinoderm skeletal debris. The limestones are medium to coarse grained, sandy, oolitic and bioclastic packstones.

Boundaries — The base of the Hibernia Formation is defined as the base of the first thick sandstone-dominated sequence conformably overlying the Fortune Bay Shale. This contact is readily apparent in cuttings samples and well logs. Where the Hebron Well Member is developed the top of the formation is a sharp but usually conformable contact with massive limestone of the "B" marker. Elsewhere, it is in gradational contact with thick shale/siltstone of the Whiterose Shale. In either case the top of the formation is marked by clear changes in log character.

Distribution — The Hibernia Formation is best developed in the Hibernia field / Hebron I-13 / Terra Nova field region (Fig. 3) of the Jeanne d'Arc Basin. It is absent on the Bonavista Platform, south of the Egret Fault, and on the Outer Ridge Complex due to nondeposition or to updip truncation by a suite of mid-Cretaceous unconformities. It is also absent to the north where it passes laterally into the Whiterose Shale. The transition occurs between the Trave E-87 and the South Tempest G-88 wells.

Age — Tithonian to Berriasian at the reference section by micropaleontology (Williamson, 1987 ; Ascoli, 1988).

Depositional environment — Latest Jurassic and Early Cretaceous subsidence of the Jeanne d'Arc Basin formed a locus of deposition for large fluvial systems draining the Avalon Uplift to the south and hinterlands to the west and east, the Bonavista Platform and Outer Ridge Complex respectively. The Hibernia Formation sandstones and siltstones are interpreted as prograding deltaic sediments of these fluvial systems.

Initial progradation is recorded in a widely persistent, coarsening upward sequence of delta-front/prodelta sediments (e.g. Hebron I-13, 3430-3490 m). Coastal plain-delta top sedimentation followed (e.g. Hibernia K-14, 3901-4062 m). This sequence consists of moderately high sinuosity, fluvial channel sandstones, and sheet-geometry transgressive sandstones encased in predominantly muddy, fine grained, interdistributary bay sediments. As the delta system was transgressed and abandoned, shallow-marine sandy siltstones and shales were deposited (e.g. Hibernia K-14, 3839-3901 m). Following transgression, coarse clastic input was re-established in the southeastern part of the basin and led to deposition of a thick estuarine/tidal channel complex recorded by the massive sandstones of the Hebron Well Member.

Subdivisions — As noted above, four lithological subdivisions of the Hibernia Formation can be recognized, two at the type section and two at the reference section. Only the upper subdivision at the reference section is accorded formal status here and is designated the Hebron Well Member.

Hebron Well Member, new

FIGURE 19

Name — From the Hebron I-13 well where the member is best developed in the Jeanne d'Arc Basin and where its type section is located. The Hebron Well Member is defined as the first sequence of massive sandstones immediately underlying the "B" marker.

Well type section — Mobil et al. Hebron I-13 from 2887 to 3098 m, 211 m thick, is here designated the type section (Fig. 19, Table 1).

Lithology — The lithology as described earlier for the type section is typical of the known distribution of the member.

Boundaries — The Hebron Well Member is characterized by its "blocky" gamma-ray signature. The base is defined as the base of the lowest massive sandstone bed of the member. It usually overlies a sequence of thinly interbedded shales, siltstones, and sandstones, equivalent to the upper unit of the Hibernia Formation at the type section, and is easily picked in samples and well logs. The top is the same as described for the Hibernia Formation where the member is present.

Distribution — The Hebron Well Member is well developed only along the southeastern margin of the Jeanne d'Arc Basin from Beothuk M-05 (2408-2527 m) to Fortune G-57 (3294-3572 m). North of Fortune G-57 and West Ben Nevis B-75 (3370-3685 m), and west of Hebron I-13, the member thins rapidly and passes laterally into marine shales of the lower tongue of the Whiterose Shale. The member is absent south of the Beothuk M-05 well and on the Outer Ridge Complex due to updip depositional pinchout or erosion.

Age — Berriasian at the type section by micropaleontology (Williamson, 1987 ; Ascoli, 1988) and by palynology (E.H. Davies, pers. comm., 1983).

Depositional environment — As discussed for the Hibernia Formation.

"B" marker, new from McKenzie (1980)

FIGURE 20

Name — First used by McKenzie (1980) to designate a seismic event at the Hibernia field near the top of a Lower Cretaceous sandstone unit now known as the Catalina Formation. Subsequently, Butot (1981) and Benteau and Sheppard (1982) used the name to identify that sandstone unit, and more recently its usage has been restricted to a limestone unit below the base of the Catalina Formation (e.g. Tankard and Welsink, 1987). This limestone provides a useful regional lithostratigraphic marker and seismic event and is here designated the "B" marker.

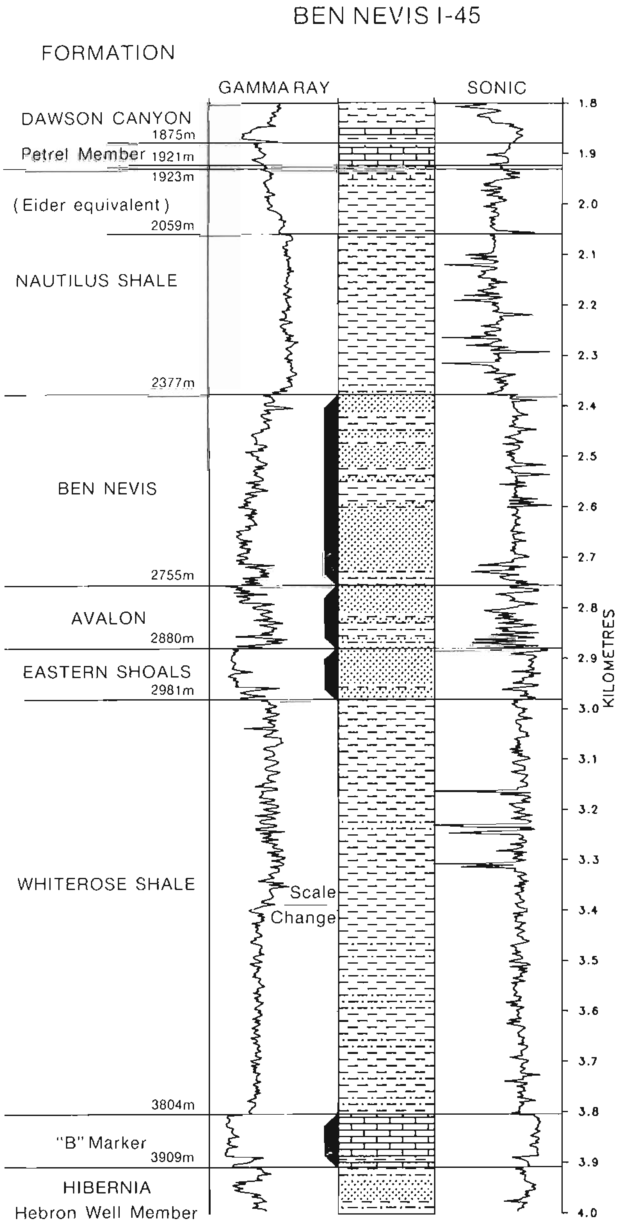

Figure 20. Gamma-ray/sonic log and lithostratigraphy of Ben Nevis I-45 well. Well type section for "B" marker and Eastern Shoals, Avalon, and Ben Nevis formations. Legend as in Figure 11.

Well type section — Mobil et al. Ben Nevis I-45 from 3804 to 3909 m, 105 m thick, is here designated the type section (Fig. 20, Table 1).

Lithology — The type section is dominated by massive, buff to light grey, oolitic/skeletal, lime grainstones and packstones. The medium grained ooids commonly have quartz nuclei and the limestones are variably sandy and silty and locally very argillaceous. Bioclasts include fragments of bivalves, echinoderms, gastropods, and coralline algae. Thin beds of light grey, calcareous, fine grained sandstone and dark grey calcareous siltstone and shale are intercalated with the limestones near the base of the unit (3888-3909 m).

Boundaries — The "B" marker limestones are clearly defined by their low gamma-ray response and high acoustic velocity (Fig. 10 and 20). The lower boundary is usually a fairly abrupt, but conformable contact with the underlying Whiterose Shale or Hibernia Formation. Locally at basin margin structures, underlying beds are seen on seismic to toplap beneath the "B" marker but erosional truncation appears minor. The upper boundary with the Catalina Formation or Whiterose Shale is conformable and usually abrupt.

Distribution — The "B" marker is a remarkably consistent and laterally extensive stratigraphic unit. Its thickest development occurs in the Hebron, Ben Nevis, and Terra Nova areas (see Fig. 3), but it has been encountered as far south as Port au Port J-97 (1446 -1515 m) and as far north as Flying Foam I-13 (2467-2490 m) and Whiterose N-22 (3085-3100 m). Beyond this known regional extent the "B" marker is inferred, by its strong seismic reflectivity, to be present throughout the southern part of the Lower Cretaceous depocentre of the Jeanne d'Arc Basin. Lack of seismic expression, north of the Hibernia to Ben Nevis trans-basin fault trend and basinward of the Flying Foam and Whiterose wells (see Fig. 3), indicates its absence there, probably due to a deeper water paleoenvironment.

Age — By palynology, Valanginian at the type section (J.P. Bujak, pers. comm., 1981) and early Valanginian at Whiterose N-22 (Bujak Davies Group, 1988c). But in several wells, for example Hibernia P-15 (3418-3439 m), the "B" marker has been dated as late Berriasian (E.H. Davies, pers. comm., 1986).

Depositional environment — The oolitic/skeletal limestones of the "B" marker indicate deposition in a warm, shallow, high energy marine environment with low clastic input. The limestones form a blanket deposit laid down at the end of a period of marine transgression that led to drowning of the Hibernia delta. Because of their widespread development and relatively uniform thickness, they are interpreted to record a period of relative basin stability.

Catalina Formation, new from Rayer (1981)

FIGURES 21, 22, and 23

Name — Rayer (1981) introduced the name Catalina sands as alternative nomenclature for the "B" marker sands (Butot, 1981) which occur beneath the "B" seismic marker (McKenzie, 1980) at the Hibernia oil field. Arthur et al. (1982) informally designated this sandstone unit the "C" member (Hibernia P-15, 3210-3362 m) and defined it as the middle oil reservoir unit of the Missisauga Formation at the Hibernia field. The Catalina Formation has also been referred to as the "B" seismic marker zone (Benteau and Sheppard, 1982) and the seismic "B" marker (Catalina) zone (Handyside and Chipman, 1983). The Offshore Schedule of Wells (Canada Oil and Gas Lands Administration, 1983) used the terms Catalina member or Catalina sandstone interchangeably for the formation at the Hibernia field and for stratigraphic equivalents at other locations in the Jeanne d'Arc Basin. This usage is currently the most widely accepted.

The Catalina Formation is defined here as the first laterally persistent sandstone/carbonate sequence directly overlying the "B" marker limestone.

Well type section — Chevron et al. Hibernia P-15 from 3211 to 3418 m, 207 m thick, is here designated the type section (Fig. 21, Table 1). These boundaries differ slightly from those of Arthur et al. (1982).

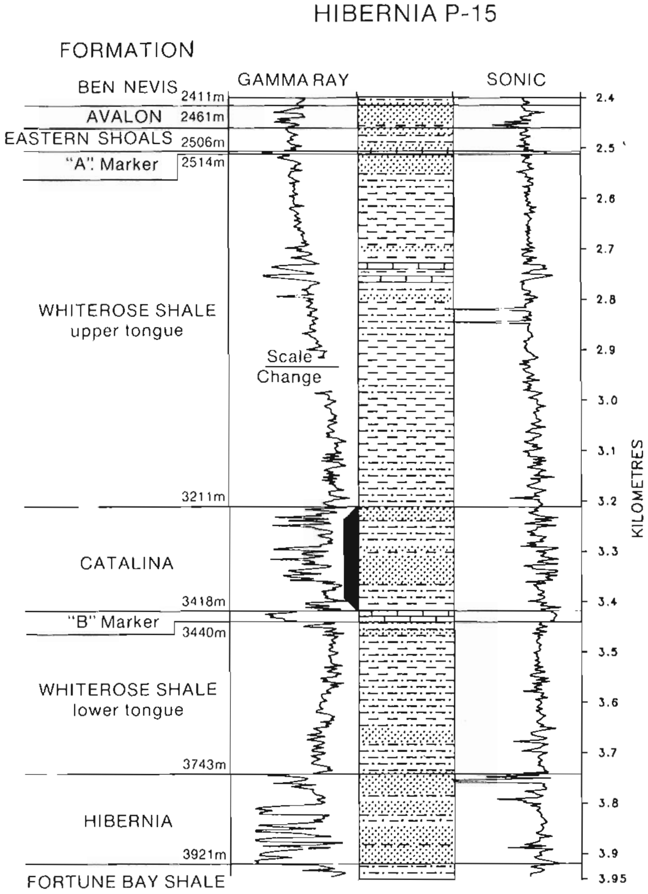

Figure 21. Gamma-ray/sonic log and lithostratigraphy of Hibernia P-15 well. Well type section for Catalina Formation. Legend as in Figure 11.

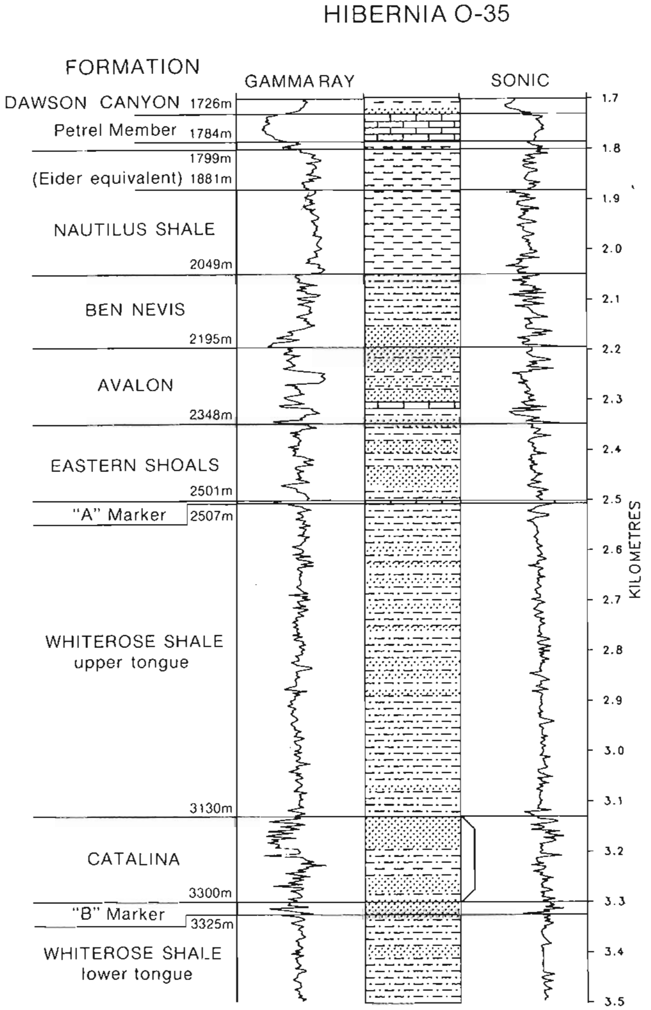

Figure 22. Gamma-ray/sonic log and lithostratigraphy of Hibernia O-35 well. Well reference section for Catalina Formation. Legend as in Figure 11.

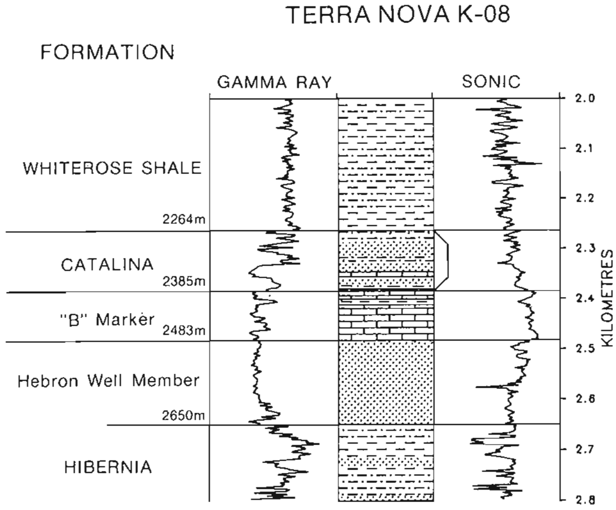

Figure 23. Gamma-ray/sonic log and lithostratigraphy of Terra Nova K-08 well. Well reference section for Catalina Formation. Legend as in Figure 11.

Well reference sections — Mobil et al. Hibernia O-35 from 3130 to 3300 m, 170 m thick and Petro-Canada et al. Terra Nova K-08 from 2264 to 2385 m, 121 m thick (Fig. 22 and 23, Table 1).

Lithology — Ditch cuttings and wireline logs from the type section show a thinly bedded sequence of sandstones, siltstones, shales, and minor limestones. The clastic lithologies, cored at Hibernia O-35, are characterized by thin (< 1.0 m), very fine to medium grained, locally argillaceous sandstones and argillaceous siltstones exhibiting horizontal lamination, current ripples, erosive bases, and abundant burrows. Local concentrations of fossil fragments, carbonaceous wood/plant debris, and intraformational mudclasts are accessory features. The sandstone and limestone lithologies, cored at Terra Nova K-08, are characterized by interbedded, fine grained, locally argillaceous sandstones and medium to coarse grained, sandy, oolitic and skeletal packstones and grainstones. The sandstones exhibit horizontal lamination, cross-bedding, burrows, carbonaceous wood fragments, and common calcareous ooids and bioclastic (bivalve and gastropod) debris. Concretionary and disseminated calcite cements occur throughout.

Boundaries — The lower boundary is a sharp but apparently conformable contact with the "B" marker limestones and is easily picked on the gamma-ray log. The upper boundary with the Whiterose Shale is gradational. It is picked on the gamma-ray log at the top of the highest sandstone bed of the first persistent sandstone/carbonate sequence immediately overlying the "B" marker limestone.

Distribution — The Catalina Formation is present only in the southern part of the Cretaceous depocentre of the Jeanne d'Arc Basin. Maximum recorded thicknesses occur along the western side of the basin ; the formation is 351 m thick (2116-2467 m) at Flying Foam I-13, 276 m thick (3101-3377 m) at Hibernia K-18, and 105 m thick (1431-1536 m) at Egret K-36. The formation thins to the northeast as it passes laterally and vertically into the Whiterose Shale, and the depositional limit lies approximately along a north-northwest-south-southeast line to the west of the Adolphus D-50 and Ben Nevis I-45 wells. To the south the formation thins by rapid convergence of Neocomian strata. For example, the Catalina Formation at Port au Port J-97 (1420-1453 m) is 33 m thick and is directly overlain by the Eastern Shoals Formation.

Age — By palynology, late Berriasian to Valanginian at the type section (E.H. Davies, pers. comm., 1986).

Depositional environment — No terrestrially deposited lithofacies are recognized within the generally fine grained clastics and oolitic limestones of the Catalina Formation. Cored sandstones, siltstones, and shales near the western margin of the basin contain common wood debris and bivalve and gastropod shell fossils. They were probably fluvially supplied into a nearshore marine environment and locally reworked by waves and bioturbated. These sediments are interpreted as interdistributary bay and marginal-marine facies deposited away from the strongly wave influenced open shoreface. The paleoshoreline was probably located immediately west of the present outline of the Jeanne d'Arc Basin and south of the Egret Fault. Farther east, frequently sharp based, horizontally laminated, and rarely cross-bedded shelly-oolitic sandstones and oolitic-skeletal sandy limestones are the dominant lithofacies. Fossils in these deposits include bivalves, echinoderms, gastropods, calcareous worm tubes, and coralline algae representing a fully marine macrofauna. The environment there is interpreted as a gently sloping shoreface characterized by marine shelf storm deposits and probable minor oolitic shoals. Northeastward the Catalina Formation passes transitionally via lower shoreface muddy sandstones into offshore silty shales of the Whiterose Shale.

"A" marker, new from Rayer (1981)

FIGURE 21

Name — Rayer (1981) named a "thin carbonate stringer" near the base of the Avalon sands (the latter being his equivalent for the Eastern Shoals, Avalon, and Ben Nevis formations, as defined here) at the Hibernia field the "A" marker, but unfortunately, created confusion by using the same name for a seismic event near the top of the Avalon sands. McKenzie (1980) and Butot (1981) applied the name to the same seismic event. Subsequently, Rayer's lithostratigraphic intention has been used for regional correlation in several unpublished lithostratigraphic descriptions and in publications by Tankard and Welsink (1987), the Canada-Newfoundland Offshore Petroleum Board (1988a), and Sinclair (1988). However, the interpretations of Tankard and Welsink (that the "A" marker consists of several diachronous limestone beds intertonguing with bottomset deposits of the Avalon sequence) and of Sinclair (that these limestone beds are a member of the Avalon formation and are equivalent to the Eastern Shoals Formation on the eastern side of the basin) are in disagreement with the interpretation presented here. The "A" marker is defined as a thin (<25 m) limestone marker that occurs at or closely below the base of the Eastern Shoals Formation and that is useful for lithostratigraphic correlation in the west-central part of the Jeanne d'Arc Basin.

Well type section — Chevron et al. Hibernia P-15 from 2506 to 2514 m, 8 m thick, is here designated the well type section (Fig. 21, Table 1).

Lithology — The "A" marker consists mainly of limestones similar in composition to those described for the "B" marker. Minor thin beds of calcareous sandstone, siltstone, and shale are locally intercalated within the unit.

Boundaries — The "A" marker usually shows as a distinctive "funnel-shape" couplet on gamma-ray/sonic logs. Both lower (gradational) and upper (abrupt) boundaries are probably conformable.

Distribution — The "A" marker occurs only in the vicinity of the Hibernia field to the South Mara C-13 well (3226-3240 m). Seismic data indicate that it is probably a sheet deposit. The "A" marker should not be confused with several lower stray limestone beds within the Whiterose Shale in the same area. Some wells that have penetrated the "A" marker are Nautilus C-92 (3436-3448 m), Hibernia B-08 (2251-2268 m), Hibernia C-96 (2439-2461 m), and Mara M-54 (2816-2836 m).

Age — At the type section, Hauterivian by palynology (E.H. Davies, pers. comm., 1986) but Barremian by micropaleontology (Williamson, 1987). The marker is interpreted here to be probably late Hauterivian-early Barremian.

Depositional environment — The "A" marker, on the basis of detailed seismic, lithostratigraphic, and biostratigraphic correlation, is interpreted to be a synchronous, shallow-marine unit deposited under conditions similar to those of the "B" marker.

Eastern Shoals Formation, new from McAlpine and Grant (1986)

FIGURES 20 and 24

Remarks — Since the discovery of the Hibernia oil field in 1979 and the recognition there of a thick succession of reservoir sandstones of late Neocomian and Aptian-Albian age, these sandstones have generally been included in one stratigraphic unit, the Avalon sand zone (McKenzie, 1980) or Avalon member (Arthur et al., 1982; Grant et al., 1986a,b; the Proponent's interpretation in Canada-Newfoundland Offshore Petroleum Board, 1986). Further subdivisions of the Avalon zone have been reported recently by Boudreau et al. (1986; the Avalon formation of Barremian to Aptian age and the Ben Nevis formation of Aptian to Albian age) and by McAlpine and Grant (1986; the Eastern Shoals formation of Valanginian to Barremian age,

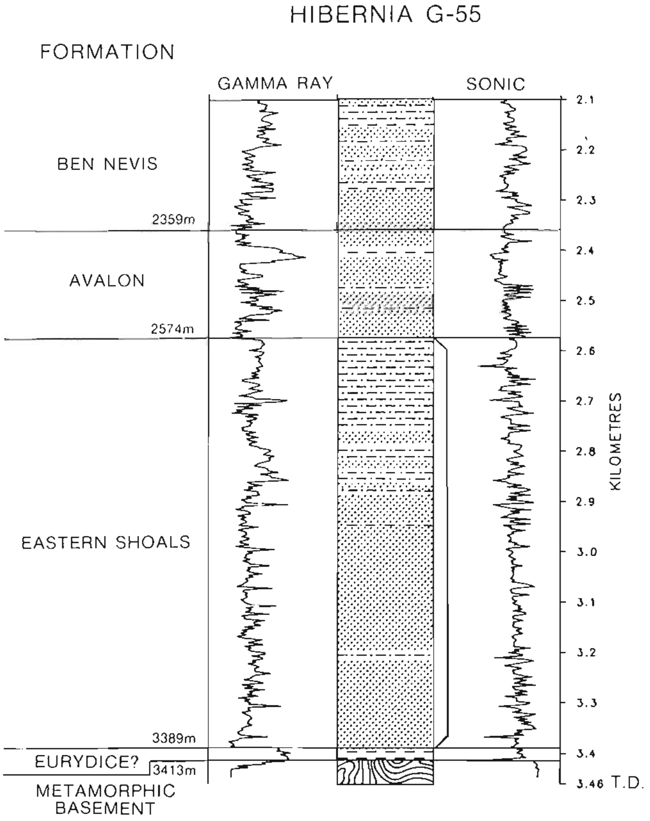

Figure 24. Gamma-ray/sonic log and lithostratigraphy of Hibernia G-55 well. Well reference section for Eastern Shoals Formation. Legend as in Figure 11.

the Avalon formation of Barremian to Aptian age, and the Ben Nevis formation of Aptian to Albian age). Because the units of the latter subdivision are demonstrably mappable within wide geographic areas, they are proposed here as formal units of formation rank.

Name — From the Eastern Shoals, a prominent bathymetric high on the Grand Banks formed by an outcrop of Precambrian or early Paleozoic quartzite, rising to within about 16 m of sea level and lying approximately 100 km west of the Jeanne d'Arc Basin. The Eastern Shoals Formation is defined here as the first laterally persistent sandstone- and sandy limestone-dominated unit lying above the Whiterose Shale, or alternatively above the Catalina Formation in proximal areas. The formation lies below the Avalon member described by Arthur et al. (1982) as a 30 m thick sandstone interval in the Hibernia P-15 well (2420-2450 m) but is equivalent to the lower part of the Avalon member, sandstone, or zone of other authors, for example McKenzie (1980), Butot (1981), Benteau and Sheppard (1982), Handyside and Chipman (1983), Boudreau et al. (1986), Grant et al. (1986a,b), and Tankard and Welsink (1987). The "A" marker member of the Avalon formation as designated in Sinclair (1988) and in several well history reports is a synonym for part or all of the Eastern Shoals Formation (e.g. Petro-Canada Incorporated, 1986a) as is the lower Avalon member (e.g. Petro-Canada Incorporated, 1986b).

Well type section — Mobil et al. Ben Nevis I-45 from 2880 to 2981 m, 101 m thick, is here designated the well type section (Fig. 20, Table 1).

Well reference section — Mobil et al. Hibernia G-55 from 2574 to 3389 m, 815 m thick (Fig. 24, Table 1).

Lithology — Two major lithofacies compose the Eastern Shoals Formation, a massive calcareous sandstone/oolitic limestone sequence and a thick sequence of interbedded sandstone and siltstone, exemplified by the type section and reference section respectively.

The first lithofacies has not been cored. Ditch cutting and wireline log studies reveal a distinctive "cleaning upward" unit consisting of mixed and gradational sandstone and carbonate lithologies with minor interbedded shale and rare coal beds. Sandstones are dominant. They are light grey to light brown, quartzose, very fine to fine grained, subangular, medium to well sorted, fossiliferous, locally glauconitic, and generally tightly calcite cemented. Limestones are mottled white and grey, chalky, sandy, oolitic, pelletal, and bioclastic wackestones and packstones. The shale is multicoloured grey, green, and red, waxy, pyritic, and silty, and occurs in thin beds.

The interbedded sandstone and siltstone lithofacies has been cored at Hibernia wells B-27, G-55, I-46, and K-14. There, the formation is a sequence of grey, very fine to fine grained, quartzose, subangular to subrounded, poorly to moderately well-sorted, argillaceous and bioturbated, or clean and horizontally laminated and low-angle cross-bedded, sandstones. Concretionary calcite cements are common. The sandstones contain local concentrations of pebbles, mudclasts, carbonaceous material, and bivalve and indeterminate shell fossils. Thin siltstones and shales are dark grey, containing rippled and burrowed sand lenses.

Boundaries — At the western side of the basin, the contact between the interbedded sandstone and siltstone lithofacies of the formation with the underlying and laterally equivalent Whiterose Shale or the Catalina Formation is conformable and gradational and the boundary is not easily picked by logs or samples. Eastward, where the massive calcareous sandstone/oolitic limestone becomes dominant, the lower contact is sharp and easily distinguished on the gamma-ray log.

The upper contact with the Avalon Formation is sharp and unconformable to disconformable. It is placed below the distinctive multicoloured mudstone unit at, or near, the base of the Avalon Formation. In some wells the top of the Eastern Shoals is picked at the base of a thin clean sandstone unit that underlies the multicoloured mudstone (e.g. Mara M-54 at 2709 m). In other wells the multicoloured mudstone is not developed, and the top is picked where a noticeable increase in the gamma-ray log response occurs in the sandstones of the Avalon Formation (e.g. Terra Nova K-18 at 1800 m). Nevertheless, the upper boundary is always sharp and clearly visible on the gamma-ray and sonic logs. On seismic sections the upper boundary is seen as a prominent and widely correlatable reflector (Fig. 4, Barremian reflector) commonly referred to as the "A seismic marker". This reflection clearly originates at a stratigraphically higher position in the section than the "A" marker limestone and the two should not be confused.

Distribution — The Eastern Shoals Formation appears to be confined to that part of the Jeanne d'Arc Basin between the Egret Fault and the Whiterose field (Fig. 3). It is thickest on the western side of the basin (e.g. Hibernia G-55 and I-46), apparently due to tilting of the basin during deposition, but may also develop substantial thicknesses near the eastern side of the basin, north of the Hibernia to Ben Nevis trans-basin fault zone (e.g. Fortune G-57, 2695-2993 m). The formation thins to the south by updip depositional pinchout (e.g. Terra Nova K-18, 1800-1928 m and Port au Port J-97, 1378-1420 m) and thins markedly in the basin axis due to distance from source (e.g. Mara M-54, 2709-2766 m).

Age — Barremian by palynology at the type section (J.P. Bujak, pers. comm., 1981) and Hauterivian to Barremian by micropaleontology at the reference section (Ascoli, 1988).

Depositional environment — The Eastern Shoals sandstones show evidence of wave action and tidal currents and were probably deposited in a shallow-marine to marginal-marine setting. Micropaleontological analysis of the Hibernia G-55 well suggests an environment ranging from inner neritic to marginal marine and continental (P. Ascoli, pers. comm., 1983). The basin margin distribution pattern and the generally fine grained nature of the interbedded sandstone and siltstone lithofacies suggest a period of little depositional relief when sediment supply kept pace with subsidence. The massive calcareous sandstone/oolitic limestone facies, located in the basin centre, is interpreted as a high energy, middle shoreface to offshore sheet deposit.

The clastic components were probably removed from the upper shoreface by periodic storm-surge ebb currents. The thin beds of multicoloured mudstones and coal may have been deposited in tidal flat and lagoonal or swampy environments along the low-lying coast.

Whiterose Shale, new

FIGURE 25

Name — From the type section at the Husky-Bow Valley et al. Whiterose N-22 well. The Whiterose Shale is defined here as the distal lateral equivalent of the sandstone-dominated Hibernia, Catalina, and Eastern Shoals formations. It intertongues with these formations and separates them vertically. Where the Catalina Formation or "B" marker limestone is developed, a lower and an upper tongue of the Whiterose Shale can be distinguished.

Well type section — Husky-Bow Valley et al. Whiterose N-22 from 2728 to 3357 m, 629 m thick, is here designated the type section (Fig. 25, Table 1).

Lithology — At the well type section a thin "B" marker limestone (3085-3100 m) enables subdivision of the Whiterose Shale into a lower tongue (3100-3357 m) and an upper tongue (2728-3085 m). The lithology of both tongues is similar, consisting of predominantly medium to dark grey, silty and calcareous, locally carbonaceous, blocky shale. Minor thin siltstone and limestone beds are present and the siltstones grade to sandstones near the base of the formation. Siltstones are light to medium grey and variably argillaceous and calcareous. Limestones are light grey, argillaceous and silty, chalky mudstones. The basal sandstones are light grey, very fine grained, silty, and calcite cemented.

In locations near the lateral gradational contacts with sandstone-dominated formations, siltstones or very fine grained sandstones may be more common in the Whiterose Shale. Stray oolitic limestones are commonly present in the upper tongue of the formation, including the "A" marker which is the most areally extensive.

Boundaries — The Whiterose Shale is clearly distinguished on petrophysical logs from its arenaceous lateral equivalents. Vertical and lateral boundaries are commonly gradational, however, and the positions of the contacts are not always clear in wells. Where the Whiterose Shale is underlain by the Hibernia Formation, the lower boundary is usually picked at a weak "shoulder" on the gamma-ray/sonic log caused by the higher gamma-ray response and lower sonic velocity of the Whiterose Shale. Beyond the depositional limit of the Hibernia Formation the Whiterose Shale overlies the Fortune Bay Shale. Their contact may be recognized by the more regular sonic log response and higher sonic velocity of the Whiterose Shale (e.g. South Tempest G-88 at 3143 m). The upper contact with the overlying Eastern Shoals Formation is usually sharp and easily identified by log character. Where the Eastern Shoals Formation is not developed the upper boundary is usually an easily identified unconformity at the base of the Avalon Formation.

Distribution — The formation is widely distributed in the Lower Cretaceous depocentre of the Jeanne d'Arc Basin. It is absent near the basin margins where it passes laterally into arenaceous units or is eroded.

Age — At the type section, interpreted by Bujak Davies Group (1988c) to be late Kimmeridgian to Barremian. But, for the same reasons stated for the ages of the Jeanne d'Arc Formation and the Fortune Bay Shale, the Whiterose Shale is considered here to be late Tithonian to Barremian in age.

Depositional environment — The fine grained clastics and oolitic limestones of the Whiterose Shale are interpreted to be fully marine sediments deposited seaward of their lateral arenaceous equivalents. The upper and lower tongues were deposited during periods of low sediment supply and shoreline retreat when subsidence rates were slow or sea level was rising.

Avalon Formation, new from McKenzie (1980)

FIGURE 20

Name — McKenzie (1980) introduced the Avalon sand zone to designate the uppermost hydrocarbon reservoir at the Hibernia oil field. Arthur et al. (1982) called the same unit the Avalon member of the Missisauga Formation, extending the stratigraphic framework of Jansa and Wade (1975) for the southern Grand Banks to the Jeanne d'Arc Basin. Several subsequent authors have used the same

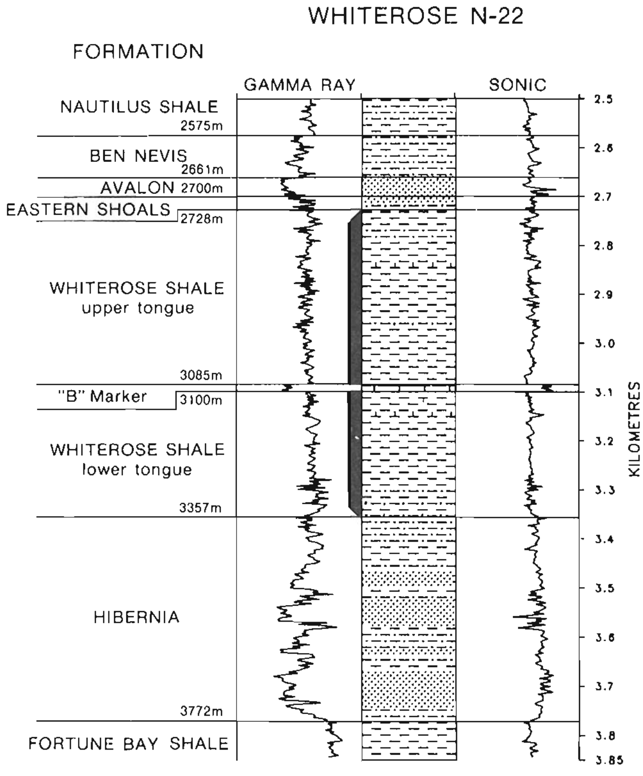

Figure 25. Gamma-ray/sonic log and lithostratigraphy of Whiterose N-22 well. Well type section for Whiterose Shale (upper and lower tongues). Legend as in Figure 11.

name in other parts of the Jeanne d'Arc Basin and applied it to a heterogeneous group of terrigenous deposits located between the Catalina Formation and the Petrel limestone. The Avalon member is here given formation rank. The Avalon Formation is restricted to the middle part of the Avalon member (as defined by Arthur et al., 1982) and redefined as the coarsening upward mudstone- and sandstone-dominated unit underlain by the Eastern Shoals Formation and overlain by the Ben Nevis Formation.

Well type section — Mobil et al. Ben Nevis I-45 from 2755 to 2880 m, 125 m thick, is here designated the well type section (Fig. 20, Table 1).

Lithology — The Avalon Formation is a complex and variable siliciclastic sequence. However, three subdivisions displaying a gross overall coarsening upward pattern are identifiable locally and regionally.

At the type section, the basal subunit (2838-2880 m) is a ''red mudstone'' sequence characterized by varicoloured shales containing a few thin interbeds of sandstone. The shales are reddish brown, greyish green, and mottled red and green, waxy, silty, locally calcareous, and fissile; they are carbonaceous and fossiliferous. The sandstones are grey to light brown, very fine to fine grained, subangular, moderately to well sorted, carbonaceous, fossiliferous, and calcareous. The lower subunit consistently displays a low velocity sonic log signature that is useful for basinwide correlation (e.g. South Mara C-13, 3109-3132 m and Hibernia O-35, 2324-2340 m). The sequence was cored at Hibernia K-14 (2406-2419.5 m) and Hibernia B-27 (2588-2599 m) where the shales appear as silty, red-brown and grey mudstones with greenish reduction mottles, and contain common bivalve and gastropod fossils and rootlets, and local siderite concretions. Local thin interbeds of sandy bioclastic packstone and fine grained calcite cemented sandstone also occur.

The middle subunit (2801-2838 m) at Ben Nevis I-45 contains more common and thicker sandstone beds than the ''red mudstone'' sequence, and the interbedded shales are generally grey. The sandstones are white to light grey, very fine to fine grained, subangular, well sorted, and generally friable but silica and calcite cemented in part.

The upper subunit of the Avalon Formation is a slightly coarsening upward, sandstone-dominated unit that occurs ubiquitously at the top of the formation. At the type section (2755-2801 m) the sandstone is white to light brown, very fine to fine grained, subangular, moderately to well sorted, and poorly cemented with silica and calcite. Coal fragments, abundant in the upper half of the unit, probably occur as laminae. Thin beds of grey fossiliferous fissile shale are also present. In other wells, this subunit occurs as a massive sandstone but still retains its slight coarsening upward character. For example, at Hibernia J-34 (2498-2550 m, fully cored) the subunit is characterized by a sequence of stacked sandstone beds (less than one metre to a few metres thick) containing a few thin interbeds of limestone. The sandstones are medium dark grey to pale grey (calcite cemented), very fine and fine grained, argillaceous and bioturbated, locally laminated, and contain scattered concentrations of mudclasts, carbonaceous wood debris, bivalve, brachiopod, gastropod, echinoderm, calcareous worm tube, and indeterminate fossil debris. Pyrite and concretionary calcite and siderite cements are common throughout. The limestones are pale grey, sandy, bioclastic packstones containing gastropods and bivalves. At Terra Nova K-18 (1665 to 1704 m, not cored), the sandstone is slightly coarser, fine to medium grained and locally coarse grained, and contains more interbedded limestone.

Boundaries — The lower contact with the Eastern Shoals Formation is always sharp and clearly marked by gamma-ray and sonic log breaks and by lithological changes discussed previously with the upper contact of the Eastern Shoals Formation. On regional seismic profiles the Avalon Formation and the laterally equivalent Nautilus Shale are seen as a seismic onlap fill sequence overlying the Barremian event (Fig. 4 and 5).

The upper contact with the Ben Nevis Formation is sharp and unconformable at the basin margins and over major structures, becoming disconformable to conformable toward the basin axis. It is placed at the top of the coarsening upward, massive sandstone of the upper subunit of the Avalon Formation. The boundary is difficult to distinguish in well-cuttings samples, except by the generally finer grained texture of the Ben Nevis Formation, but is usually clear on gamma-ray and sonic logs where it is picked at the point where the coarsening upward Avalon formation gives way to the fining upward Ben Nevis Formation. The upper subunit is ubiquitous and gives rise to a prominent basinwide seismic event that climaxes the Avalon seismic fill sequence (Fig. 4 and 5).

The Avalon Formation grades laterally into the Nautilus Shale.

Distribution — The distribution of the Avalon Formation and its controls are as described for the underlying Eastern Shoals Formation. However, the Avalon is locally seen to thin dramatically over some structures, for example Hebron I-13 (1926 -1990 m) and Fortune G-57 (2625-2695 m). In those wells the upper subunit overlies the lower one. The middle subunit is absent due to nondeposition on the crests of synsedimentary highs.

Age — Aptian by palynology at the type section (J.P. Bujak, pers. comm., 1981). At the Hibernia O-35 well, the biostratigraphic age of the Avalon Formation (2195-2348 m) is late Barremian to late Aptian or early Albian by both palynology (E.H. Davies, pers. comm., 1986) and micropaleontology (Ascoli, 1988), which is consistent with a synthesis of biostratigraphic ages from several wells.

Depositional environment — Waning subsidence during the Neocomian had led to sedimentation of the shallow- and marginal-marine sandy/oolitic sheet deposits of the Eastern Shoals Formation. By late Barremian time, the basin was nearly full. The lower ''red mudstone'' subunit of the Avalon Formation, locally emergent and rootleted, probably records a period of very slow, possibly intermittent deposition. The environment envisaged is that of a flat, low-lying coastal plain containing brackish lagoons and swamps bordering a large, tide-dominated shallow estuary. By early Aptian, increased subsidence resulted in rejuvenated sediment supply into the Jeanne d'Arc Basin. Transgressive/regressive deposits of the middle/upper subunits were probably deposited, respectively, in a shallow-marine embayment characterized by grey mudstones interbedded with shoal-water bar, barrier bar, and shoreface sandstones, and in a shallow estuarine channel and estuarine tidal flat environment characterized by clean massive sandstones and thin shales. Rare coal beds in the upper subunit suggest marginal-marine lagoon or nonmarine swamp environments.

Ben Nevis Formation, new from Petro-Canada Incorporated (1985)

FIGURE 20

Name — From the Ben Nevis I-45 well where the formation is best developed. Synonyms include the upper Avalon sands and post-Avalon sands. The name first appeared in industry well-history reports (e.g. West Ben Nevis B-75, Petro-Canada Incorporated, 1985) and, subequently, has been used in several unpublished stratigraphic columns. The Offshore Schedule of Wells (Canada Oil and Gas Lands Administration, 1987) used the term in the summaries of some wells in the Jeanne d'Arc Basin. Boudreau et al. (1986) and McAlpine and Grant (1986) described the unit, both giving it informal formation status. Tankard and Welsink (1987, 1988) referred to the Ben Nevis sequence. The Ben Nevis Formation is defined here as the first fining upward, sandstone-dominated terrigenous sequence immediately overlying the Avalon Formation.

Well type section — Mobil et al. Ben Nevis I-45 from 2377 to 2755 m, 378 m thick, is here designated the well type section (Fig. 20, Table 1).

Lithology — The type section comprises two subunits, but only the upper is present throughout the lateral extent of the formation. The lower subunit (2712-2755 m) consists of thinly interbedded shale and sandstone and local coal beds. The shales are medium to dark grey, fissile, silty, pyritic, and carbonaceous. Sandstones are off-white to light brown, quartzose, friable in part, very fine and fine grained, subangular, well sorted, and partly calcite and silica cemented. The coal is black, vitreous, partly silty, and blocky. This subunit, where present, displays a low velocity signature on the sonic log, making it a distinctive log marker, as for example in North Ben Nevis M-61 (3049-3081 m).

The upper subunit (2377-2712 m at the type section) is a fining upward sandstone sequence. The sandstones are light grey, fine grained near the base, grading through very fine grained to silty at the top. They are quartzose, subangular, moderately to well sorted, carbonaceous, and shelly near the base, becoming slightly argillaceous toward the top, and variably siliceous and calcareous. The sequence has been cored at several wells including Hebron I-13, South Mara C-13, Hibernia J-34, and Hibernia O-35. In those wells, the Ben Nevis Formation is characterized near the base by stacked, fining upward successions of light grey, very coarse to very fine grained, horizontally laminated sandstones displaying sharp erosive bases with lags of macrofossil debris, carbonaceous wood fragments, pebbles, and intraformational mudclasts. Porosity in poorly cemented sandstones is locally reduced by concretionary calcite cement. Upward, the sandstones become more thinly bedded, very fine and fine grained, predominantly argillaceous and bioturbated, and contain abundant macrofossils and common mudclasts. At Hebron I-13, the sandstones are interbedded with thin sandy bioclastic lime packstones showing sharp bases and intraformational mud clasts.

Boundaries — The Ben Nevis Formation overlies the Avalon Formation, the upper contact of which was described previously. The top of the Ben Nevis Formation is marked by the appearance of marly and silty shales of the Nautilus Shale. The contact is abrupt and is picked at a noticeable shoulder on the gamma-ray and sonic logs. Regional seismic studies demonstrate that the contact is unconformable to disconformable near the basin margins and over major structures as indicated by onlap of the overlying beds (Fig. 4 and 5, Albian unconformity). This is often confirmed in wells where the dipmeter indicates a significant change in dip azimuth or angle (e.g. Ben Nevis I-45).

Seismically, the Ben Nevis sequence is distinguished from the Avalon sequence by its lower amplitude and weakness of internal reflections. Seismic onlap to the Aptian unconformity is observed and depositional thinning toward the basin margins and major structures is accompanied by convergence of internal reflections.

Distribution — The Ben Nevis Formation is known in the Jeanne d'Arc Basin from Port au Port J-97 (1226-1254 m) north to Whiterose J-49 (2956-3094 m). The thickness fluctuates markedly due to syndepositional growth of basin structures, being thickest on the eastern side of the basin and in the basin axis. Representative sections include Hibernia G-55 (1870-2359 m), Hibernia J-34 (2113-2498 m), Hibernia O-35 (2049-2195 m), South Mara C-13 (2682-2958 m), Hebron I-13 (1860-1927 m), Archer K-19 (2112-2170 m), and Terra Nova K-18 (1590-1665 m).

Age — Late Aptian to late Albian, by palynology, at the type section (J.P. Bujak, pers. comm., 1981).

Depositional environment — Although the Ben Nevis Formation was deposited during a period of significant basin structuring and growth faulting, the uniform, fine grained texture of the formation suggests that depositional relief was low and that sediment supply to the basin kept up with differential subsidence. In general, the fining upward Ben Nevis sandstones record a period of transgression. The sediments are suggestive of a large estuary fed by low gradient, northeasterly flowing rivers. Major estuarine/tidal channel facies pass laterally, in an offshore direction, and vertically into shallow tidal channel and bioturbated tidal flat environments.

Eider Formation, new from Amoco and Imperial (1973)

FIGURES 14 and 26

Name — From the Amoco IOE A-1 Eider M-75 well in the Whale Basin where the type section is located. The "Eider Unit" was introduced informally by Amoco and Imperial (1973) to designate the first transgressive sand-shale sequence overlying the "mid-Cretaceous unconformity" (Avalon Unconformity), and they tentatively correlated the unit to the Logan Canyon Formation (McIver, 1972). Jansa and Wade (1975) referred to the Eider member in the vicinity of the Avalon Uplift and described it as corresponding to the upper sandstone pulse of the Logan Canyon Formation in the Scotian Basin.

The Eider Formation is defined here as a sandstone-dominated unit deposited across the Avalon Uplift and directly overlying the Avalon Unconformity where it is a well-developed peneplain. In peripheral basins (Jeanne d'Arc, Carson, and South Whale) the formation shales out rapidly but may be developed locally over structures.

Well type section — Amoco IOE A-1 Eider M-75 from 708 to 830 m, 122 m thick, is here designated the well type section (Fig. 26, Table 1).

Well reference section — Mobil et al. Rankin M-36 from 1582 to 1730 m, 148 m thick, is designated the well reference section for the Jeanne d'Arc Basin (Fig. 14, Table 1).

Lithology — At the type section the Eider Formation comprises a basal mudstone, 23 m thick, overlain by a sandstone-dominated (62 percent) terrigenous sequence. Quartzose sandstone beds, 3 to 5 m thick, stacked at the top and base of the upper unit are interbedded with shale and siltstone in the middle of the unit. The stacked sandstones are light grey to white, unconsolidated to friable, medium to very coarse grained, subangular to subrounded, and medium to well sorted. Coal, pyrite, and siderite are common accessories. Sandstones in the middle of the unit are calcite cemented, fine grained, subangular, and medium to well sorted. Glauconite grains and pelecypod shell fragments are common. Interbedded with these sandstones are light to dark grey, calcareous mudstones and marls containing abundant siderite concretions.

In the Jeanne d'Arc Basin the Eider Formation is generally a coarsening upward sequence of sandstone and mudstone with lesser limestone and marl. At Rankin M-36, thinly bedded sandstones near the base of the formation are white, calcite cemented, very fine grained, subangular, and well sorted, containing abundant shell fragments and glauconite. Interbedded mudstones are grey to brown, calcareous, shelly, and glauconitic. Between 1628 and 1682 m, the section consists of thinly interbedded limestones, marls, mudstones, and very fine grained sandstones. The limestones are white to grey, chalky, glauconitic, and sandy. Above 1628 m, the formation is predominantly sandstone, poorly consolidated to friable, medium to coarse grained, medium to well sorted, locally calcite cemented, and glauconitic. In other wells, coal and carbonaceous material are accessory constituents.

Boundaries — Across the Avalon Uplift, where the Avalon Unconformity is a conspicuous peneplain, the base of the Eider Formation is in marked unconformable contact with either older Mesozoic rocks or Paleozoic or Precambrian basement rocks. Off the flanks of the Avalon Uplift the formation probably rapidly loses its identity in equivalent marine shales. Seismic data from the Jeanne d'Arc Basin show that, crossing the Egret Fault, the youngest of the divergent suite of unconformities related to the Avalon Unconformity also marks the base of the Eider Formation (Fig. 6, 9, and 10). Northward in the basin, this surface rapidly becomes paraconformable and, eventually, occurs in conformable beds of the Nautilus Shale. In that area, the equivalent base, although not usually recognized in samples, remains a good log marker allowing identification of an Eider Formation equivalent of the Nautilus Shale. This log marker is picked in wells at the base of a reverse shoulder on the sonic and gamma-ray logs, for example, West Ben Nevis B-75 at 1845 m. The upper boundary is usually a sharp and probably conformable contact with the overlying Dawson Canyon Formation. In Jeanne d'Arc Basin wells it is usually picked at the base of a thin, low velocity shaly unit just below the Petrel Member.

Distribution — In the Jeanne d'Arc Basin, the Eider Formation passes into distally equivalent, fine grained sediments of the upper Nautilus Shale north of the Rankin M-36 and the Terra Nova field structures. However, local sand developments over basin margin structures are also included in the formation, for example, Mercury K-76 (1875-2362 m) and Whiterose L-61 (2650-2805 m).

Age — By palynology, Cenomanian to Turonian at the type section (Barss et al., 1979) and late Albian to late Cenomanian at the reference section (Bujak Davies Group, 1988a), which is consistent with the range of ages in the Jeanne d'Arc Basin. At the Pelican J-49 well (in the Whale

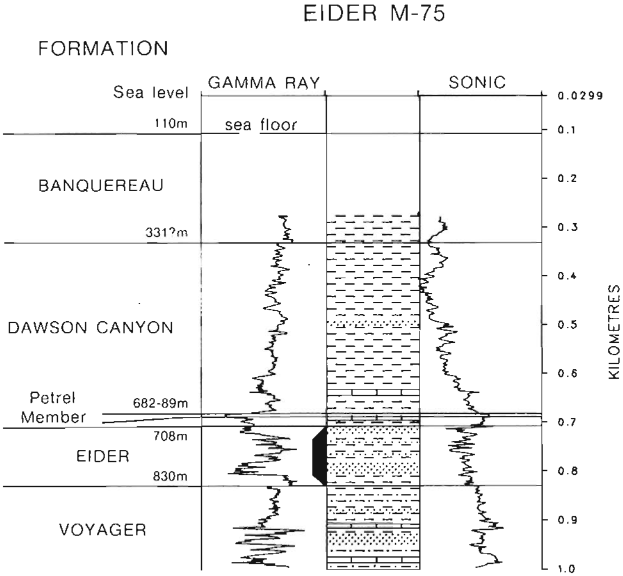

Figure 26. Gamma-ray/sonic log and lithostratigraphy of Eider M-75 well. Well type section for Eider Formation. Legend as in Figure 11.

Basin), the Eider Formation (811-1079 m) is Berriasian to Cenomanian in age (Barss et al., 1979). Conceivably, the formation's age could span Kimmeridgian to Turonian over the Avalon Uplift, reflecting the ages of the upper Mesozoic unconformities that coalesce to form the Avalon peneplain.

Depositional environment — The Eider Formation is the first sedimentary unit deposited on top of the Avalon Unconformity. A frequent lack of marine dinoflagellates and microforaminifera, along with the common occurrence of siderite nodules and coal, indicates that nonmarine conditions prevailed during deposition of parts of the formation. The overall depositional environment envisaged is one of a broad alluvial plain rapidly giving way to marginal- and shallow-marine conditions off the flanks of the Avalon Uplift.

Nautilus Shale, new

FIGURE 27

Name — From the Nautilus C-92 well where the formation is well developed and the type section is located. The Nautilus Shale is defined as the lateral fine grained equivalent of the Avalon, Ben Nevis, and Eider formations. This formation, usually left unnamed in published and unpublished stratigraphies that have focused on potential reservoir units, is probably synonymous with the informal Shortland shale of Jansa and Wade (1975) and Wade (1978, Fig. 7).

Well type section — Mobil et al. Nautilus C-92 from 2668 to 3285 m, 617 m thick, is here designated the well type section (Fig. 27, Table 1).

Lithology — The Nautilus Shale is a monotonous unit dominated by grey calcareous shale or mudstone, depending on the degree of lithification.

At the type section, the formation consists mainly of shale, light to medium grey and rarely multicoloured, variably calcareous and silty, and blocky to platy. Nodular or bedded siderite, pyritized fossils, and carbonaceous debris are common, and glauconite is rare.

Mechanical logs allow a threefold subdivision of the type section that is reflected in slight lithological variations (Fig. 27). This subdivision is corroborated by seismic interpretation. The lower 70 m of the basal subunit (3048-3285 m, Ben Nevis Formation equivalent) contains significant intercalated beds of brown, very fine grained, silty sandstone that grades upward into siltstone. Grey to brown, calcareous and sandy siltstone beds are common in the remainder of the lower unit. The middle subunit (2847-3048 m) contains rare siltstone beds and sandstone stringers. The upper subunit (2668-2847 m, Eider Formation equivalent) contains common grey, very calcareous and argillaceous siltstone and white to grey, argillaceous, silty, microcrystalline to chalky, limestone beds.

This subdivision is typical of the formation regionally, for example South Mara C-13 (lower unit, 2633-2829 m ; middle unit 2377-2633 m ; upper unit, 2258-2377 m), North Trinity H-71 (lower unit, 1910-1978 m ; middle unit, 1762-1910 m ; upper unit, 1650-1762 m), and Terra Nova K-18 (lower unit, 1550-1590 m ; middle unit, 1521-1550 m ; upper unit developed as Eider Formation, 1460-1550 m).

Boundaries — The Nautilus Shale is easily distinguished in samples and mechanical logs from its arenaceous equivalents or the overlying Petrel Member limestone of the Dawson Canyon Formation. The lower contact, usually taken to be the Albian unconformity where the Ben Nevis Formation is present, is abrupt and unconformable to conformable as demonstrated by its seismic onlap relationship with underlying units (Fig. 4, 5, and 6). The upper contact is also abrupt but probably conformable.

Distribution — The Nautilus Shale is virtually ubiquitous in the Jeanne d'Arc Basin where middle Cretaceous strata were deposited and preserved. The middle unit and the upper unit (Eider Formation equivalent) are the most widespread.

Age — Early Aptian to late Albian-Cenomanian by micropaleontology at the type section (Williamson, 1987). The formation has potentially the same overall age range, late Barremian to late Cenomanian-Turonian, as its lateral equivalents, the Avalon, Ben Nevis, and Eider formations.

Depositional environment — The Nautilus Shale was deposited in a transgressive (lower and middle units)/regressive (upper unit), low energy, open marine shelf environment. Clastic input was limited, especially during deposition of the middle unit.

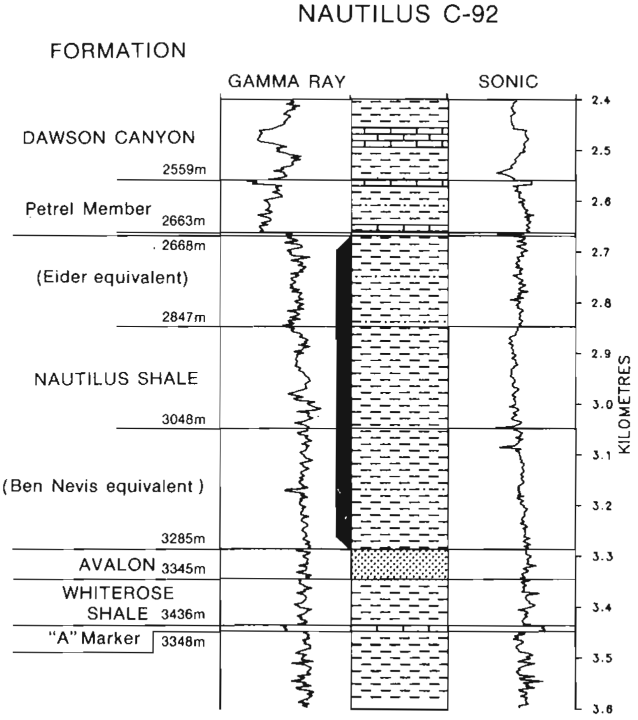

Figure 27. Gamma-ray/sonic log and lithostratigraphy of Nautilus C-92 well. Well type section for Nautilus Shale. Legend as in Figure 11.

SEDIMENTARY EVOLUTION

This interpretation of the sedimentary evolution of the Jeanne d'Arc Basin is based on the recognition of several regionally mappable seismic sequences (Fig. 4 and 5). Correlation of lithostratigraphic and biostratigraphic data bases with these geophysical sequences has provided a framework for dividing the stratigraphic record into six distinctive depositional sequences (Fig. 4 and 6). Although the basin lies well inboard of the present continent-ocean boundary, these depositional sequences may be correlated approximately with rifting and spreading events associated with the formation of the North Atlantic Ocean and the Labrador Sea. In brief, the six Mesozoic-Cenozoic sequences record two periods of rift-related subsidence associated with seafloor spreading that were separated by a tectonically quiet period and that were followed by a two-phase transition to passive margin subsidence.

Sequence 1 — Aborted Rift (Late Triassic to Early Jurassic)

Sequence 1 overlies pre-Mesozoic basement. During the Late Triassic, a vast and apparently coherent rift system began to develop between the North America-Greenland plate and the Europe-Africa plate with an arm extending into the area of the present North Sea. The first sediments to fill these rifts were continental sands and muds (Eurydice Formation). As rifting progressed, the sediments record a vertical sequence of environments that reflects a gradual flooding by marine waters from the Tethys Sea. Restricted evaporite basins developed initially and extensive salt deposits (Osprey and Argo formations) accumulated in an arid climate. The thin unit of subaerial basalt flows encountered in the Jeanne d'Arc Basin between the Osprey and Argo salts is broadly synchronous with a widespread igneous event associated with the first stage of North Atlantic rifting (Jansa and Pe-Piper, 1986). Eventually, as more marine conditions were encountered, anhydritic dolomite and oolitic and skeletal limestones (Iroquois Formation) were deposited in coastal sabkhas, restricted lagoons, and finally a warm shallow sea. Similar lithofacies occur in the Scotian Shelf, northwest Africa, the Celtic Sea, the Northwest Approaches of the British Isles, and in southern North Sea basins.

Sequence 2 — Epeiric Basin (Early to Late Jurassic)

Sometime during the Early Jurassic, Africa decoupled from North America and continental and marine sands and muds were deposited on their developing oceanic margins. However, plate movement was apparently accommodated by transform motion at or parallel to the Newfoundland Fracture Zone (Fig. 2), and rifting was aborted to the north. Sequence 2 consists predominantly of marine shales and limestones deposited in a broad epeiric sea that flooded the old rifted topography. Remnants of these deposits occur in the basins of the Grand Banks and also in the Celtic Sea, southern England, and the southern North Sea.

The shales and limestones of the Downing Formation indicate a low energy, shallow, epicontinental sea depositional environment dominated by eustatic sea level changes. Shoaling and infilling of the sea is suggested by fine grained sandstone, shale, and coal, and subordinate oolitic limestone of the Voyager Formation deposited in an interpreted deltaic nearshore to marginal-marine environment. Very shallow water oolitic limestones and minor fine grained sandstones dominate the Rankin Formation in the southern part of the Jeanne d'Arc Basin. North of the Hibernia to Ben Nevis trans-basin fault zone, the Rankin Formation consists of fine grained siliciclastics suggesting a deeper marine environment. The Egret Member is a distinctive, organic-rich shale of early Kimmeridgian age. Its interpreted environment is that of a restricted silled basin where clastic influx was low, possibly indicating fragmentation of the sea into discrete depocentres.

Sequence 3 — Late Rift (latest Jurassic and Neocomian)

The base of sequence 3 is a major middle Kimmeridgian unconformity probably associated with the initiation of the Avalon Uplift and, by inference, with the renewal of tensional conditions and rifting that continued throughout the Early Cretaceous between North America and Europe. Sequence 3 is homotaxial to the Missisauga Formation on the Scotian Shelf. Previous shale and carbonate deposition in an epeiric sea was replaced by a clastic-dominated rift sequence in the developing graben on the flanks of the Avalon Uplift (South Whale, Carson, and Jeanne d'Arc basins). However, regional uplift and associated peneplanation outpaced trough development around the axis of the Avalon Uplift. Hubbard et al. (1985) suggested that Early Cretaceous subsidence in the Jeanne d'Arc Basin was influenced by the northwest-trending Labrador rift system. The similarly northwest-trending Egret Fault has a throw of about 2 km and overlies a major basement fault (Fig. 3 and 4). Movement on both faults probably began in the Berriasian which may coincide with the initiation of volcanic activity and rifting on the Labrador Shelf (McWhae, 1981). Thus, the timing and the orientation of these faults, parallel to the southwestern boundaries of the East Newfoundland Basin and the Labrador Shelf basins, suggest an overprinting of the Grand Banks-Iberia and Labrador Sea tensional regimes which enhanced subsidence and complicated the Lower Cretaceous stratigraphy of the Jeanne d'Arc Basin.

The average sediment accumulation rate for Middle Jurassic to early Kimmeridgian time appears to have almost doubled at the onset of sequence 3. The initially high subsidence rate led to the deposition of fluvial fan and fan-delta conglomerates and coarse grained sandstones of the Jeanne d'Arc Formation. As subsidence slowed, the basin was filled by a variety of sediments : coastal plain-delta top and delta front-prodelta sandstones of the Hibernia Formation ; interdistributary bay and shallow-marine shoreface facies of the Catalina Formation ; estuarine to tidal flat sandstones and siltstones of the Eastern Shoals Formation ; and Fortune Bay and Whiterose shales that isolate the sandstone units vertically, one from the other.

The source area for these sediments was the Avalon Uplift, south of the Egret Fault, and the Bonavista Platform and the Outer Ridge Complex to the west and east (Fig. 2). The sediments fine upward overall, and this is interpreted to reflect gradual peneplanation of the source areas and exposure and erosion of progressively older and finer grained Jurassic and Triassic rocks.

Sequence 4 — Transition to Drift: Phase I (Barremian to Cenomanian)

The siliciclastic units of sequence 4 were probably deposited during the transition from rifting to continental separation between the Grand Banks and Iberia. Incipient spreading may have occurred between the Grand Banks and northern Europe during this time.

Sequence 4 is coeval with and stratigraphically similar to the Logan Canyon Formation of the Scotian Shelf. Basin subsidence and sediment accumulation had waned during the Neocomian. In the latest Barremian and Aptian, subsidence began slowly to increase, but the hinterland was still low lying and initial deposits of the Avalon Formation were lagoonal and tidal flat mudstones and fine grained estuarine sandstones. The multicoloured mudstone unit, in the lower part of the Avalon Formation, is equivalent to the Naskapi Member of the Logan Canyon Formation.

A new period of basin deformation is recorded by the Hibernia to Ben Nevis trans-basin fault trend. Figure 4 shows that most fault movement occurred during the Albian, a stage bound by unconformities. This is the last period of deformation to affect the Jeanne d'Arc Basin and may correspond in time to the beginning of spreading between the Grand Banks and Iberia. The late Aptian unconformity shows well-developed angularity both near the basin margins and over structures. There is little seismic evidence of tectonic movements involving basement during this period ; most of the disruption in the sedimentary section may be accounted for by salt flowage. Many of the faults of the trans-basin trend appear to be listric at depth, but the seismic data involved are difficult to interpret (Fig. 4). Although some faults may sole out in salt, most appear to be restricted to younger strata and sole out in overpressured Jurassic shales.

The Ben Nevis Formation is a syntectonic deposit related to this phase of basin development. Sediment was supplied from the margins and down the axis of the basin and locally from high standing fault blocks. Reworking and winnowing of sediments, especially along the trans-basin fault trend, was an important factor in producing reservoir quality sandstones.

The late Albian unconformity at the top of the Ben Nevis Formation was less erosive than the late Aptian unconformity. Angularity is observed only at the basin margins and over the most prominent structures. In a sense it represents a base-level surface caused by syntectonic infill and bevelling of the Albian structures. In the basin depocentre, prominent seismic onlap can be observed over this surface indicating that the basin was subsiding faster than sediment was filling it. The southern part of the basin was tectonically stable. There, the Eider Formation sandstones and conglomerates were deposited in a continental to marginal-marine environment. Farther north, shallow water marls and shales of the Nautilus Shale accumulated.

Sequence 5 — Transition to Drift: Phase II (Late Cretaceous and Paleocene)

Sequence 5 records the final transition to a passive margin setting. Complete separation of the Grand Banks and the British Isles probably occurred during this period. Sediment supply was intermittent and produced overlapping deltaic sequences with distal turbidites. Deep water chalky limestones were deposited when subsidence outpaced sediment supply. The Late Cretaceous and Tertiary unconformities are interpreted to correspond respectively to the break-up between Labrador and Greenland and Greenland and northern Europe.

Transgressive marine shales of Cenomanian and Turonian age, in the lower part of the Dawson Canyon Formation, underlie the chalky Petrel Member deposited in an outer neritic environment. Within the Senonian (Coniacian-Maastrichtian), prograding clinoforms observed on seismic lines (Fig. 5) indicate sediment influx from the west that formed an offlapping clastic wedge. Equivalent sediments in the basin depocentre are chalky, outer neritic limestones of the Wyandot Formation.

The top of the Late Cretaceous is an unconformity exhibiting conspicuous channelling into the underlying Dawson Canyon Formation (Fig. 5). The overlying South Mara unit of Paleocene age consists of delta front sands and prodelta turbidites.

Sequence 6 — Passive Margin (Tertiary)

By Eocene time, sediment supply had dwindled. The Grand Banks were surrounded by oceanic crust of the proto-Atlantic Ocean, and tensional conditions that had dominated since the Late Jurassic were absent. Thermal subsidence and seaward tilting of the passive margin led to deposition of deep neritic shales and minor chalks, siliceous mudstones, and rare sand-silt beds of the Banquereau Formation as the modern shelf was established.

Paleoenvironmental data from Tertiary sections in the East Newfoundland Basin indicate a change in Oligocene time from deep neritic and bathyal deposition to shallow neritic environments (Gradstein and Williams, 1981). Sea level lowered again in Middle to Late Miocene time and much of the Grand Banks may have been exposed subaerially. At the present time, the erosional and depositional record of this regression cannot be distinguished unequivocally from the effects of Pleistocene lowerings of sea level (Grant et al., in press).

PETROLEUM POTENTIAL

Until the present time, significant discoveries of offshore hydrocarbon accumulations have been made only on the Canadian portion of the North American eastern continental margin. While the discoveries off the Nova Scotian and the Labrador coasts are mainly gas, the Jeanne d'Arc Basin is the site of many significant oil discoveries and has a relatively small proportion of gas (Grant et al., 1986a, b). The potentially commercial oil reserves in this basin reflect the favourable association of a mature, organic-rich, oil-prone source rock, good reservoir beds and trapping mechanisms, proper timing of trap formation, and good migration pathways. This combination of ingredients, which has not been located elsewhere, derives from the unique geological history (explained previously) of the Grand Banks and, particularly, of the Jeanne d'Arc Basin. The parameters and their interaction will be discussed below in more detail.

Geochemical studies conducted by the Geological Survey of Canada on the oils and sediments of the Jeanne d'Arc Basin over the last several years have provided a good understanding of hydrocarbon generation and entrapment in that area. Early results by the Survey (Powell, 1984 ; Grant et al., 1986a, b ; McAlpine and Grant, 1986 ; McAlpine et al., 1986) and others (Swift and Williams, 1980 ; von der Dick and Meloche, 1986 ; Creaney and Allison, 1987) indicated that all the discovered oils belong to the same genetic family and had a common oil-prone source, defined in this paper as the Egret Member of the Rankin Formation. More recent studies by Survey researchers have provided evidence of significant, but yet unquantified, hydrocarbon contributions from more terrestrial, gas-prone organic material (Snowdon and Krouse, 1986) in potential source rocks within the Voyager Formation and the upper unit of the Jeanne d'Arc Formation (Fowler et al., 1988 ; McAlpine et al., 1988).

Rock-Eval pyrolysis data identify potential hydrocarbon source rocks and yield quantitative geochemical parameters that characterize their quality. Figure 28 shows typical Rock-Eval results from two widely spaced wells ; Rankin M-36 is located south of the Hibernia field and Panther P-52 lies over 100 km to the northeast on the Outer Ridge Complex (Fig. 3). The data from both wells establish the presence of source potential within the Voyager Formation and in a zone of the Rankin Formation focused at the Egret Member. The third potential source is evident within the upper Jeanne d'Arc Formation at the Panther P-52 well. The first two parameters in Figure 28 are low-focus indices of maturity that increase systematically with depth. The S2/S3 and hydrogen index (HI) parameters detect kerogen having source potential and classify its type ; the high S2/S3 values for the Egret Member indicate that it contains highly oil-prone Type II — I kerogen, whereas relatively lower values in the Voyager and Jeanne d'Arc formations indicate a greater proportion of gas-prone Type III kerogen. Biomarker data on most recovered oils suggest that the contributions from the lower and upper sources may be relatively minor (Fowler et al., 1988 ; M.G. Fowler, pers. comm., 1988), a theory supported by their relatively low (S1 + S2) values that indicate poor genetic potential. Moreover, the uppermost potential source rock appears to have limited regional extent, thus far confined to the northeastern part of the basin. The rest of this section, therefore, deals mainly with the hydrocarbon potential of the Egret Member.

Powell (1984) used gasoline range data, including normalized composition of C_7 compounds, saturate fraction gas chromatograms, and paraffin indices, to indicate that the oils in the Jeanne d'Arc Basin belong to one genetic family. Furthermore, he suggested that they could be traced to a potential source rock first identified geochemically in 1980 by Swift and Williams (the Egret Member). Biological marker data confirm these interpretations. Figure 29 shows biological marker "fingerprints", obtained by gas chromatography-mass spectrometry (GC-MS), of an extract of the Egret Member and two oils recovered from three scattered wells (McAlpine et al., 1986). The striking similarity among the mass fragmentograms shows a strong correlation between the oils and the extract. Recent bio-marker data by the Geological Survey of Canada indicate that the Voyager Formation has contributed to some of the oils especially in the Ben Nevis-West Ben Nevis area (Fig. 30).

Although the oils in the Jeanne d'Arc Basin are similar, Powell's (1984) data also provided evidence that they had been generated over a wide range of maturation levels. A similar interpretation based on bio-marker data was reported by McAlpine et al. (1986) who showed that the oils even differed locally in degree of maturity in stacked pools within the same well. Most of the hydrocarbon discoveries have been made in the Upper Jurassic to Lower Cretaceous rift and rift-drift transition sequences 3 and 4 ; reservoir units include the Jeanne d'Arc, Hibernia, Catalina, Eastern Shoals, Avalon, and Ben Nevis formations. Nevertheless, the Egret Member occurs near the top of the stable epeiric basin sequence 2. Clearly, the oil has migrated long distances vertically and it is evident from the vertical variations in maturity that more than one episode of oil migration has occurred in some areas.

In much of the prospective area of the Jeanne d'Arc Basin the source rock is now overpressured, while the majority of discovered hydrocarbons are in the overlying, hydrostatically pressured regime. The laterally continuous Fortune Bay Shale generally forms the caprock for the overpressure. Figure 31 illustrates a combined plot of shale sonic transit times and pressures in porous rocks versus normalized depth for five Hibernia field wells. Similar data from all wells in the basin demonstrate that the Fortune Bay is consistently undercompacted, although the overpressure may be absent now due to past leakage. It is interesting that wells that do not exhibit overpressure are usually dry holes, leading to speculation that the overpressure is a significant factor in hydrocarbon accumulation. Besides retaining connate and diagenetic fluids in the rocks until thermal conditions are ideal for the generation of hydrocarbons, the overpressure may, in fact, promote subsequent migration. The main path for oil migration appears to be along faults and fractures that have opened sporadically in response to buildup of abnormally high fluid pressures. Pressure plots for many wells show that the rate of pressure increase with depth, within the sealed zone, is faster than can be accounted for by simple loading, probably because of thermal expansion and hydrocarbon generation. This means that the shales will become mobile at depth and cause faults and fractures in the overlying section that become avenues for pressure and fluid escape and oil migration. This process is cyclic because the faults would close after pressure release.

The timing of hydrocarbon generation and migration can be estimated by determining when the source rock reached thermal maturity. For Type II kerogen, oil generation should begin at a vitrinite reflectance (Ro) level of about 0.5, peak at Ro 0.8, and end at about Ro 1.35 (Dow, 1977). Figure 32 is a schematic structure map on top of the Egret Member that also shows where the source rock intersects the present day oil generative window. The areas of relative maturity were determined by cross-contouring the Egret Member structure map with structure maps on the top and the base of the oil generative window based on Ro data from 18 wells. It is evident that the majority of oil discoveries lie within the area underlain by the present day mature zone and that the gas-prone wells are within or proximal to the overmature zone. This circumstantial evidence suggests that the Egret Member is the dominant hydrocarbon contributor in the basin and that the gas may be an overmature product of this source rock, rather than a normal product of the Voyager or Jeanne d'Arc potential source intervals. Because the structural framework of the Jeanne d'Arc Basin was essentially established prior to Late Cretaceous time, the present thermal maturation configuration is likely to have existed throughout the last 100 Ma and to have ascended stratigraphically as the basin was buried beneath a relatively uniform blanket of Late Cretaceous and Tertiary strata. Time-temperature index numerical modelling indicates that, near drilled structures, oil generation typically began only about 100 Ma ago and that peak generation was not reached until about 50 Ma ago during the early Tertiary, long after the structural traps had been formed (Ervine, 1985; Brown et al., 1989). Therefore, all drillable structures that are suitably located with respect to mature Egret Member source beds can be considered prospective for hydrocarbon entrapment.

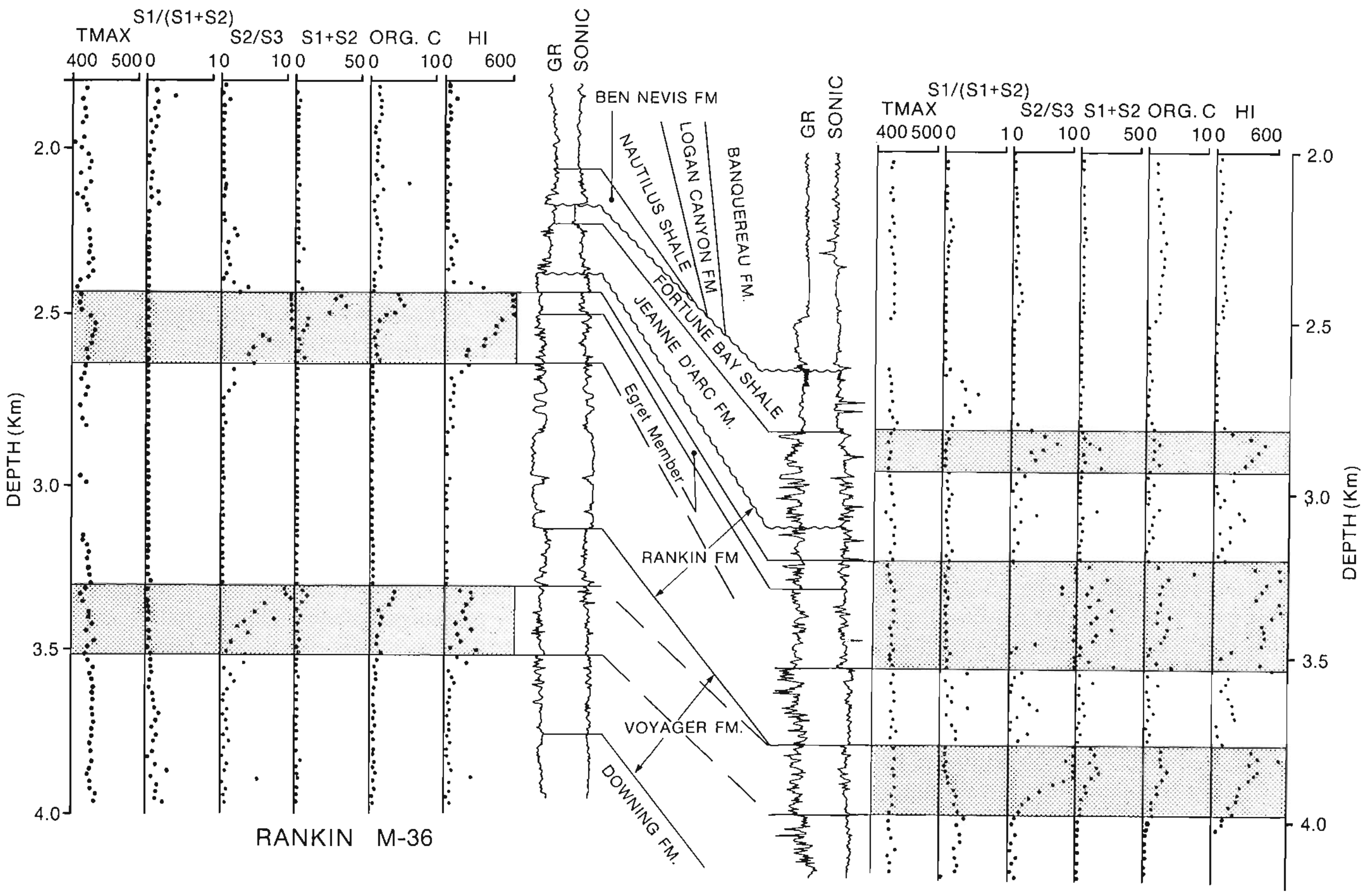

Figure 28. Rock-Eval pyrolysis data and lithostratigraphic correlation for Rankin M-36 and Panther P-52 wells. Well locations in Figure 3. Pyrolysis is a process whereby a rock sample is heated under controlled conditions in the absence of oxygen until thermal decomposition of the dispersed organic matter occurs. Organic compounds are released in two stages; S1 is indicative of free hydrocarbons that are indigenous or migrated into the sample and S2 represents hydrocarbons produced by thermal conversion of the dispersed organic matter. S3 is a measure of the carbon dioxide released and TOC is the weight percent of organic carbon. The hydrogen index (HI) is the ratio S2/TOC. See text for discussion.

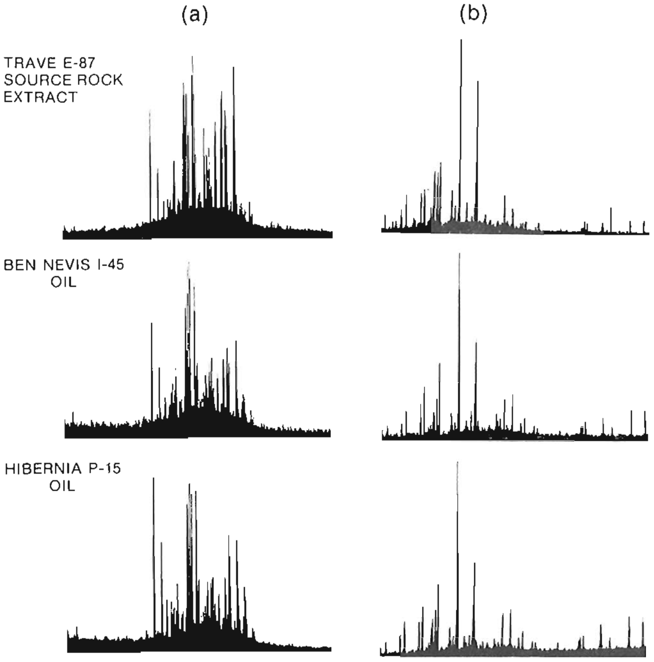

Figure 29. Comparison of the distributions of (a) steranes (m/e 217 mass fragmentograms) and (b) triterpanes (m/e 191 mass fragmentograms) obtained by GC-MS from an extract of the Egret Member at Trave E-87 and oils at Ben Nevis I-45 and Hibernia P-15. Data from McAlpine et al. (1986). Well locations in Figure 3.

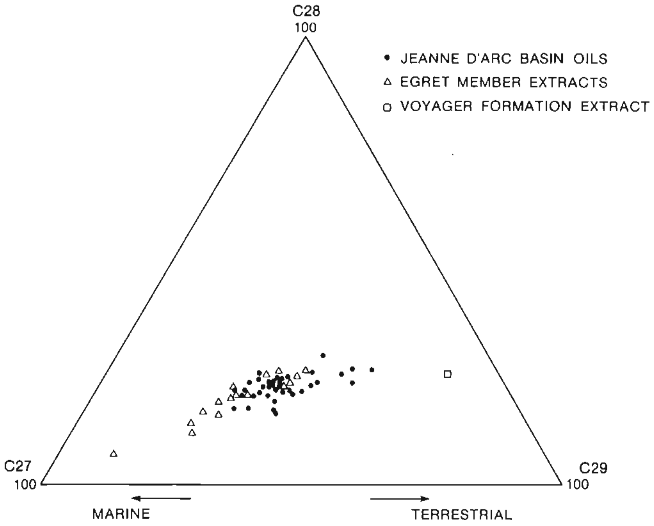

Figure 30. Ternary diagram of $C_{27}:C_{28}:C_{29}$ regular sterane abundances in oils and source rocks in the Jeanne d'Arc Basin. Note range of oils compared to source rocks. Most oils plot toward C_{27} (marine side) while a few plot more toward C_{29} (terrestrial) side (e.g. Ben Nevis and West Ben Nevis) and outside the Egret Member data scatter (unpublished results, courtesy of M.G.Fowler).

A quantitative evaluation of the ultimate oil potential of the Jeanne d'Arc Basin was made by combining geological and geochemical data for the main oil source rock interval. The following summary is based on data presented by McAlpine et al. (1988).

Fifteen wells, including two on the Outer Ridge Complex, are interpreted to have penetrated the source interval and Rock-Eval pyrolysis analyses have been performed on eleven of these wells. To characterize the source rock and obtain parametric data for the calculations, isopach and geochemical maps were constructed for both the entire Rankin Formation source zone and for the Egret Member contained within it. The results summarized in Table 2 are weighted averages, calculated by planimetering the area between contours on the maps. The average values pertain only to the mature and overmature area of the source rock in the basin shown in Figure 32 and do not include the Outer Ridge Complex. Most of the geochemical data were from samples that were fairly immature but still within the oil window. Moreover, the geochemical values increased basinward, as might be expected, indicating that, although the TOC and HI numbers are slightly depressed, they are accurate reflections of source quality.

Two methods were used to calculate the potential oil yield of the Egret Member, a geochemical mass balance method (Goff, 1983) and a more direct method employing HI values. Using the mass balance method, the volume of oil generated is the mathematical product of the bulk volume of the source rock, the percent by volume of organic material, the genetic potential (about 70 percent for Type II kerogen), the fraction of oil in the hydrocarbon yield (about 80 percent), the transformation ratio (about 0.5 from Rock-Eval data), and the volume increase on oil generation (1.15 using specific gravities of 1.0 for kerogen and 0.87 for the oil). Using the HI method the volume of oil generated is the mathematical product of the bulk volume of the source rock, the density of the source rock, the percent by weight TOC, the HI, the fraction of oil in the hydrocarbon yield, and the volume increase on oil generation. Both methods provided similar results (Table 3). The average estimate for the entire Rankin Formation source interval is 43 billion cubic metres or 271 billion barrels of oil generated. The calculations for the Egret Member yielded an average value of 34 billion cubic metres or 214 billion barrels, about 80 percent of the total.

These figures do not take into account expulsion, migration, and trapping inefficiencies and, of course, do not include potential contributions from the Voyager and Jeanne d'Arc formations. However, even assuming a pessimistic value for these inefficiencies of 15 percent of the oil ending up in traps, potential oil in place in the Jeanne d'Arc Basin could be as high as 6.5 billion cubic metres or 41 billion barrels (Table 3). A recovery factor of 30 percent would give recoverable reserves of 1.95 billion cubic metres or 12.3 billion barrels (Table 3).

Available estimates for the recoverable oil potential of the area at the average expectation are 1.13 billion cubic metres (7.1 billion barrels) by the Geological Survey of Canada (Procter et al., 1984) and 1.96 billion cubic metres

Table 2 Source rock parameters used to calculate volume of oil that could potentially have been generated in the Jeanne d'Arc Basin.

	QUANTITY		QUALITY	
	AREA (KM²)	THICKNESS (KM)	TOC wt % (vol %)	HI mgHC/gOC
EGRET MEMBER	7020	0.12	3.5 (10.5)	600
ENTIRE RANKIN FORMATION	7020	0.24	2.5 (7.5)	450

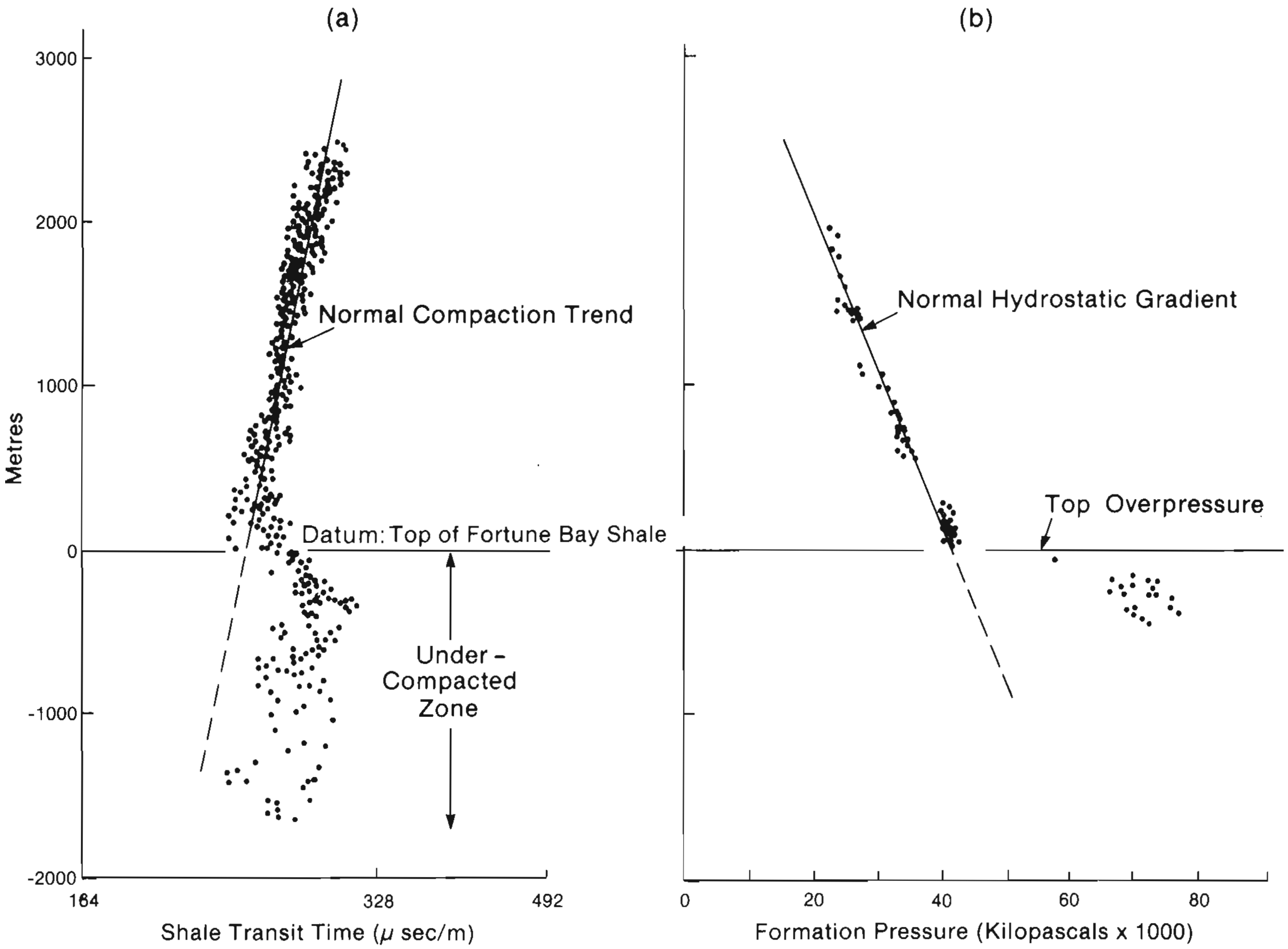

Figure 31. Plots of combined (a) shale sonic transit times and (b) measured pressures in porous rocks for Hibernia wells B-08, B-27, K-18, O-35, and P-15 (modified from Grant et al., 1986a).

(12.3 billion barrels) by the Petroleum Directorate of Newfoundland and Labrador (Sheppard and Hawkins, 1983). All the values are much higher than the current best estimate of discovered, recoverable oil carried by the Canada-Newfoundland Offshore Petroleum Board (1988b), a figure of only 195.2 million cubic metres (1.2 billion barrels ; excluding confidential information on Fortune G-57). The calculations offered here and the available estimates suggest that perhaps as little as 10 percent of potential recoverable oil reserves in the Jeanne d'Arc Basin may presently be discovered.

In conclusion, favourable structure, stratigraphy, geochemistry, and timing account for the hydrocarbon accumulations presently trapped in the Jeanne d'Arc Basin. A rich, oil-prone source rock was deposited in Late Jurassic time near the end of a period of relative tectonic stability. Basin subsidence during the latest Jurassic and Early Cretaceous led to deposition of a thick sequence of sandstones and shales that formed potential reservoirs and seals. Structuring was virtually complete by the Late Cretaceous before significant hydrocarbon generation had begun. Subsequent burial beneath a layer of Tertiary shales provided the thermal conditions necessary to generate oil and gas. It appears that significant oil reserves remain to be discovered and that the Jeanne d'Arc Basin will continue to be a very attractive target for petroleum exploration.

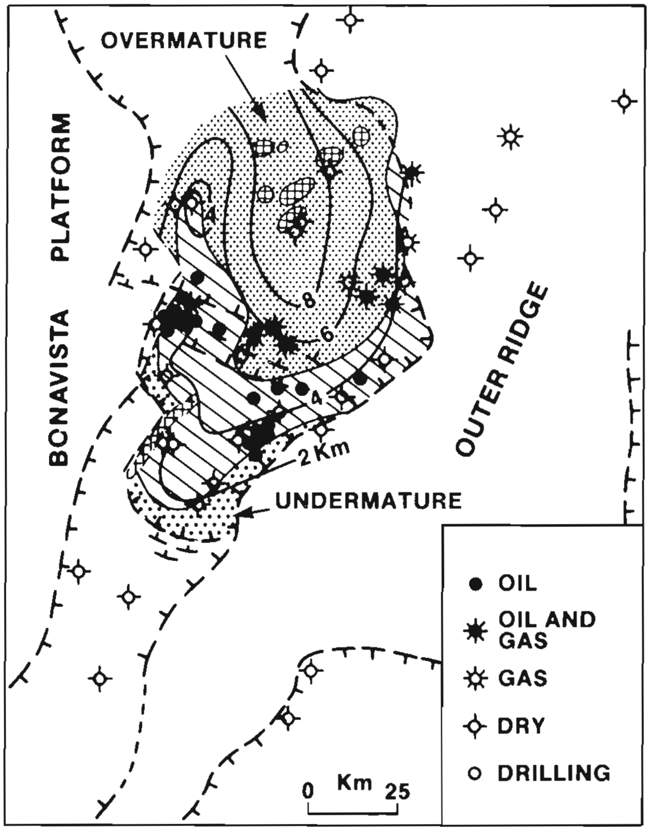

Figure 32. Map of depth and present-day maturity of the Egret Member in the Jeanne d'Arc Basin. Other symbols as in Figure 3.

Table 3 Calculated volumes of oil generated, trapped, and recoverable, and available estimates of recoverable reserves in the Jeanne d'Arc Basin. Units are 10 ^{9}m ^{3} (Bbbls).

CALCULATED OIL VOLUMES, JEANNE D'ARC BASIN (this paper)

METHOD	ENTIRE RANKIN FORMATION	EGRET MEMBER
Hydrogen index	41 (260)	37 (231)
Mass balance	45 (282)	31 (197)
Average	43 (271)	34 (214)
15% trapped	6.5 (41)	
30% recoverable	1.95 (12.3)	

ESTIMATED RECOVERABLE OIL RESERVES, JEANNE D'ARC BASIN

Probabilistic (Procter et al., 1984)	1.13 (7.1)
Monte Carlo (Sheppard and Hawkins, 1983)	1.96 (12.3)

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