2 GEOLOGY AND GEOPHYSICS

This section summarizes the regional geology of the Jeanne d’Arc Basin and discusses the geology and geophysics of the White Rose Field. Section 2.1 deals with the regional geology, including the tectonic history, stratigraphy, structure and geochemistry, and then more specifically, the geology of the White Rose Field. Section 2.2 includes data obtained from seismic studies and the geophysical interpretation of the White Rose Field and Section 2.3 describes the reservoir maps generated from core and log data and reservoir modelling. The reservoir maps are provided in Appendix 2.A.

The section is organized as follows:

• Geology;
• Geophysics; and
• Reservoir Maps.

2.1 Geology

This subsection describes the regional geology of the Jeanne d’Arc Basin and the geology specific to the White Rose Field.

2.1.1 Regional Setting

The White Rose Field is located on the eastern margin of the Jeanne d’Arc Basin, 350 km east-southeast of St. John’s and 50 km from both the Terra Nova and Hibernia fields (Figure 1.1-1). This section describes the regional setting of the Jeanne d’Arc Basin and is organized into the following:

• Regional Tectonic History;
• Regional Stratigraphy and Depositional Environments;
• Regional Structure; and
• Regional Geochemistry.
2.1.1.1 Regional Tectonic History

The Grand Banks rifted area is limited by the Bonavista Platform to the west, the Cumberland Belt-Flemish Cap (CBFC) Paleozoic lineament to the north, the continent-ocean boundary (COB) to the east, and the Newfoundland Transform Fault Zone (NTFZ) to the south (Figure 2.1-1). The western rift shoulder, the Bonavista Platform, is a submerged and peneplained sector of the Appalachian Orogen, partially covered by thin Upper Paleozoic, Mesozoic, and Cenozoic strata and situated landward from the Murre Fault. The Murre Fault is a regional basin-bounding, crustal penetrative fault dipping oceanward, which was crucial to the formation of basins on the Grand Banks. The NTFZ is a major ocean transform fault that was active during the separation of North America from Africa/Iberia.

A series of interconnected sedimentary basins, including the Jeanne d’Arc, were formed on the Grand Banks of Newfoundland as a result of Early Mesozoic break-up of the Pangea continental mass and birth of the Atlantic (Figure 2.1-1). The network of basins (South Whale, Whale, Horseshoe, Carson, Flemish Pass and Jeanne d’Arc), adjacent sub-basins (Flemish Cap, Anson Graben, Salar) smaller troughs and cuvettes, have had a common evolution, though differences in their structure and stratigraphy exist. They are separated by elongate basement ridges bounded by faults that are linked at depth to the Murre detachment fault.

Three major Mesozoic rifting episodes affected the Grand Banks:

1) **Tethys phase** (Late Triassic-Early Jurassic). During this rifting episode the main basins were formed as half-grabens in the downthrown side of a major crustal detachment. The failed rift was followed by Atlantic opening south of the Grand Banks, on the Scotian margin.

2) **North Atlantic phase** (Late Jurassic-Early Cretaceous). Previously formed basins and new sedimentary troughs were affected by north-south trending faulting. The Jeanne d'Arc basin was reactivated along the Egret Fault, that forms its current southern boundary, and along the Voyager Fault, with the Central Ridge area emerging as a regional high. The southern Grand Banks area, known as the Avalon Uplift, which includes a series of rift basins, was uplifted and eroded. The Atlantic Ocean was opened south of the NTFZ. The Egret source rock was deposited during the thermal sag interlude within the Kimmeridgian.

3) **Labrador phase** (Mid to Late Cretaceous). During this episode numerous northwest-southeast trending faults severely fragmented the basins and intervening ridges. In the Jeanne d’Arc Basin, the Trans Basin Fault Zone (TBFZ) was formed. Also, several imbricates of the Voyager Fault created terraces along the basin’s eastern margin. The Avalon Formation sandstone reservoir was deposited on the eastern flank of the White Rose structural high. The Atlantic Ocean opened, separating the Grand Banks from Iberia and the British Isles.
Figure 2.1–1  Grand Banks of Newfoundland – Distribution of Mesozoic Basins

LEGEND

- 00m Water Depth
- 50m Mesozoic Basins

Grand Banks of Newfoundland
DISTRIBUTION OF MESozoic BASINS

Newfoundland

SYDNEY BASIN

LAURENTIAN BASIN

ABÉNAKI / SABLE BASINS

NITZ

SOUTH WHALE BASIN

HORSESHOE BASIN

CARSON BASIN

GRAND BANKS OF NEWFOUNDLAND

ORPHAN BASIN

CUMBERLAND BELT

JEANNE D’ARC BASIN

FLEMISH PASS BASIN

FLEMISH CAP

Atlantic Ocean

Legend:
- 00m Water Depth
- 50m Mesozoic Basins

Figure 2.1-1
Each of the described rifting episodes had associated tectonic subsidence and was followed by post-rift thermal subsidence. The Tethys failed rift episode was the most important and defined the configuration and size of the basins. It was followed by a passive margin phase while the subsequent rifting episodes rejuvenated existing basins and opened new depositional areas.

Extensional and minor trans-tensional tectonic movements, accompanied by salt movement and several erosional interludes, have shaped the basin sedimentary fill. The basin infill can be divided into:

1. **Extensional stage sedimentary sequences** (Late Triassic- Early Cretaceous). These are strongly compartmentalized by normal fault systems and contain numerous structures;

2. **Thermal subsidence stage sedimentary sequences** (Late Albian to Present). These are usually tectonically undisturbed (that is, no extension) but contain depositional and erosional features.

Alongside extensional tectonics, halokinesis and halotectonics played an important role in basin evolution and structure. Prominent salt-cored structures are presently found throughout the Grand Banks. Salt features are interpreted to underlie the Hibernia, Terra Nova and White Rose fields.

### 2.1.1.2 Regional Stratigraphy and Depositional Environments

High resolution biostratigraphy, sequence stratigraphy, and workstation-based three-dimensional (3-D) seismic stratigraphy have been fully integrated into a tectono-stratigraphic framework (Figure 2.1-2) to develop an understanding of the stratigraphy of the Jeanne d’Arc Basin. This has been essential for the definition of unconformities, their relationship to tectonics and subsequent reservoir development. It is particularly true for the Avalon and Ben Nevis Formations within the basin and how their tectono-stratigraphic definition is carried into the White Rose area.

### Principal Reservoirs

Beginning in the mid-Kimmeridgian, several cycles of coarse-grained clastics were deposited throughout the Late Jurassic and Early Cretaceous. These are the primary hydrocarbon reservoirs in the basin. The Kimmeridgian Jeanne d’Arc Formation sandstones unconformably overlie the source and are the reservoirs at Terra Nova. The Berriasian-Valanginian Hibernia Formation sandstone is the primary reservoir at the Hibernia Field. The Aptian Avalon Formation sandstones contain the reserves at White Rose and North Ben Nevis. The Albian Ben Nevis Formation are the sandstone reservoirs at Hebron, West Ben Nevis and Ben Nevis.
Figure 2.1–2  Stratigraphy of the Jeanne d'Arc Basin

STRATIGRAPHY OF THE JEANNE D'ARC BASIN

<table>
<thead>
<tr>
<th>Age</th>
<th>S.W. Structural Cross-Trend</th>
<th>N.E. (Deep Basin)</th>
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<td>Carnian</td>
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P.J.M. M.E.E October 1999
Triassic-Mid. Jurassic Mega-Sequence: The Early Mesozoic break-up of Pangea was a complex process which resulted in the formation of a several fault-bounded Mesozoic rift basins, one of which was the Jeanne d’Arc. Sedimentation was initiated during the Late Triassic when a classic rift sequence developed over the Grand Banks. The sequence commenced with deposition of continental red beds of the Eurydice Formation, followed by restricted marine evaporite facies of the Argo Formation. The overlying Lower Jurassic Iroquois Formation, consisting of interbedded carbonates and evaporites, indicates a transition to a more open marine environment which continued with the deposition of the Middle Jurassic Whale Formation shales and carbonates. The overlying Voyager Formation consists of interbedded limestone, shale and sandstone, the latter exhibiting poor to fair porosity, and may have generated minor amounts of the oil in the Jeanne d’Arc Basin.

Oxfordian-Mid. Kimmeridgian Mega-Sequence: The Upper Jurassic Rankin Formation is composed of marls, oolitic limestones, shales and carbonate-cemented sandstones, some with minor porosity. The carbonates create important seismic reflectors throughout the Jeanne d’Arc, even at considerable depth. Most importantly, the major source rock, the Egret Member, is found near the top of the formation. It consists of marls and organic rich laminated shales deposited in a silled basin during this highstand event. Uplift and renewed rifting of the Grand Banks during the Late Jurassic is indicated by the angular mid-Kimmeridgian Unconformity, with subsequent deposition of coarse clastics of the Jeanne d’Arc Formation sandstones.

Mid. Kimmeridgian-Valanginian Sequence: Beginning at the mid-Kimmeridgian and continuing into the Early Cretaceous, sandstones were transported into the basin from the southwest. This entry point was structurally controlled, bounded in the west by the Murre Fault and to the east by the Voyager Fault. Tectonic uplift and the associated lowstand event formed multiple incised valleys into the underlying north-northeast dipping Rankin Formation, south and southwest of the Terra Nova field.

The Jeanne d’Arc Formation sandstones are the primary reservoir at Terra Nova, forming laterally continuous braidplain to marine sandstones. They have also tested oil throughout the southwest part of the basin at Hebron, West Ben Nevis, Hibernia and King’s Cove. Away from the depositional trend, and where they are more deeply buried at Hibernia, reservoir quality deteriorates. The overlying Fortune Bay shales and siltstones form hydrocarbon seals and indicate a major transgression. This highstand cycle reached a maximum near the end of the Jurassic, and is followed by increasing silt content towards the top of the Fortune Bay. Shallowing water and increasing coarse clastic content culminated in the deposition of the regressive Lower Cretaceous Hibernia Formation sandstones.

The Hibernia Formation can be subdivided into a lower and upper section, separated by a middle shale unit. The Lower Hibernia sandstones are widely distributed, beginning with a basal upward-coarsening, prograding sandstone, overlain by fluvial and shallow marine bars and channels. The Upper Hibernia sandstones are present in the shallower southwest part, and on the flanks of the Jeanne d’Arc Basin. Siltstones, minor sandstones and shales extend into the central basin as a more marine deposit. Hibernia
Formation reservoir quality is excellent at Hibernia, decreases at Hebron, and has low permeabilities at White Rose. At White Rose, the Upper Hibernia Formation is restricted to the south, towards Archer K-19, while the Lower Hibernia is present as a more distal facies, with much lower net to gross ratios than elsewhere in the basin. North of White Rose, at Trave E-87, the depositional limit of the sandstone has nearly been reached.

**Hauterivian-Upper Barremian Sequence:** Near the end of Hibernia Formation deposition in the Late Valanginian, minor uplift occurred, resulting in erosion and non-deposition in the southern Jeanne d’Arc and on the flanks of the basin. A subsequent marine transgression allowed the deposition of a widespread oolitic limestone, the B Marker. This unit is regionally correlatable on logs and creates an excellent seismic marker. In the southern and western part of the basin, this was followed by the deposition of the Catalina Formation, an interbedded calcareous limestone/sandstone, which forms a minor reservoir at the Hibernia Field. Elsewhere, the Cape Broyle Formation siltstones and shales were deposited, as a major transgression advanced over the entire basin, culminating in maximum flooding in the Late Hauterivian. Deposition of Hauterivian aged coarse clastics is restricted to the basin flanks. These clastics mark the onset of the Eastern Shoals Formation, a time transgressive, shallowing-upward sandstone/limestone unit with minor porous intervals. Development of shallow marine limestones, which are locally correlateable within this unit, was common during the Early Barremian, and are locally referred to as the A Marker, A sandstone or A limestone.

Subsidence and faulting continued on the basin margins in the Jeanne d’Arc Basin during the Early Cretaceous. Based on isochron and well isopach data, minor east-west extension had ended by the Late Hauterivian. In the Late Barremian major tectonism was renewed. The shallowing-upward Eastern Shoals Formation culminates in non-marine to brackish sediments over most of the Jeanne d’Arc Basin, although shallow marine sandstones and shales are more prevalent in the White Rose area. Much of the younger Barremian aged sections has been eroded because of continued uplift during the Early Aptian in the southern White Rose area.

**Aptian-Upper Albian/mid-Cenomanian Sequence:** The Eastern Shoals Formation is unconformably overlain by the Avalon Formation of Aptian age, which consists of stacked aggradational shoreface sandstone units, culminating in an upward-fining shaly siltstone. Typically, the Avalon sandstones are cleaner and finer grained in the White rose area, compared to the Avalon found in the central and western Jeanne d’Arc Basin. The Avalon Formation on the eastern flank of the basin unconformably overlies considerably older Lower Cretaceous section. In the Archer K-19 well, Upper Hibernia sandstones subcrop beneath the Avalon, removing the Barremian-Hauterivian section compared to other White Rose wells. As indicated by the White Rose A-90 well, erosion appears to have removed most of the Neocomian sandy section south and east of Archer K-19 and White Rose E-09. This huge volume of clastic sediment was subsequently re-deposited as the Avalon Formation at White Rose.
Tectonic activity in the basin centre culminated towards the end of the Aptian or early Albian when the uplifted TBFZ collapsed during a final episode of northeast-southwest extension, allowing deposition of the Albian aged Ben Nevis Formation in the resulting subsiding grabens, as found at Ben Nevis I-45. This formation was deposited during Albian transgression, filling accommodation space resulting from ongoing tectonic extension, initially as coarse clastic deposits, grading to lower shoreface and inner shelf silty sandstones as water depths increased. The formation shales out in a northerly and westerly direction as indicated by Albian deposition in North Ben Nevis and in the White Rose area. These overlying siltstones and calcareous shales are the Nautilus Formation and provide a regional seal.

Late Albian-Tertiary: The final thermal subsidence stage of the Jeanne d’Arc Basin has been ongoing since the end of the Lower Cretaceous, although a period of uplift allowed deposition of the Cenomanian shallow marine Eider Formation north of the North Ben Nevis field. For the most part, siltstones and shales of the Nautilus Formation filled topographic relief, followed by the marls and shales of the Dawson Canyon Formation, which blanketed the entire basin. Reactivation of a few fault blocks has occurred in some instances, such as at Mara M-54, where uplift and subsequent erosion has left a very thin Albian section underlying a Coniacian clastic wedge. A number of westerly-sourced clastic wedges, either submarine fans or fan deltas, are found on the western flank of the Jeanne d’Arc Basin in the uppermost Cretaceous and Tertiary. These are the Otter Bay, Fox Harbour and South Mara members, respectively. The South Mara is more widespread, extending to the western flank of White Rose, on the eastern side of the basin.

2.1.1.3 Regional Structure

The structural interpretation of the Jeanne d’Arc Basin is based on in-house and published regional seismic interpretations performed on widespread seismic horizons such as Base Tertiary, Petrel, A Marker, B Marker, Top Rankin/Kimmeridgian Unconformity, inferred Top Salt and inferred Acoustic Basement. These horizons were correlated to geological events intersected in some 40 wells drilled in the basin. Timing of structural and tectonic events was completed by using biostratigraphic analysis, isopach maps and palinspastic reconstructions.

The Jeanne d’Arc Basin is a fault-bounded Late Jurassic-Early Cretaceous reactivated sector of a larger Late Triassic-Early Jurassic depositional area on the Grand Banks. The basin forms an elongate trough trending north-northwest south-southeast, encompassing an area of roughly 10,500 km², bounded by the Murre Fault to the west, the CBFC lineament to the north, the Voyager fault zone to the east and the Egret Fault to the south (Figure 2.1-1). The basin tapers and shallows to the south. Over 20 km of Upper Triassic to Cenozoic sedimentary infill is present in its depocentre situated north of the TBFZ. Virtually all significant hydrocarbon discoveries in the Grand Banks are confined to the Jeanne d’Arc Basin (Figures 2.1-3 and 2.1-4).
Jeanne d’Arc Basin and Environ

MAJOR STRUCTURAL ELEMENTS

Figure 2.1-3 Jeanne d’Arc Basin and Environs – Major Structural Elements
Jeanne d'Arc Basin and Environs – Salt Distribution and Major Sedimentary Structures

Figure 2.1–4

Jeanne d'Arc Basin and Environs
SALT DISTRIBUTION AND MAJOR SEDIMENTARY STRUCTURES

LEGEND
- Anticline
- Syncline
- Salt withdrawal feature
- Non-salt cored rollover
- Dispers (diapirs, swells, etc.)
- Dispers penetrating subtertiary unc.
- Salt floored anticlinorium
- Oil field

Modified after Enachescu, 1987; Updated Feb. 2000

Figure 2.1-4
Late Triassic to Early Jurassic extension created the Jeanne d’Arc Basin as a half-graben on the downthrown side of a major basin forming detachment fault, known as the Murre-Mercury Fault. This extensional fault system, its associated antithetic and synthetic faults and its conjugated shear faults, compartmentalize the basin into numerous fault blocks. Major boundary faults, such as Murre, Voyager and Egret, are separated by relay ramps that accommodated diminishing extension on one fault and increasing slip on the other fault. During this rifting stage the major internal architecture of the Jeanne d’Arc Basin was established. The Upper Triassic-Lower Jurassic salt (Osprey and Argo formations) deposited in the incipient rift basin now underlies most of the basin, and forms salt pillows, diapirs and ridges (Figure 2.1-4). Salt induced structural and stratigraphic features are likely responsible for the formation of the White Rose structural complex. Thermal sag followed the initial rifting phase.

Jeanne d’Arc Basin extension continued during the Late Jurassic to Early Cretaceous phase of rifting characterized by a dominant east-west direction of extension. Basin growth occurred on the bounding faults, Murre and Voyager, and at its southern extremity marked by the Egret fault. Uplift, non-deposition and erosion affected a broad region in the southern Grand Banks, including portions of the Jeanne d’Arc Basin. Developing as a separate block in the footwall of the Voyager Fault, the Central Ridge started to emerge as a prominent and permanent regional high. Numerous north-south faults formed, especially on the Central Ridge and in the eastern portion of the basin where the White Rose field is located. Salt diapirs and salt cored ridges were formed, influencing sedimentation and local fault patterns.

In the Early Cretaceous, unconformities that developed during the Late Barremian to Early Albian mark the approximate end of the second rift phase in the Jeanne d’Arc Basin and the beginning of separation between the Grand Banks and Europe. Successive sag, rifting and then, ocean opening took place during this period. During the Aptian to Albian, northeast-southwest extension and block reorganization took place in the centre and along the margins of the Jeanne d’Arc Basin.

In the central part of the basin, towards the end of the Aptian, the TBFZ collapsed during major northeast-southwest extension, allowing deposition of Albian aged clastics (Ben Nevis Formation) into the subsiding grabens and low fault blocks. Clastics were deposited in a northerly direction reaching the western part of the White Rose Complex, but they exhibit poor reservoir properties. In the White Rose area, towards the end of the Barremian, important salt movement occurred, particularly under the North Amethyst structure, Trepassey Depression and on the White Rose salt dome area (Figure 2.1-5). Concurrently, significant erosion of older pre-Barremian clastics and sediment redeposition took place during the Aptian in these areas.
Figure 2.1–5 White Rose Complex – Regional Composite Marker Time Structure

White Rose Complex
REGIONAL COMPOSITE MARKER TIME STRUCTURE
There is some uncertainty as to the age of the last rifting episode in the basin. In the White Rose/Amethyst area, the post-Avalon unconformity of late Albian age, may mark the cessation of extensional events. However, small block readjustments took place up to Paleocene time.

The Base Tertiary unconformity configuration reflects tilting of the basin and thickening of post-rift sediments toward the north. Late salt movements and compaction rejuvenated a few larger faults. These faults (for example, Amethyst Fault) penetrate the unconformity and terminate in lower Tertiary sediments forming tectonic lineaments and sedimentary features, but no major structural closures.

2.1.1.4 Regional Geochemistry

The Jeanne d’Arc Basin is unique amongst East Coast basins in that it is a proven oil province containing large oil and gas fields. The rich oil-prone Kimmeridgian Egret Member source rock (Figure 2.1-6), the principal proven source (Fowler and McAlpine 1994), is similar in age and quality to the prolific Upper Jurassic Kimmeridge Clay Formation of the North Sea. The Egret Member is widespread in the Jeanne d’Arc Basin, and has been penetrated in three White Rose area wells: White Rose A-90, Archer K-19 and Trave E-87. Three additional potential source intervals occur sporadically throughout the basin, within the Jeanne d’Arc Formation, Lower Rankin Formation and Voyager Formation, but are not believed to be substantial hydrocarbon generators (Fowler and Brooks 1990).

The Egret Member is found near the top of the Rankin Formation, and consists of marls and organic-rich laminated shales (up to 8 percent total organic carbon (TOC)). These shales were deposited during highstand cycles, allowing the concentration of organic rich debris in deep silled basins (Powell 1985). The unconformable contacts bounding the Rankin Formation likely indicate tectonic formation of the paleotopography necessary for a stratified water column, and the concentration and preservation of organic material. The Egret Member was deposited over a large area, likely in a series of interconnected basins, but has since been largely eroded to the south of the Jeanne d’Arc Basin in the Horseshoe and Whale Basins.

The present day maturity pattern of the Egret was likely well established by the Late Cretaceous, due to rapid subsidence and high sedimentation rates during the Early Cretaceous. The maturity modelling work of Williamson (1992) indicates that the Egret began to generate oil in the deepest, central, Jeanne d’Arc Basin area at this time, with the mature/non-mature boundary moving progressively towards the basin’s margins during the Tertiary. With the onset of maturity, hydrocarbon migration would have begun, with evidence for both vertical and lateral migration in the basin.

Current maturity values, as modelled, indicate that the source rocks are overmature in the central Jeanne d’Arc, generating only gas (Figure 2.1-6). Early mature source rocks are still present on the eastern and southern flanks of the basin, and have been penetrated at Terra Nova and White Rose (Fowler and Snowden 1989).
Figure 2.1–6 Jeanne d’Arc Basin – Egret Source Rock Maturity Map

Jeanne d'Arc Basin
EGRET SOURCE ROCK MATURITY MAP

LEGEND
- Orange: Overmature
- Brown: Mature
- Yellow: Undermature
- Light Blue: No Source
- Purple: Salt Structure
- Grey: Pre-Rift Basement
- Green: Oil Discovery
- Pink: Gas Discovery
- Black: Contours in km

BONAVISTA PLATFORM

N. CENTRAL RIDGE

RAGNAR LOW

S. CENTRAL RIDGE

Depositional Edge

JEANNE d’ARC BASIN

Hibernia

N. Ben Nevis

White Rose

Terra Nova

MORGENA UPLIFT (ANTICLINORIUM)

SOUTH JEANNE d’ARC BASIN

Eroded

Figure 2.1-6
2.1.2 White Rose Field General

The White Rose Field is a highly faulted complex of rotated fault blocks, cored by salt at depth. White Rose is bounded to the north and west by basinward-dipping flanks of the White Rose salt dome. The eastern margin of the structure abuts against the basin-bounding Voyager Fault, while the southern boundary of the field encompasses the White Rose Terrace. The Terrace is bounded by major faults at its western, eastern, and probably, southern limits (Figure 2.1-5).

The principal reservoir is the Aptian Avalon Formation, which consists of fine to very fine grained quartzose sandstones deposited in a shallow marine to shoreface setting. As of April 2000, the field had been delineated by nine wells. Pressure measurements and fluid contracts indicates that the Avalon reservoir is divided into three separate pools. The West Avalon Pool has been penetrated by one well, J-49. The North Avalon Pool has been penetrated by two wells, N-22 and N-30. The most significant pool, South Avalon, has 350 m of sandstone with over 100 m of net oil pay. Four wells have penetrated the Avalon Formation in this most southerly pool. They are White Rose E-09, L-08, A-17 and H-20. The A-90 well did not penetrate the reservoir section, but helps define the eastern extent of the field. The L-61 well tested gas from the Paleocene South Mara Member sandstone, however the Avalon Formation was not well developed and tested a small amount of water and gas. The Hibernia Formation sandstones have tested small amounts of oil and gas from overpressured lower quality shaly sandstones in N-22 and E-09. Oil was also recovered from a Jurassic overpressured zone at the base of E-09 (Tempest Sandstone?). Analysis of the results of the H-20 well drilled in 2000 are currently ongoing.

This section is organized into the following:

- White Rose Stratigraphy;
- White Rose Structural Geology;
- White Rose Geochemistry; and
- Description of Reservoir Stratigraphy and Facies Interpretation.

2.1.2.1 White Rose Stratigraphy

The stratigraphic section penetrated by the wells drilled in the White Rose region contains Tertiary to Upper Jurassic rocks (Figures 2.1-7 and 2.1-8). Of the formations penetrated, the South Mara, Avalon, Eastern Shoals and Hibernia sections have reservoir quality sandstones. The following paragraphs review the stratigraphy of the Late Jurassic to Tertiary as seen in the White Rose region, beginning with the oldest formation penetrated. The Aptian Avalon Formation, the most economically significant formation will be discussed in more detail in the Stratigraphy and Depositional Environments subsection. The formations penetrated and fluids sampled in the White Rose Field and area are outlined in Table 2.1-1a and 2.1-1b.
Figure 2.1-7  Stratigraphy of White Rose Field

### Stratigraphy of White Rose Field

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Deutsch/Meehan
April 14, 2000

Figure 2.1-7
Figure 2.1–8 White Rose Area – Paleocene to Late Jurassic Stratigraphic Cross Section
### FORMATION TOPS AND FLUIDS SAMPLED (MDT & DST)

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### Table 2.1-b

### LEGEND

- **G**: Free Gas
- **L**: Liquids
- **SG**: Solution Gas
- **F**: Filtrate
- **O**: Oil
- **W**: Water

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The oldest rocks penetrated in the White Rose region are from the Voyager Formation in the White Rose N-22 well. The Upper to Middle Jurassic Voyager Formation is Bathonian to Oxfordian in age. Although the full section was not penetrated, it is composed primarily of grey, dolomitic to calcareous shales and siltstones.

Unconformably overlying the Voyager Formation is the Rankin Formation containing the Egret Member source rock and the Tempest Member sandstones. The Rankin Formation is Oxfordian to Kimmeridgian in age, and consists of a mixture of shales and siltstones with minor limestones and sandstones. The Egret member, the main source rock for the hydrocarbons in the White Rose area, has been penetrated in the A-90 well and consists of organic rich grey calcareous shales and marls. Although a similar aged section was penetrated towards the base of the White Rose N-22 and E-09 wells, the Egret Member was not encountered. Oil bearing, over pressured sandstones, probably the Tempest Member were penetrated in the E-09 well.

The Jeanne d’Arc Formation has shaled out in the White Rose area, and its stratigraphic equivalent in the Fortune Bay Formation is organic rich and is found in the Archer K-19 and Trave E-87 wells. The Kimmeridgian to Portlandian aged Fortune Bay Formation has been penetrated in White Rose N-22 and J-49 and at the bottom of the A-17 well where it unconformably overlies the Rankin Formation. The Fortune Bay Formation is comprised predominantly of grey, silty marine shales deposited as part of a major transgression in the Late Jurassic.

The oldest Cretaceous aged rocks encountered in the White Rose area form part of the Ryazanian to Valanginian age Hibernia Formation. The Hibernia Formation has been penetrated in the White Rose A-17, E-09, N-22 and J-49 wells. The Hibernia sandstones form a regressive succession which can be separated into an upper and lower member, with a distinctive basal unit. The upper Hibernia Member is not well developed in the White Rose area and consists of poor quality siltstones and shales with only minor sandstones. The upper Hibernia decreases in quality and thickness to the north through the field.

The lower Hibernia Member has been penetrated in the E-09 and N-22 wells where thin shaly marine sandstones contained small amounts of oil. The lower Hibernia Member consists of fine to medium grained, light grey/brown and slightly silty sandstones. It was deposited primarily as a prograding shoreface succession as part of an overall regional regressive package. The shoreface succession contains minor fluvial and marginal marine deposits. The gross sandstone thickness varies from 272 m in White Rose J-49 where it is poorly developed, to only 86 m in the A-17 well where it has been largely eroded.

Hibernia Formation deposition is followed by a regional transgressive package of marine shales. The Neocomian to Barremian Cape Broyle Formation in the White Rose area is dominated by marine shales with minor siltstones. The B Marker, a shelly limestone which is regionally correlative through much of the Jeanne d’Arc Basin, is thin and poorly developed at White Rose. Although present in White Rose N-22 and E-09, no correlative limestone interval is observed in J-49, probably because of a deeper
depositional environment. It is eroded in the Archer K-19, White Rose A-17 and the Trave E-87 wells. No reservoir quality rocks or hydrocarbon shows have been seen in the Cape Broyle Formation in the White Rose area.

The Hauterivian to Barremian Eastern Shoals Formation unconformably underlies the Avalon Formation throughout much of the White Rose Field. The White Rose E-09, L-08, N-30, N-22, L-61 and J-49 wells all penetrate the Eastern Shoals directly below the Avalon Formation. In the E-09 and L-08 wells the Eastern Shoals is largely eroded, leaving only a 60 m thick limestone, while in the N-30, N-22 and J-49 wells, it is comprised of interbedded shale, siltstone and sandstone. The A Marker, a shelly limestone within the Eastern Shoals Formation, is preserved in the J-49 and L-61 wells. The Eastern Shoals Formation has been eroded in the White Rose A-17 and A-90, and the Trave E-87 wells.

The Aptian aged Avalon Formation is the primary reservoir in the White Rose Field. The Avalon Formation will be covered in significant detail in following subsections. In general, the Avalon is a marginal marine, shoreface succession through much of the field. The Avalon is dominated by very fine to fine grained sandstones, siltstones and shales, and ranges from 0 to 400 m in thickness. The main sandstone accumulations occur in the southeastern portion of the field with the E-09, L-08 and A-17 wells (South Avalon Pool) exhibiting thicknesses of up to 350 m of sandstone. The Avalon Formation is absent in the White Rose A-90 and Trave E-87 wells.

The Nautilus Formation is primarily Albian in age and is present in all the wells in White Rose, although not to the north in the Trave E-87 well. The Nautilus Formation conformably overlies the Avalon Formation, and is laterally equivalent where the Avalon Formation shales out. It represents a regional transgressive event, reaching up to 350 m in the A-17 well. The Nautilus Formation is comprised of grey siltstones and shales with very minor sandstones. No reservoir quality rocks are present in the Nautilius Formation in the White Rose Field.

Unconformably overlying the Nautilus Formation is the Cenomanian to Coniacian aged Dawson Canyon Formation which consists primarily of marls and calcareous shales. The Dawson Canyon Formation ranges in thickness from 100 to 500 m in the White Rose Field. The Petrel Member is present at the top of the Dawson Canyon Formation in the White Rose area, except where eroded in the vicinity of the A-17 well. It consists of a thin light grey to brown argillaceous limestone.

The Banquereau Formation in the White Rose Field is composed of Tertiary clastics deposited during thermal subsidence. The Banquereau Formation is a thick shale succession (up to 2500 m) with coarser clastics at the base. The South Mara Member sandstone is occasionally present at the base of the Banquereau, directly overlying the Base Tertiary Unconformity. More often a sandy siltstone is present.
A sandstone from this zone tested gas and condensate in the White Rose L-61 well. In L-61, the South Mara Member is a 30 m section of brown, glauconitic silty fine to very fine grained sandstones. The basal net porous sandstone is 5 m thick.

2.1.2.2 White Rose Structural Geology

Three episodes of rifting affected the White Rose area. During the first rifting phase, thick Osprey/Argo salt beds were deposited. This salt was tectonically mobilized during the second rifting stage forming elongated salt walls parallel with the emerging Central Ridge. The Central Ridge was formed in the footwall of the Voyager Fault Zone. Major north-south and northeast-southwest faults dissect the sediments deposited above the northerly plunging salt wall, including the source rocks. The third rifting stage had a pronounced influence on the area as the salt ridge was divided by salt withdrawal into a major ridge (Amethyst) and a northerly circular diapir (White Rose). A fault fan, creating numerous rotated fault blocks occupies the saddle zone between these salt features. In the southeastern White Rose area, imbricates of the Voyager Fault created low blocks and terraces where the Avalon Formation was deposited, and high blocks that were subjected to erosion. Toward the end of the extensional stage, two major salt withdrawal synclines in the area, Trave and Grand Bruit, were formed. The crestal areas of both Amethyst Ridge and White Rose Diapir were elevated by salt and repeatedly subjected to erosion. The existence of Avalon Formation in these areas is difficult to prove by seismic correlation alone. With the exception of the Amethyst Ridge and the northern diapir, only minor salt movements occurred during latest Cretaceous and Early Tertiary in the White Rose area.

As no extensional stage seismic marker is continuous over the entire White Rose area to allow consistent structural time mapping, a complex depositional (in the west)/erosional (in the east) surface at the base of the Avalon Formation was interpreted for structural and tectonic characterization of the field. The seismic interpretation was completed on every line, cross-line and selected dip lines using a Composite Regional Marker (Figure 2.1-5) that varies from A Marker in the west, to Base Avalon and Base Reservoir in the central area. The mid-Kimmeridgian Unconformity to Base Tertiary Unconformity markers were mapped in the eastern portion of the White Rose area.

Time structure on the Composite Seismic Marker shows the main structural elements of the White Rose area (Figure 2.1-5).

a. high areas: the Amethyst Ridge in the south, the White Rose Diapir in the north, and the rotated blocks adjacent to Voyager Fault Zone;

b. low areas: the Trave Syncline in the northeast and the Grand Bruit Low representing the southeastern tip of the basin depocenter;
c. **intermediate elevated areas:** the Terrace (A-17) block, the L-08 and E-09 blocks, the central blocks elongated in a north-south direction and the North Trepassey Depression and the numerous blocks on the fringe of the White Rose diapir;

d. **complexly faulted area:** the collapse zone and northwest-southeast trending fault fan north of Amethyst ridge; the intensely faulted southwestern flank of the White Rose diapir dissected by numerous northeast-southwest trending faults; the collapse zone on the western side of the White Rose diapir and the collapse zone east of the N-22 well.

The White Rose area abuts the Voyager Fault, a very complex zone of fault imbrication and ramping, bordering the Central Ridge. The Amethyst salt cored ridge and White Rose Diapir once formed a continuous salt cored high in front of the Voyager Fault Zone. Between these two structural features, salt withdrawal, initiated during Aptian and culminating in the Albian, caused a central collapse zone now occupied by a westerly dipping extensional fault fan. In some areas, the Cretaceous structural elevation relationships have been reversed due to post-Aptian salt movement. Thus, the seismically mapped Avalon Formation abnormally thickens toward the north and west, having the thickest interval in the rotated blocks, just east of the Central Fault.

Three intersecting fault systems oriented northeast-southwest, north-northwest south-southwest and north-south, compartmentalize the area. As indicated by reservoir pressure data, a few major faults (for example, West Amethyst, Central, Twin faults) together with a low structural trend oriented north-northeast south-southwest segment the area into three pools (Figure 2.1-5):

1. The South Avalon Pool (E-09, L-08, A-17 and environs);

2. The West Avalon Pool (J-49 field and environs) and


Structurally, the White Rose pools reside in a complexly faulted area located on the hangingwall of the Voyager Fault Zone and are situated above the deep-seated Amethyst salt ridge and White Rose diapir (Figure 2.1-4 and 2.1-5). These three pools are associated with the White Rose Complex and are outlined in four schematic structural cross-sections, generated from seismic data across the field (Figures 2.1-9 and 2.1-10).
White Rose Area
STRUCTURAL CROSS SECTIONS C-C' AND D-D'

Figure 2.1-9
Figure 2.1-10 White Rose Area – Structural Cross Sections A-A’ and B-B’

White Rose Area
STRUCTURAL CROSS SECTIONS A-A' AND B-B'

Figure 2.1-10
South Avalon Pool

The South Avalon Pool occupies an area of approximately 18 km², located east of the Amethyst Ridge and Central Fault and includes the E-09, L-08, A-17 wells (Figures 2.1-5, 2.1-9 and 2.1-10 Section A-A’). The pool is geologically complicated; the trap is structural, but may have a significant stratigraphic component. The trap is a collection of three- and four-way fault closed blocks and possible stratigraphic components toward the south and east. This pool is limited by the East Amethyst, Central and Twin faults to the west, and by structural dip toward the north and east. At the southernmost tip of the Terrace, the Avalon reservoir either thins out, onlapping the mid-Kimmeridgian unconformity or is faulted down to the north. Poor seismic data in this area precludes a definite understanding of the southern boundary.

With the exception of the Terrace, the larger blocks are tilted eastward and bounded by westerly dipping faults. Structural dip outside the Terrace varies from 7° to 12° east. The reservoir is cut by major and secondary non-sealing faults of variable throw oriented northeast-southwest. Major faults, such as the Amethyst Fault and Central Fault have a vertical throw of 500 m and 300 m and dips of 45° east and 28° west, respectively. The sandstone reservoir is in communication across the North Terrace and North E-09 faults, as shown by minimal change of fluid contact levels in the delineation wells (Section 2.2, Figure 2.2-15). Minor faults (throw less than 30 m) were carefully mapped or extracted from derivative maps in order to assess the structural complexity within the pay zone.

Most of the faults offset both Top and Base of the Avalon Formation and continue at depth beyond the mid-Kimmeridgian unconformity. Several secondary faults affect only the top or the base of the reservoir. All minor faults having vertical throws as low as 30 to 20 m, are seismically mapped (Figure 2.1-5), while smaller ones are identified as trends on the gradient maps and coherency displays (refer to Section 2.2).

No clear flat events are observed on the seismic data that might be associated with fluid contacts, although AVO modelling indicates flat spots should exist. The lack of flat events may be due to high background noise and severe demultiple routines applied to the data.

West Avalon Pool

The West Avalon Pool, which includes the J-49 well, encompasses a 16-km² area and is confined between the West Amethyst, Central and North J-49 faults and the crestal erosional edge. Structurally, the West Avalon Pool occupies the central collapse area between the northern plunge of the Amethyst Ridge and the southern part of the White Rose Diapir (Figure 2.1-5). The trap is structural and the reservoir consists of a thinner sequence of Avalon Formation than the sequence drilled in the South Avalon Pool (Figures 2.1-9 Section C – C’ and 2.1-10 Section B – B’). Elongated faults of variable throw, dissect the area into many thin blocks, oriented northwest-southeast. The Base of Avalon in this area does not coincide with the mapped A Marker since erosional incision here is not as significant. Two
highly complex areas that are poorly imaged by seismic data are located in the downthrown side of the Central Fault separating the South and West Avalon Pools and just north of the Amethyst Ridge. A central low trend lies between the area adjacent to the J-49 well and the area immediately north of the Amethyst Ridge.

In general, the easternmost faults have larger throws. The highest part of the pool is the northern portion where Avalon beds are gently dipping toward the southeast. However, dense north-south faults affect this part of the pool. The eastern blocks dip toward the southeast at about 8 to 10°. The block-bounding faults dip towards southwest at 30 to 38°. The western part of the pool represents the portion of the underlying Amethyst salt ridge that is unaffected by crestal collapse. It plunges, initially at 8°, and then steeper, at 14° toward the Grand Bruit Syncline. Conjugate, northeast-southwest, small faults of 20 to 30 m are mapped around the J-49 location (Figure 2.1-5).

North Avalon Pool

The North Avalon Pool includes the N-22 and N-30 wells and occupies an area of about 10 km². It is bounded by the Central Fault, White Rose Diapir erosional edge, Trave Fault and southeastern end of the Trave Syncline (Figure 2.1-5). The North Avalon Pool is located on the southeastern flank of the White Rose Diapir. The area is dissected by numerous faults trending mainly north-northwest south-southeast and north-northeast south-southwest. Two major faults bound the N-22 block. The first fault dips to the west at 40° and the second fault to the east at approximately 50° (Section 2.2, Figure 2.2-12). The structural dip on this block is 7° southeast. Two other major faults, the Central and Twin faults, bound the N-30 blocks. Another important fault forms a rotated block on the western flank of the Trave syncline. This fault dips to the northwest at approximately 20°.

The trap is structural for the area tested by the N-22 and N-30, but a stratigraphic component may exist toward the northwest, where the Avalon sandstone may be absent due to truncation or onlap. As the area is generally higher than the rest of the White Rose Complex, the Avalon Formation appears to thin over the top of the White Rose Diapir and is completely missing on its crest (Figure 2.1-5 and Section 2.2, Figure 2.2-12).

The northwestern part of the White Rose Complex is cut by a series of radial faults oriented northeast-southwest and by minor intersecting faults, part of a swarm parallel to the crestal zone. Numerous small fault blocks are formed and occupy this side of the White Rose Diapir. One of these blocks was tested by the L-61 well. The crestal zone of the White Rose Diapir trends approximately north-south. An intensively faulted high block marks the higher part of the deep-seated salt diapir. Mapping the base Avalon marker in this area is difficult as the crest is dissected by several faults having opposing dips.
Structure of the mid-Kimmeridgian Unconformity. The mid-Kimmeridgian unconformity corresponds to the Top of the Rankin Formation, which includes the Egret Member oil source rock and correlates to a strong amplitude reflector at Archer K-19, White Rose N-22 and A-90 and immediately below the White Rose A-17 well (Figure 2.1-11). This mid-Kimmeridgian unconformity is situated immediately under the reservoir on the Terrace and North Trepassey areas, is faulted down to 800 m in the central area and abruptly rises on the eastern side where it lies under Albian shaly carbonates (Nautilus Formation). The Egret source rock, if preserved, is also high in a local horst located west of the N-22. The structural lows, Grand Bruit, Trave and South Badger form veritable hydrocarbon kitchens and are extensively faulted at the Rankin marker level. These 30 - 40° dipping faults form excellent migration conduits.

Over the greater White Rose area the source rock is structurally bounded by major faults, coinciding to the three distinct pools and their hydrodynamic systems (South, North and West Avalon Pools, respectively) (Figure 2.1-5 and Section 4.5, Figures 4.5-1 and 4.5-2 Pressure Profiles in Reservoir Engineering).

In conclusion, three separate structural areas have been delineated within the White Rose Complex corresponding to three distinct oil accumulations: South Avalon Pool, West Avalon Pool and North Avalon Pool. They were identified in the White Rose area, by drilling a series of exploration and delineation wells and by interpreting structural and tectonic maps of two seismic horizons: 1. The Composite Marker map (Figure 2.1-5) and 2. mid-Kimmeridgian Unconformity map (Figure 2.1-11). These pools have a complicated structural trapping mechanism and a stratigraphic component toward the southern and northern part of the White Rose Complex.
Figure 2.1-11 White Rose Complex – Mid-Kimmerindgian Unc. Time Structure

White Rose Complex
MID-KIMMERIDGIAN UNC. TIME STRUCTURE

Figure 2.1-11
2.1.2.3 White Rose Geochemistry

The Kimmeridgian Egret member source rock is the principal proven source (Fowler and McAlpine, 1994) in the Jeanne d’Arc Basin, and has been penetrated in three White Rose area wells. They are White Rose A-90, Archer K-19 and Trave E-87. The Geological Survey of Canada has published Rock-Eval data for these wells (Fowler and McAlpine 1994), where it appears the source maturity is marginal to early mature (Table 2.1-2). However, the interbedded nature, and subsequent variable lithologic and geochemical character, suggests that the Egret Member may be generating exploitable oil, even when the overall average maturity value appears marginally mature to immature (Bateman 1995). TOC values, on average for the three wells, range from 2.9 to 3.1 percent. The Egret Member is 170 m thick in Archer K-19. The 138 m Egret Member penetrated in White Rose A-90 and 74 m interval in Trave E-87 likely understate the true thickness, as both have unconformable upper contacts with overlying sediments.

Table 2.1-2 Rock-Evaluation Results for White Rose Area Wells

<table>
<thead>
<tr>
<th>Well</th>
<th>Top (m)</th>
<th>Base (m)</th>
<th>No. of Samples</th>
<th>TOC range (%)</th>
<th>TOC avg (%)</th>
<th>HI range</th>
<th>HI av.</th>
<th>T max range (ºC)</th>
<th>T max av. (ºC)</th>
<th>Sample problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>JEANNE D’ARC FORMATION SOURCE ROCK INTERVAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trave E-87</td>
<td>2,720</td>
<td>2,840</td>
<td>9</td>
<td>1.27 – 3.12</td>
<td>2.56</td>
<td>137 – 731</td>
<td>381</td>
<td>419 – 429</td>
<td>423</td>
<td></td>
</tr>
<tr>
<td>EGRET MEMBER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trave E-87</td>
<td>3,050</td>
<td>3,120</td>
<td>8</td>
<td>2.35 – 4.24</td>
<td>3.05</td>
<td>680 – 810</td>
<td>746</td>
<td>426 - 431</td>
<td>428</td>
<td></td>
</tr>
<tr>
<td>White Rose A-90</td>
<td>2,890</td>
<td>2,960</td>
<td>8</td>
<td>2.33 – 3.3</td>
<td>2.88</td>
<td>450 – 604</td>
<td>545</td>
<td>441 – 450</td>
<td>445</td>
<td>Light oil-based mud</td>
</tr>
<tr>
<td>LOWER RANKIN FORMATION SOURCE ROCK INTERVAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Other potential source horizons are present in the White Rose area (Table 2.1-2). Archer K-19 and Trave E-87 both penetrated a minor potential source in Jeanne d’Arc Formation equivalent shales and a lower Rankin Formation interval with some source potential was also penetrated in the Archer K-19 well. Regional Jeanne d’Arc Basin geochemical studies indicate only a minor hydrocarbon charge contribution from these horizons. In the White Rose area, Rock-Eval data show these horizons are generally thinner and immature where penetrated.

Although no mid-Kimmeridgian unconformity map has yet been generated for the entire White Rose area, seismic indicates the surface plunges rapidly to the west, from the White Rose A-90 well, across several mega-faults, towards the J-49 well. The underlying Egret member is increasingly mature as burial depth increases. Similarly, increasing maturity is indicated north of White Rose N-22, west of Trave E-87 and west of Archer K-19. As anticipated by the Egret depth trends, Snowden (1999) Husky
Consultant Report, in a White Rose reservoir compartmentalization study, found the biomarker ratios for White Rose J-49, N-22 and L-61 oils higher maturity than those from the South Avalon Pool. He also looked at the geochemical properties of all available White Rose oils and condensates and suggested that the two geochemical signatures are from the same Egret source, but likely from two different kitchen areas; one of which charged J-49.

The extensive faulting present in the White Rose area can be used to argue that vertical charging of the reservoirs was the dominant migration mechanism, in addition to the fact that at least three separate pools are present within the Avalon Formation reservoir. Alternatively, lateral migration can be postulated because of the thick, widespread Avalon sandstone. Lateral migration helps to explain the large gas cap over the prominent North Avalon Pool, since an overmature source is laterally accessible to the northwest. Lateral migration is also evident in the Trave E-78 well. The gas/condensate reservoir fluid, indicative of highly mature source rock conditions, could not have migrated vertically from the marginally mature Egret Member penetrated in the well. Although there is evidence to support both vertical and lateral migration, deciphering this complex history will await the acquisition and integration of additional data as more wells are drilled.

2.1.2.4 Description of Reservoir Stratigraphy and Facies Interpretation

The Avalon Formation (Aptian) has been modelled using three principal reservoir layers in the South Avalon Pool and two principal reservoir layers in the West Avalon and North Avalon Pools.

Petrographic, petrophysical, sedimentological, dipmeter/FMI, production test and seismic data were used to define the stratigraphic framework and develop a depositional model for the White Rose Field.

The section includes:

- main reservoir and non-reservoir lithofacies and facies;
- general facies associations;
- paleogeography;
- reservoir modelling facies;
- local tectonic features and influence on the reservoir; and
- geometry and stacking pattern of the reservoir layers and facies.

Main Reservoir and Non-Reservoir Lithofacies and Facies

Two main lithofacies; sandstone and siltstone/sandstone, were identified from an analysis of 467 m of core recovered from five wells in the field. The two lithofacies were further subdivided into reservoir and non-reservoir facies, as outlined in the table below (Table 2.1-3). A description and interpretation of the individual facies is provided in the following subsection.
Table 2.1-3  Description of Reservoir and Non-Reservoir Lithofacies and Facies Described in Core Within the White Rose Avalon Reservoir

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Facies*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siltstone/Sandstone¹</td>
<td>(2)  interbedded siltstone and fine sandstone¹</td>
</tr>
<tr>
<td>Sandstone</td>
<td>(3)  ioturbated fine to very fine silty sandstone</td>
</tr>
<tr>
<td></td>
<td>(4)  aminated very fine sandstone</td>
</tr>
<tr>
<td></td>
<td>(5)  hell Beds/Concretions¹</td>
</tr>
<tr>
<td></td>
<td>(10) Bioclastic sandstone</td>
</tr>
</tbody>
</table>

* (after Plint 1999a; 1999b; 1999c)
¹ Dominantly non-reservoir

For a detailed analysis and description of the facies, refer to three reports: Husky et al. White Rose L-08, A-17 and N-30, Preliminary Core Description and Revised Stratigraphy for the White Rose area (Plint 1999a; 1999b; 1999c). Facies 2, 3, 4, 5 and 10 described in these reports are the facies encountered in core in the White Rose Field.

**Facies 2 - Interbedded Siltstone and Fine Sandstone.** This facies is intergradational with bioturbated mudstone. The facies consists of cm scale, sharp-based beds of very fine to fine-grained sandstone, interbedded with and grading abruptly into cm to dm scale beds of bioturbated silty mudstone. Sandstone beds range from undisturbed, fine parallel lamination, or low-angle inclined lamination, to massive. The basal part of the sandstone beds commonly contains a layer of bioclasts. The silty/muddy portion of each bed is highly bioturbated. Small concretions are occasionally present and trace fossils are abundant.

Facies 2 is interpreted as storm deposits on a low-energy muddy shelf in water depths of 20 to 50 m, based on the trace fossil assemblage and the lack of evidence for fair-weather reworking of the deposits. This facies is best developed in core 1 of the Avalon Formation in White Rose L-61 and L-08.

**Facies 3 - Bioturbated fine to very fine silty sandstone.** This facies forms units typically 0.1 to 3 m, to a maximum of 9 m thick, consisting of very fine-grained, slightly to moderately silty sandstone. The facies is pervasively bioturbated, with only faint vestiges of primary lamination, consisting of dark micaceous mudstone preserved. Abundant trace fossils, in addition to common serpulid worm tubes and associated oyster and clam shells, are present. Wood fragments are common.

Facies 3 is interpreted to represent a shallow inner shelf environment, in water depths of 20 to 40 m, which for a period of time experienced a relatively low supply of sediment. This permitted a complete biological reworking of the sediment. The facies occurs interbedded with laminated very fine sandstone of Facies 4, invariably lying gradationally above it forming ‘laminated to scrambled’ beds typically 10 to 30 cm thick. Facies 3 also forms much thicker homogeneous units from 1 to 9 m without the laminated sandstones. Facies 3 possibly represents a more nearshore equivalent of Facies 2.
The facies constitutes a very small portion (less than 5 percent) of the total reservoir in the South Avalon Pool but may include as much as 50 percent of the gross reservoir facies in the West and North Avalon Pools.

**Facies 4 - Laminated very fine sandstone.** This facies consists of very fine grained (very fine upper) clean, well sorted sandstone ranging in thickness from about 20 cm to 1 m thick, deposited in less than 20 m of water. Individual beds, up to 4 m in thickness, have been observed and may represent single depositional units. However, amalgamated beds, separated by subtle erosion surfaces, are common. The sandstones generally show a fine, mm to cm scale parallel to low-angle (typically < 10º), planer to gently curved lamination. Occasionally the beds are massive. The laminated sandstones are interbedded with bioturbated silty sandstone of Facies 3 and shell beds of Facies 5. Burrows are neither significantly large or abundant.

Facies 4 is interpreted to represent deposition in a shoreface setting during intense storms when plane bed, swaley bedforms or massive beds developed. Recognition of beach/foreshore deposits in this unit is difficult because of the uniform and very fine grain size of the sand. Individual laminated sandstone units may represent a single or possibly amalgamated storm event. The absence of mud laminae in Facies 4 suggests that deposition took place in an environment in which all traces of mud, deposited during fair weather, was removed by storms. Facies 4 is genetically related to the shell beds discussed below.

The laminated very fine sandstone facies make up approximately 90 percent of the reservoir in White Rose A-17 and L-08 and one-half of the total cored reservoir interval in White Rose N-30.

**Facies 5 - Shell Beds/Concretions.** This facies consists principally of serpulid worm tubes and various species of bivalves, including several species of oysters. Rare brachiopod, belemnite guards and rare echinoderm plates are also present. Shell debris is generally dispersed through a matrix of very fine sand but is occasionally clast-supported. The facies ranges in thickness from one shell thick (that is, < 5 mm) but is typically 5 to 30 cm thick and is generally cemented with calcite.

Concretions, which represent the most significant diagenetic facies encountered in the White Rose core, are invariably associated with shell beds. In most cases, concretions appear to have nucleated on shell beds. The concretions range in thickness from a few centimetres to a maximum of 2.8 m. Calcite cement commonly extends several decimetres above and below the shell beds, sometimes resulting in several shell beds being incorporated into one large concretion. It is postulated that much of the cement in the concretions was provided by the dissolution of aragonite shells dispersed throughout the cored interval. Concretions have sharp boundaries with uncemented sandstone and are easily recognizable on the FMI log. Many show converging upper and lower boundaries and are interpreted as highly lenticular rather than laterally-continuous cemented intervals.
The shell beds of Facies 5 are interpreted as a basal lag and are overlain by the genetically related laminated to massive shoreface sandstones of Facies 4. Each package is interpreted to represent a major storm event.

Shell beds make up approximately 8 percent of the cored interval in White Rose L-08 and A-17 but less than 2 percent of the cored interval in N-30. Concretionary zones constitute approximately 15 percent of the cored interval in White Rose A-17, L-08 and N-30.

**Facies 10 - Bioclastic Sandstone.** This facies consists of medium- to very coarse-grained shell hash that includes numerous coarser bioclasts and other pebbles, set in a matrix of very fine-grained quartzose sandstone. Bioclasts include oysters, belemite guards, serpulid worm tubes and the coral Thamnasteria. The facies is crudely stratified at an angle of about 20º to massive. Burrows are common.

The bioclastic sandstone facies is interpreted as a transgressive deposit that accumulated on the Eastern Shoals Formation by marine erosion associated with the basal Avalon transgression. The facies constitutes a very minor part of the N-30 core but is significant in that it is the only example of basal Avalon Formation cored in the White Rose Field.

**General Facies Associations**

There is no clear organization of vertical facies within the White Rose core. However, the repetitive erosive-based, laminated sandstone, sometimes marked by a shell lag, grading up into bioturbated silty sandstone indicates a genetic relationship between Facies 3, 4 and 5. These facies are interpreted as classic examples of laminated to scrambled storm beds. The rising phase of the storm is represented by an eroded surface, cutting into the laminated or bioturbated sandstone of the underlying unit. The waning phase of the storm is represented, first by a lag of bioclasts (shells/shell bed-Facies 5) or mud pebbles eroded from the sea floor, overlain by several decimetres of laminated, very fine sandstone (Facies 4) deposited by high velocity currents generated by storm waves. The bulk of the lamination is horizontal, indicating that upper-plane bed conditions prevailed at most times. The upper bioturbated part (Facies 3) of many beds represents a protracted period which records the recolonization of the sea floor by burrowing organisms and epifauna which progressively destratified the upper portion of the storm bed. Mud was probably introduced into the sediments as faecal pellets and from background settling of suspended material. The sharp-based storm beds of Facies 2 may represent a slightly more distal equivalent of Facies 3, deposited where silt was slightly better able to accumulate. Finally Facies 10, dominantly of biogenic origin, accumulated on a rocky sea floor cut into the Eastern Shoals Formation above the basal Avalon unconformity as a transgressive deposit and forms the base of the reservoir sequence.
Paleogeography

During the time of deposition of the main sandstone package of the Avalon Formation, a period of relative stillstand or aggradation occurred where subsidence rates kept up with depositional rates. The thick sandstone sequences seen in the E-09, L-08 and A-17 wells suggest continuous deposition in a lower to middle shoreface environment with no significant breaks indicated. The inferred paleogeography during this time is illustrated in Figure 2.1-12. The shoreline appears to have trended in a south southwest to north north-east orientation with the more distal, offshore deposits to the northwest of this trend. The sources for the sediment would have been predominantly to the southeast, where erosion of the Central Ridge was taking place. Sediments sourced to the shoreline were then distributed by currents moving northward along the shoreline. The sequences within the J-49, N-30 and N-22 wells confirm this orientation with more distal deposits of bioturbated mudstones and siltstones and much thinner sandstone sections. No wells have been drilled to the southeast of the shoreline trend, and no sediments deposited above the middle shoreface have been encountered to date.

Reservoir Modelling Facies

The Aptian aged Avalon Formation is the main reservoir in the White Rose Field. The Avalon Formation consists of sandstones, siltstones and shales with calcite concretions which have developed from available bioclastic material. The Avalon is an aggradational fining upwards succession comprised of shoreface sands. In all wells in the field, the higher quality and percentage of sandstone occurs at or near the base of the Avalon, with the amount and quality of sandstone decreasing upwards. The thickest section of sandstone occurs in the vicinity of the South Avalon Pool with up to 320 m of gross sandstone encountered in the E-09 well. The south to north trending sandstone accumulation appears to have been deposited as stacked shoreface deposits transgressed and overlain by marine mud and silts near the end of Aptian time. To the northeast of this trend, the J-49, N-30 and N-22 wells have a much thinner interval where sandstone is present, with more shale and siltstone both above the sandstone and interbedded with them. This illustrates the more distal nature and lower energy deposition of this area.

The Avalon was divided into four main reservoir facies, Reservoir Sandstone, Siltstone and Tight Sandstone, Shale, and Calcite Concretions. The sandstone facies are used in the construction of the geological model for simulation purposes and are based on petrophysical facies. The divisions between different reservoir and non-reservoir units have been identified on the basis of porosity and permeability cutoffs, defined by thick cored intervals which have been calibrated to petrophysical data.

1) Reservoir Sandstone

The main reservoir facies of the Avalon is a light brown very fine to fine grained, well sorted, quartz-rich compositionally and texturally mature sandstone (predominantly Facies 4 as described by Plint (1999a; 1999b; 1999c).
Figure 2.1-12 White Rose Area – Paleography Late Aptian Time
Most of the sandstones were deposited as middle to upper shoreface sandstones, which were subsequently reworked as storm deposits in a lower to middle shoreface setting. These storm deposits are represented as sharp based, fining upward successions which can be as thin as 1 cm or as thick as 1 m. These successions are better seen on the FMI log (Figure 2.1-13 and FMI interpretation reports L-08 and A-17 (Deutsch 1999)) than in the core due to the very fine-grained nature of the rock and the lack of significant heterogeneity or contrast in the core. The fining upward nature translates to permeability trends which were confirmed by the minipermeameter work done on the A-17 core. Permeability trends identified from the minipermeameter data in the A-17 core are shown in Figure 2.1-14.

The reservoir sandstones exhibit porosities ranging from 10 to 22 percent, averaging approximately 16 percent, and permeabilities in the 10 to 300 milliDarcies (mD) range, averaging between 70 and 100 mD in the oil section of the South Avalon Pool. A well-defined porosity/permeability relationship can be illustrated by core and petrophysical data (Figures 2.1-15 to 2.1-17). For the purposes of this report, the reservoir quality sandstones have been restricted to those having more than 10 percent porosity. The most recent porosity and permeability from core indicates that an 8 percent cutoff for pay can be used (Sections 3.2 and 3.5). This would result in slightly higher net pays.

Two principal reservoir facies have been identified. Sandstones having more than 15 percent porosity are the main flow units in the reservoir, with an average permeability of greater than 100 mD. Sandstones with porosities between 10 and 15 percent have permeabilities averaging in the 10 to 50 mD range. Any sandstones with less than 10 percent porosity are effectively non-reservoir. The porosity of the sandstones remain very similar from well to well, with the changes reflecting net-to-gross differences only.

2) Siltstone and Tight Sandstone Facies

Siltstones occur mostly near the top of the Avalon. These are identified as facies 2 by Plint (1999a; 1999b; 1999c). As the sandstones in the Avalon are very fine grained, the differentiation between the sandstones and siltstones is gradational. For the purposes of reservoir modelling, the siltstone petrophysical facies includes all of the very fine-grained rock as well as fine-grained rock whose porosity is occluded by calcite to less than 10 percent porosity. The siltstones occur mainly near the top of the Avalon and represent more distal equivalents to the sandstone facies. As a result the amount of siltstone increases towards the northwest.

Some siltstones occur near the top of the fining upwards storm deposit cycles, within the sandstone units. The siltstones become the main constituent of the storm deposit cycles, when found near the top of the sandstone.
Figure 2.1-13 Well Defined Bedding in the L-08 Well

WELL DEFINED BEDDING IN THE L-08 WELL.
MINIPERMEAMETER DATA FROM HUSKY ET AL WHITE ROSE A-17

- Fining upwards cycles shown by declining upwards permeability
- Calcite Cemented
- Sandstones

Figure 2.1-14 Minipermeameter Data From Husky et al White Rose A-17
Figure 2.1-15 Porosity vs. Permeability Husky et al White Rose A-17

POROSITY vs. PERMEABILITY - HUSKY et al WHITE ROSE A-17

Calcite Cemented SS + Shale
Siltstone + Tight Sandstones

Sandstone 2 P-Facies 9
Sandstone 1 P-Facies 8

Permeability md
Porosity %

Petrophysics
Core

Figure 2.1-15
Figure 2.1-16 Porosity vs. Permeability Husky et al White Rose L-08

POROSITY vs. PERMEABILITY - HUSKY et al WHITE ROSE L-08

Figure 2.1-16
Figure 2.1–17 Porosity vs. Permeability Crossplot White Rose Field

POROSITY vs. PERMEABILITY CROSSPLOT WHITE ROSE FIELD
3) Calcite Concretions

Throughout the reservoir sandstones, calcite concretions take up approximately 8 percent of the reservoir volume. The calcite concretions are typically related to shell hash horizons. The shells have provided both the nucleation sites and some of the calcite which was dissolved and mobilized, providing material from which the nodules grew. Petrographic work suggests that the nodules occurred quite early in the diagenetic history of the Avalon (see the following section).

Interpretations from the core and FMI strongly indicate that these nodules should not extend very far in a lateral extent (Figure 2.1-18). Plint (1999a; 1999b; 1999c) notes that while the nodules are present throughout the core, they appear to be concentrated in discrete zones.

The nodularity of the concretionary horizons is evident in more than 90 percent of the concretions seen in the core or on the FMI. Since the concretions are related to thin (less than 5 cm) shell hash horizons, the concretionary horizons are likely not continuous over a large area, because of the topography of the shoreline during deposition. In addition, as the shell horizons are dissolved and re-precipitated as nodules, the formation of the concretions concentrate the thin calcite into thicker, less continuous, lenses. Plint (1999a; 1999b; 1999c) postulates that the nodules would range from 5 cm to 2 m in thickness and 20 cm to 3 m in width.

4) Shale Facies

In the South Avalon Pool, the shale component does not play a large role, as all of the shale is confined to the top 30 or 40 m of the sandstone package. The shale represents the material deposited during the transgressive event which pushed the shoreline back, southeastward of the White Rose area. Only on the fringes of the pool are there significant reserves within the shaley zone. On a pool wide basis, 8 percent of the original oil in place (OOIP) is within this shaley zone. Reservoir simulation suggests that only a small portion of this resource will be produced.

Shale plays a larger role in the North and West Avalon Pools. In these pools, shales are present in larger amounts. The shale section at the top of the Avalon is thicker, and more shale is interbedded with the reservoir facies. This represents the more distal nature of these deposits. The presence of shales within the reservoir section will have more effect on the production of hydrocarbons from the reservoir, as well as potentially having more of an effect on fault sealing.
Figure 2.1-18 Calcite Concretion in the L-08 Well

CALCITE CONCRETION IN THE L-08 WELL

Tight Calcite Concretion

360 deg photo

Note how the laminations above and below the concretion are bent by the growth of the nodule.

Figure 2.1-18
Local Tectonic Features and influence on the Reservoir

The complicated structural history of the White Rose area has left imprints on the reservoir. The FMI log was used for the determination of bedding attitudes and the presence of faulting and fracturing within the reservoir section. Only one significant fault within the reservoir section has been penetrated in the South Avalon Pool. The fault is seen at 2,958 metres below rotary table (mbrt) in the L-08 well, with associated fractures confined mainly to the hangingwall section. How the fault appears in both the core and the FMI log is illustrated in Figure 2.1-19. Affects on the reservoir and future production are uncertain, yet with the limited amount of faulting and fracturing seen in the wellbores, significant affects on performance seem unlikely. As noted in Figure 2.1-19, the L-08 fault is filled with calcite as are all of the associated fractures. The fault would form a semi-vertical barrier dipping at 80° to the wellbore. The reservoir engineering section will discuss the affects of this fault on the tests conducted in the well.

Geometry and Stacking Pattern of the Reservoir Layers and Facies

The three-dimensional reservoir modelling completed for use in the reservoir simulations illustrates the current thinking on depositional trends of the Avalon sands through the White Rose region. The model consisted of three main layers in the immediate South Avalon Pool vicinity, and two layers through the West and North Avalon Pools. The basal layer contains the sandstone layers which are present in the E-09 and L-08 wells, in addition to the J-49, N-30 and N-22 wells, but onlaps the Aptian. Unconformity down dip of the A-17 well. The second layer from the base contains the main reservoir sandstone, which is represented in all wells in the South Avalon Pool. The third and uppermost layer represents the low net to gross sandy siltstone and shale package at the top of the Avalon in the E-09, A-17 and L-08 wells. This layer is quite poor reservoir, and very quickly becomes completely non-reservoir to the northwest of the E-09 well.

Within the geological model for the South Avalon Pool, nine layers (Figure 2.1-20) were used to help delineate the shaling out transition along the northwestern edge of the pool. Using nine layers allowed this transition to be modelled more accurately. After the basic modelling was completed, these nine layers were compressed into the three layers mentioned above for mapping purposes. The Avalon Full Field two layer model is less detailed compared to the South Avalon Pool reservoir models. The basal layers of the two and three layer models are essentially the same, with the top layer in the three layer model representing the poorer reservoir quality section as correlated through the South White Rose region (Figure 2.1-21).
L-08 FAULT ZONE

360 deg photo

The white colored rock and FMI image relate to tight calcite cemented zones

The brown or dark colored rock and FMI image relate to more porous, hydrocarbon bearing zones

Figure 2.1-19
Figure 2.1–20 South Avalon Pool 9 Layer Model

South Avalon Pool
9 LAYER MODEL

Figure 2.1-20
Figure 2.1-21 E-09 Well Illustrating the Difference Between the 9, 3 and 2 Layer White Rose Reservoir Models

<table>
<thead>
<tr>
<th>SOUTH AVALON</th>
<th>E-09</th>
<th>SOUTH AVALON</th>
<th>AVALON FULL FIELD</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 Layer Model</td>
<td>3 Layer Model</td>
<td>2 Layer Model</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>3</td>
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<tr>
<td>3</td>
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<td></td>
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<tr>
<td>2</td>
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</tbody>
</table>

Figure 2.1-21
Trend maps were used to constrain the model to a south-southwest to north-northeast trending shoreline through the South Avalon Pool (Deutsch and Hallstrom 2000). The shoreline may continue to the northeast of N-22. The J-49, N-22 and N-30 region was seaward of this shoreline and consists of more distal deposits represented by shales and siltstones. The region to the east of this trend represents a more proximal sand source area. The Avalon Full Field cross section (Figure 2.1-22) illustrates how the reservoir sandstone packages shale out towards the northwest. Note that the increase in shale works from the top of the Avalon down, with the main sandstones remaining at the base of the Formation.

2.1.3 Petrology and Reservoir Quality of the Avalon Formation

This subsection describes the petrology, diagenesis and reservoir quality of the White Rose Avalon Formation. Petrographic data includes an analysis of thin sections prepared primarily from core (or sidewall cores when core was unavailable) from seven wells in the White Rose area. These wells include White Rose L-61, N-22, J-49, E-09, L-08, A-17 and N-30. Detailed petrographic descriptions are found in reports by (Core Laboratories 2000; Haverslew 2000).

Interpretation of the Avalon Formation core indicates that the depositional environment was a marginal marine shoreface setting with frequent storm deposits. Numerous calcite concretions varying in dimensions are present, as layers of stratabound concretions or as scattered concretions. The geometry of the calcite concretions is controlled by the original amount and distribution of biogenic carbonate within the sandstones.

2.1.3.1 Primary Composition And Texture

The mineralogy of the reservoir sands is predominantly 85 to 99 percent quartz and lesser amounts of carbonate grains, bioclastic debris, feldspar, and trace amounts of pyrite, heavy minerals, and dolomite. The reservoir sandstones have subangular to well rounded grain boundaries. Grain size is predominantly very fine with some fine-grained sands. The detrital quartz grains exhibit sub-angular to rounded grain boundaries and moderate to high sphericities with moderate to well sorting. The sandstones are classified as sublitharenite to quartz arenite. A comparison of QFR diagrams (Figures 2.1-23 and 2.1-24) from L-08 and A-17 shows a similar rock classification.
Figure 2.1–22 Avalon Full Field Cross Section, Facies Model, Feb. 00 Geological Model

Avalon Full Field
CROSS SECTION, FACIES MODEL, FEB. 00 GEOLOGICAL MODEL

Figure 2.1-22
Figure 2.1-23 QFR Diagram – L-08 Well

QFR DIAGRAM - L-08 WELL

L-08 Oil Zone

L-08 Water Zone

Figure 2.1-23
Figure 2.1-24 QFR Diagram – A-17 Well
Monocrystalline quartz is the dominant framework grain, with lesser amounts of rock fragments and feldspar. Variable amounts of bioclastic debris, ranging from abraded fragments to relatively intact shell clasts, are present. Fragments consisting originally of calcite generally remain as non-ferroan calcite, however, bioclast fragments, or parts of shell fragments of less stable original composition, (usually aragonite), have been partially to completely replaced by ferroan calcite. All White Rose wells have similar dominant framework grains, but N-30, N-22, J-49 and L-61 are compositionally less mature, containing more feldspar, rock fragments and accessory minerals.

Accessory minerals include glauconite, heavy minerals, and detrital chlorite. Interstitial detrital clays are generally absent, but argillaceous burrows or clay partings are present. Authigenic minerals present are siderite, calcite, silica and ferroan dolomite, dolomite, pyrite, and clays.

### 2.1.3.2 Diagenesis

Textural relationships evident in the Avalon Formation sandstones indicate several phases of precipitation and dissolution. Reservoir properties are affected due to cement precipitation, compaction, replacement of grains, and dissolution of primary or diagenetic rock components. In many cases, such as the concretionary horizons, only one or two of the diagenetic processes have affected the reservoir.

There are three main types of compositionally different calcite cements (Table 2.1-4). These include iron free calcite, early ferroan calcite and late ferroan calcite. Early ferroan calcite cement, the most common cement occurs as pervasive pore filling mosaic or poikilotopic cement, as scattered pore fill often surrounding detrital calcite grains, as individual microcrystals and as partial to complete replacement of detrital calcite shells (rim cement). The iron free calcite is the earliest calcite cement, forming overgrowths on fossil fragments and as poikilotopic cement. Early ferroan calcite replaces iron free calcite and may also be due to the dissolution of biogenic carbonate (fossil fragments). Grain margin corrosion by late ferroan calcite completely fills the intergranular pore space. Late ferroan calcite appears to contain a higher percentage of iron than earlier formed ferroan calcite.

#### Table 2.1-4 Cements Occurring in the Avalon Formation, Composition and Texture

<table>
<thead>
<tr>
<th>Cements – Composition</th>
<th>Texture</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron Free Calcite</td>
<td>Grains or crystals</td>
<td></td>
</tr>
<tr>
<td>Early Ferroan Calcite</td>
<td>Rim (forms on rims of shells)</td>
<td></td>
</tr>
<tr>
<td>Early Ferroan Calcite</td>
<td>Mosaic</td>
<td></td>
</tr>
<tr>
<td>Early Ferroan Calcite</td>
<td>Poikilotopic (concretions)</td>
<td></td>
</tr>
<tr>
<td>Silica Cement</td>
<td>Overgrowths on quartz grains and crystal shards in fault</td>
<td></td>
</tr>
<tr>
<td>Dolomite</td>
<td>Grains or crystals</td>
<td></td>
</tr>
<tr>
<td>Late Ferroan Calcite</td>
<td>Microcrystals</td>
<td></td>
</tr>
</tbody>
</table>
Early ferroan calcite can be classified in three main textural fabrics, rim, mosaic and poikilotopic. Rim ferroan calcite forms on the rims of the bioclastic debris, while poikilotopic ferroan calcite is a blocky cement which completely occludes the pore space between the quartz grains. Mosaic cement refers to elongate crystals rimming or filling voids. Late ferroan calcite occurs texturally as pore filling poikilotopic microcrystals. This late ferroan calcite occurs only in the water zone.

Concretions consist of quartz grains, minor iron free calcite, ferroan calcite, and bioclastic debris (shells). Concretion formation occurs in all three zones (water, oil and gas) simultaneously. Early poikilotopic ferroan calcite cement fills the pore space creating the concretions. Ferroan poikilotopic cement phase occurs before early quartz overgrowths indicated by the absence of quartz overgrowths in the cemented sandstones. A ferroan calcite also occurs as pervasive pore filling mosaic cement, rim cement and partially replaces bioclasts in the concretionary horizons. The degree of replacement of bioclasts by ferroan calcite is controlled by the original composition of the fragment (for example, aragonite).

Minor to moderate quartz overgrowth development has taken place on quartz grains where little to no calcite cement is present. Silica fines are also present in a fault zone in L-08. A number of fractures are evident in thin section and core, some are filled with quartz crystals, bitumen, barite, clays (kaolinite, etc.) or with carbonate cementation.

Siderite occurs as microcrystals scattered throughout the pore system, and as a replacement of detrital clays in argillaceous burrows, clay partings and partially filling shell cavities. Pyrite occurs in trace to minor amounts, and is present as coatings on fossils (after early carbonate dissolution), and burrows.

Feldspars observed exhibit partial alteration and replacement by carbonates and clays, and dissolution of some grains. The gas zone in the South Avalon Pool contains more siltstone and clays than the oil or water zones. Where clays are present as coatings around grains or as matrix, the grains are protected from calcite replacement. Minor heavy minerals (zircons, garnet) sometimes occur and may be attributed to concentration by wave action along a coastline.

**Paragenetic sequence for the Avalon Formation**

Framework grains of quartz, bioclastic debris, with trace amounts of feldspar, siderite, and heavy minerals.

- early iron free calcite;
- early Ferroan calcite;
- quartz overgrowths;
- siderite, pyrite;
- hydrocarbon emplacement; and
- late ferroan calcite.
The original framework of the Avalon Formation consisted of quartz, bioclastic debris and trace amounts of feldspar (in South White Rose wells) siderite and heavy minerals. Early iron free calcite occurred and some was replaced by early ferroan calcite. The early ferroan calcite cement occurred next in the paragenetic sequence in different textural forms as discussed above. The ferroan poikilotopic cement phase occurred before quartz overgrowths as evidenced by the absence of quartz overgrowths in the cemented sandstones. The presence of pyrite and siderite can be explained as both late and early in the paragenetic sequence. Early as crystals and late as fillings in burrows and along shell linings. Late ferroan cement appears to be present only in the water zone, which can be explained by the fact that oil migration may have occurred just prior to this later diagenetic cement.

**Reservoir Quality**

The Avalon Formation is characterized by low to medium permeabilities because of the very fine-grained nature of the reservoir, and the degree of pore throat size reduction due to physical compaction and quartz overgrowths.

Porosity in the Avalon Formation is mainly primary intergranular with minor secondary moldic porosity resulting from dissolution of shells and other grains. In reservoir intervals where carbonate cement is abundant, porosity is very low due to cement plugging the pores. The presence of early carbonate cement prevents closer grain packing in response to increasing overburden. In cemented samples, shells show very little to no evidence of flattening due to compaction; whereas in uncemented samples shells may exhibit some deformation and flattening as a result of overburden pressure. Where a few quartz grains are closely packed together, silica cement reduces pore space, however in general silica cement only moderately reduces porosity.

There are several minerals in the Avalon Formation that have the potential to cause production problems, when they occur as fine grained rock constituents. Introducing acid into this carbonate bearing formation will introduce problems such as the formation of iron precipitates. Carbonate types are mainly calcite, ferroan calcite, and aragonite with minor siderite and dolomite. Clays in the upper portion of the reservoir may also cause problems in terms of fines migration. These clays include illite, kaolinite and chlorite (XRD/SEM analysis).

The pore system is generally clean. There is little to no authigenic clays, or other fines (with the exception of the upper portion of the reservoir) that could cause significant fines migration problems during production, or cause completion problems. The sandstones are competent and not friable, therefore sand production should not be a problem.
2.1.4 Reservoir Description: Secondary Hydrocarbon Bearing Reservoirs

A reservoir description of the secondary hydrocarbon bearing reservoirs, encountered in the White Rose Field, is outlined below. Refer to Formation Tops and Fluids Sampled (Table 2.1-1a and 2.1-1b), the stratigraphy of the White Rose area (Figure 2.1-7) and the Paleocene to Late Jurassic Stratigraphic cross section of the White Rose area (Figure 2.1-8).

The Rankin Formation was penetrated at the base of the White Rose E-09 well. This Kimmeridgian aged section consists of a mixture of shales and siltstones with interbedded sandstones, likely the Tempest Member. Drilling problems related to overpressure in this section did not allow a complete evaluation of this unit. An open hole test of the bottom 187 m of the well produced small amounts of gassy oil and water. Reservoir quality is very questionable, as no cores were taken. Both overpressure and fractures within this fault bounded zone likely contributed to enhancing fluid flow during the test.

The Hibernia Formation has been penetrated in the A-17, E-09, N-22 and J-49 wells. The Formation can be divided into Upper, Lower and Basal members. The Upper Hibernia is not well developed in the White Rose area. The Formation consists primarily of marine siltstones and shales, as it is far from the main southwest entry point into the basin. An 18-m core cut in N-22 is composed of poor quality siltstones and calcareous marine shales. Coarser clastics appear towards the base of the unit, where slightly porous, fine-very fine grained, argillaceous sandstones are found. The Lower Hibernia has been penetrated in the E-09, N-22, A-17 and J-49 wells. Two cores cut in N-22 recovered 15 m of siltstone, shale and minor amounts of fine-grained sandstone. Minor fractures, filled with calcite, are present, but reservoir quality is poor. The zone subsequently tested 60 m³ oil. The lowermost Hibernia package, the Basal Hibernia, appears slightly better developed and tested 78 m³ oil in E-09. This unit was deposited primarily as a prograding shoreface succession as part of an overall regional regressive Hibernia package. The shoreface succession contains minor fluvial and marginal marine deposits. The same basal unit, found 4.5 km further south in the A-17 well, is better developed and has good porosity described from cuttings. Although not cored, secondary enhancement of the reservoir unit immediately beneath the base Avalon Unconformity, at this location, may explain the better reservoir character. Hibernia Formation sandstone content decreases northwards, and shale content increases, until very thinly bedded, gas charged argillaceous sandstones are all that remain at Trave E-87.

The Eastern Shoals Formation has been penetrated in White Rose L-61, J-49, N-22 and N-30. In E-09 and L-08, a tight basal carbonate was encountered, indicating little prospectivity under the South Avalon Pool. In White Rose L-61, 13.5 m of Eastern Shoals core recovered thinly bedded sandstones, siltstones and shales. A drill stem test from the Eastern Shoals Formation produced 0.065 \(10^6\) m³ gas, 24 m³ oil with 14 percent water from a thin sandstone in White Rose J-49, indicating a separate pressure system from the overlying West Avalon Pool. The Eastern Shoals Formation test (0.04 \(10^6\) m³ gas) and RFT pressure points in White Rose N-22 indicated the thin sandstones were in communication with the overlying North Avalon Pool. Similarly, formation pressures in the untested upper part of the N-30
The Paleocene South Mara Member, a basal transgressive shallow marine sandstone, tested gas and condensate in the White Rose L-61 well. The South Mara Member, found at the base of the Banquereau Formation, is the thick succession of Tertiary clastics deposited during thermal subsidence. In L-61, the South Mara is a fining-upwards 30-m section of brown, glauconitic silty fine to very fine-grained sandstone. The lowermost 5 m of fine to medium grained sandstone is porous, averaging 23.5 percent porosity. Although the overlying silty shale package can be correlated throughout the field, porous sandstone appears restricted to the northwest flank of the N-22 structure, and south at Amethyst F-20.