STRUCTURAL STYLES OF THE JEANNE D'ARC BASIN, GRAND BANKS, OFFSHORE NEWFOUNDLAND, AND THEIR IMPLICATION FOR PETROLEUM EXPLORATION

by

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THE STRUCTURAL STYLES OF THE JEANNE D'ARC BASIN, GRAND BANKS

ABSTRACT

The interpretation of deep seismic sections confirmed the suggestion of Tankard and Welsink (1987) that the extension of the central Grand Banks--Galicia Bank terrain probably occurred along a low-angle intracrustal detachment gently dipping westward. The interpreted seismic cross-sections show that the Jeanne d'Arc basin in the central Grand Banks is a half-graben whose basin-bounding listric normal fault (Murre fault) soles out along this low-angle intracrustal detachment. Transfer faults accommodate the areas where the amounts or rates of extension are different. Unconformity-bounded sequences are the direct sedimentary response to the tectonic movement. A supracrustal detachment occurred within the cover sequences in Aptian time, resulting in numerous structural and stratigraphic modifications. The subsidence curves of the Jeanne d'Arc basin show an episodic subsidence pattern which resulted from several episodes of continental separation from North America.

The structural styles and subsidence history of the Jeanne d'Arc basin have important implications for petroleum exploration which include: 1) the distribution of source rocks, 2) the distribution of reservoir rocks, 3) the generation of secondary porosity 4) the maturity of source rocks, 5) the developement of hydrocarbon traps, 6) the migration, entrapment, and preservation of hydrocarbons.

RÉSUMÉ

L'interprétation de sections sismiques profondes a confirmé l'hypothèse de Tankard et Welsink (1987) qui suggère que l'extension de la partie centrale de la région entre les Grand Bancs et le Banc Galicia a probablement eu lieu le long d'une zone de detachement intracrustal à faible pendage vers l'ouest. L'interprétation de coupes sismiques transversales montre que le bassin sédimentaire Jeanne d'Arc, situé dans la partie centrale des Grands Bancs, est un demi-fossé délimité par une faille normale listrique (faille Murre) qui converge avec la zone de détachement intracrustal. Des failles recoupant le bassin ont accomodé les région où le degré et/ou le taux d'extension furent différents. Les séquences délimitées par des discordances sont la conséquence directe de mouvements tectoniques. Le détachement supracrustal s'est produit dans les séquences de couverture durant la période Aptienne causant de nombreuses modifications structurales et stratigraphiques. Les courbes de l'affaissement du bassin sédimentaire Jeanne d'Arc indiquent qu'une série épisodique d'affaissements résultaient de plusieurs épisodes de séparation continentale de l'Amérique du Nord.

Les divers styles structuraux et l'histoire de l'affaissement du bassin sédimentaire Jeanne d'Arc ont d'importantes implications pour l'exploration pétrolière qui

incluent: 1) la distribution des roches meres, 2) la distribution des roches réservoirs, 3) le développement d'une porosite secondaire, 4) le degré de maturité des roches mères, 5) la formation de pièges pour les hydrocarbures, 6) la migration, le piégeage et la préservation d'hydrocarbures.

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CHAPTER I.

INTRODUCTION

I.1 SIGNIFICANCE OF STRUCTURAL STYLES FOR PETROLEUM EXPLORATION

Basic structural styles are defined by assemblages of tectonically related elements and their spacial arrangement. These structural styles generally are repeated in regions of similar tectonic regimes. Structural styles are classified on basis of basement involvement or detachment within cover sequences (Harding and Lowell, 1979). Basement-involved styles include wrench-fault structural assemblages, compressive fault-blocks, extensional fault-blocks, and warps. Detached styles are decollement thrust-fold assemblages, detached normal faults, salt structures, and shale structures. These basic structural styles are directly related to the larger kinematics of plate tectonics, and in some situation, to particular depositional histories. Unconformity-bounded sequences are the stratigraphic response to these large-scale tectonic processes. Hence they record major episodes in basin evolution (Sloss, 1963, 1982). Smaller-scale adjustments to the tectonism are expressed in multiple stacking of depositional sequences. The structures of a petroleum province can be further complicated by superimposition of fundamentally different structural styles. In many cases, detached faults, salt structures, and shale structures are superimposed on extensional fault-blocks.

Identifying structural styles is one of the critical tasks in petroleum exploration. Following are some of its important applications. **First,** the recognition of basement-involved structural styles is important for the petroleum geologist to understand the nature of the tectonic regime and construct or test different geological models. In the case of extensional fault blocks within conjugate passive continental margins, conspicuous asymmetry of extensional geometry probably indicates a low-angle intracrustal detachment, simple shear model of Wernicke (1981, 1985) rather than pure shear extensional tectonics (McKenzie, 1978). With the simple shear model, the rift basins formed in the distal parts of conjugate continental margins are much deeper and wider, and as a result, more prospective for petroleum exploration. **Second,** because unconformity-bounded depositional sequences correspond directly to the tectonic and structural framework (Sloss, 1963, 1982), understanding the structural styles is the key to understand basin evolution, and has important implications for the distribution of the source and reservoir rocks. **Third,** with the knowledge of the structural styles, the location of hydrocarbon traps can be anticipated (see Harding and Lowell, 1979 for detail). **Forth,** the maturity of the source rocks is directly related to the subsidence history which is controlled by the tectonic framework. **Fifth,** the superimposition of later structural styles on the earlier structural ones can cause numerous structural and stratigraphic modifications, which have great influence on the migration and preservation of hydrocarbons.

In the Grand Banks, deep-penetration seismic surveys processed with modern techniques in recent years have revealed the subsurface structures and made it possible to study basement-involved structures. For the Jeanne d'Arc basin, the interpretation of seismic data, geological data combined with geochemical data will help to better understand the extensional mechanism, structural styles and subsidence history. It will also provide an opportunity to evaluate the implications for petroleum exploration, which, I believe, has great significance for this and other basins with similar structural styles.

I.1 PREVIOUS STUDIES

The Grand Banks is located in offshore Newfoundland (Figure 1.1). The continental margin around the Grand Banks developed through several phases of rifting and spreading which display a general northward migration during the Mesozoic and Tertiary (Jansa and Wade, 1975; Srivastava, 1978; Kerr, 1981; Srivastava et al., 1981). The tectonic evolution and stratigraphic units of the Grand Banks have been described by several studies (e.g. Amoco and Imperial, 1973, Enachescu, 1987 , Haworth et al., in press, Hubbard et al., 1985, Jansa and Wade, 1975, Tankard and Welsink, 1987). The stratigraphy of the Jeanne d'Arc basin is

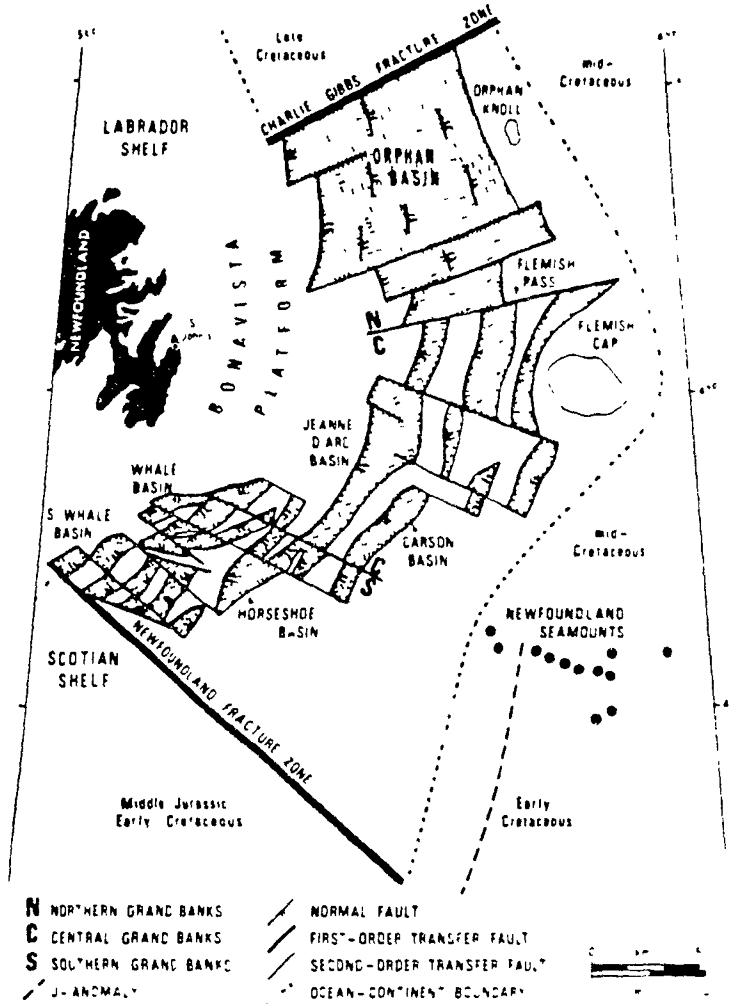


Figure 1.1 Location and major tectonic elements of the Grand Banks and times of continental separation around the Grand Banks. (From Tankard and Welsink, 1987).

a direct response to its tectonic and structural history and framework (Tankard and Welsink, 1987).

Several extensional models have been proposed for the evolution of passive continental margins, which include the uniform extensional model (McKenzie, 1978), the non-uniform extensional model (Royden and Keen, 1980; Beaumont et al., 1982; Keen et al., 1987a), and the low-angle intracrustal detachment model (Wernicke, 1981, 1985; Tankard and Welsink, 1987).

Exploration for hydrocarbons focussed initially on salt piercement structures, principally in basins of the southern Grand Banks (Amoco and Imperial, 1973). The giant Hibernia oilfield was discovered in the Jeanne d'Arc basin, central Grand Banks in 1979 (Arthur et al., 1982). Subsequent discoveries , among which are the Hebron-Ben Nevis complex, and the South Tempest, Nautilus, and Terra Nova fields, are almost all in the Jeanne d'Arc basin. These hydrocarbon occurrences are all structurally trapped in sandstones of Late Jurassic and Early Cretaceous age (Tankard and Welsink, 1987). Kimmeridgian organic-matter rich shales are the main source rocks for the Hibernia field and other discoveries in the Jeanne d'Arc basin (Arthur et al., 1982; Powell, 1985). Geochemical studies of the source rocks revealed a linear relationship between maturity and the burial depth of the source rocks in the Jeanne d'Arc basin (Creaney and Allsion, 1987). Abid (1988) discussed the diagenetic processes and secondary porosity in sandstones with increasing depth in Hibernia oil field.

So far, every study on the Jeanne d'Arc basin has concentrated on certain specific aspects of its geology. An integrated approach would be important for a better understanding of the evolution of the Jeanne d'Arc basin as a whole, and the occurrence of hydrocarbons in it.

I.1 OBJECTIVES AND APPROACHES

My research focussed on the structural styles and subsidence history of the Jeanne d'Arc basin and their implications for petroleum exploration. The work is mainly based on the interpretation of seismic profiles and logging data. The geochemical data of Creaney and Allsion (1987) were used to construct the maturity level of the source rocks in the Jeanne d'Arc basin.

38 seismic lines and 15 composite logs were used during this research (Figure 1.2, Appendix). A number of figures and interpreted seismic sections from other authors were also used, which are identified in the figure captions. In most seismic sections, the B-marker limestone reflector is continuous. It can be correlated in large area and thus used as a standard reflector for regional correlation (Figure 1.3). A Callovian unconformity divides the seismic section into two mega-sequences, each representing a rifting event followed by post-

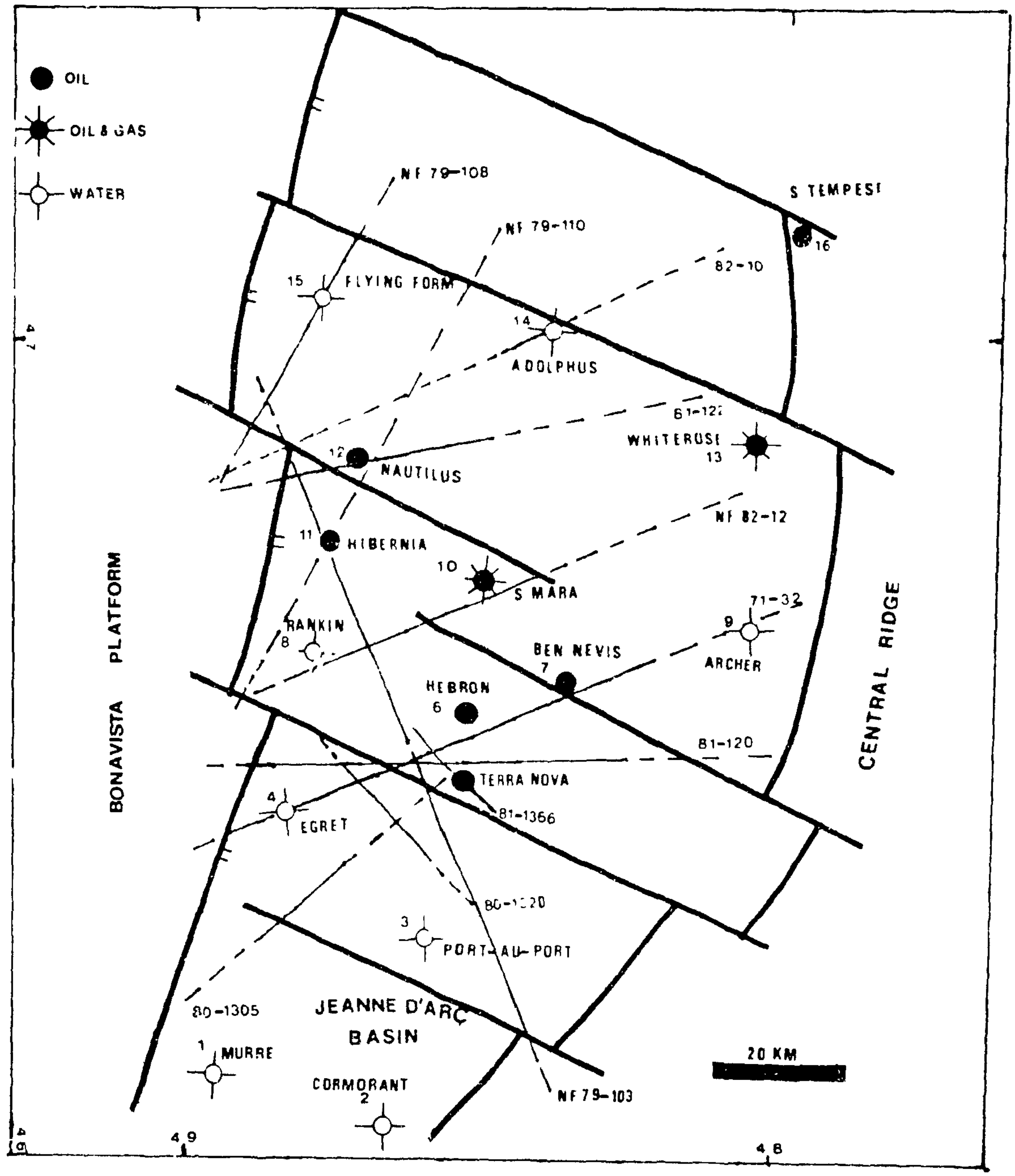


Figure 1.2 Locations of oil fields in the Jeanne d'Arc basin and seismic lines used in this paper.

rift subsidence. Each can be further divided into sequences and sub-sequences (Figures 1.3 and 1.4). The Cenomanian and Aptian unconformities divide the second mega-sequence into three sequences: a Late Jurassic-Middle Cretaceous rift sequence, a Late Cretaceous transition sequence, and a post-rift sequence. The generation and accumulation of hydrocarbons are restricted to the Late Jurassic-Middle Cretaceous rift sequence which is of main concern with respect to petroleum exploration. The Late Jurassic-Middle Cretaceous rift sequence is further divided into two sub-sequences by the Kimmeridgian unconformity: a Callovian-Kimmeridgian sub-sequence which contains the main source rocks and a Kimmeridgian-Aptian sequence which includes the main reservoir rocks. The pre-Tertiary unconformity reflector divides the post-Cenomanian post-rift sequence into two sub-sequences which are characterized by different subsidence patterns. The Cenomanian-Early Tertiary sub-sequence is characterized by differential subsidence of the main structural elements. The post-Cretaceous sub-sequence experienced an integrated subsidence as a single, unsegmented piece.

Balancing techniques were used on all seismic sections to determine the fault trajectories and the detachment depths of listric normal faults. Depositional sequence mapping was used to understand the topography, depositional systems, and source direction of clastic materials. Isochrone maps of the depositional sequences, near faults, also provided important

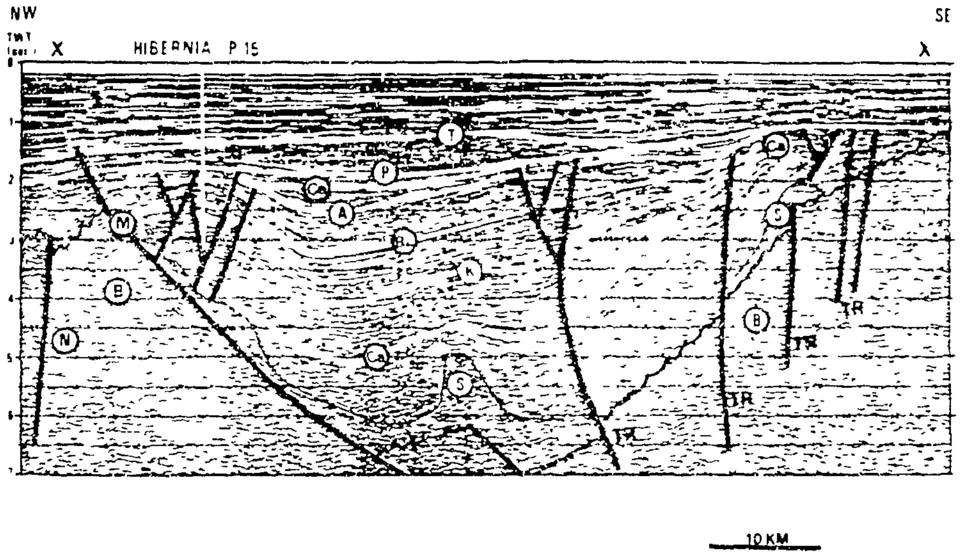


Figure 1.3 Seismic line 79-NF-103 (see Figure 2 for location) showing half-graben asymmetry of the Jeanne d'Arc basin and major unconformity-bounded sequences and sub-sequences. The Hibernia structure formed as a hanging wall anticline which is complicated by the growth of salt diapirs. T--Pre-Tertiary unconformity; P--Petrel Limestone; Ce--Cenomanian unconconformity; A--Aptian unconformity; BL--B-Marker limestone; K--Kimmridgian unconformity; Ca--Callovian unconformity; S--Argo Salt; B--Basement; M--Murre Fault; N--Nautilus Transfer fault; TR-Transfer fault; TWT--two way travel time in seconds. (adapted from Tankard and Welsink, 1987).

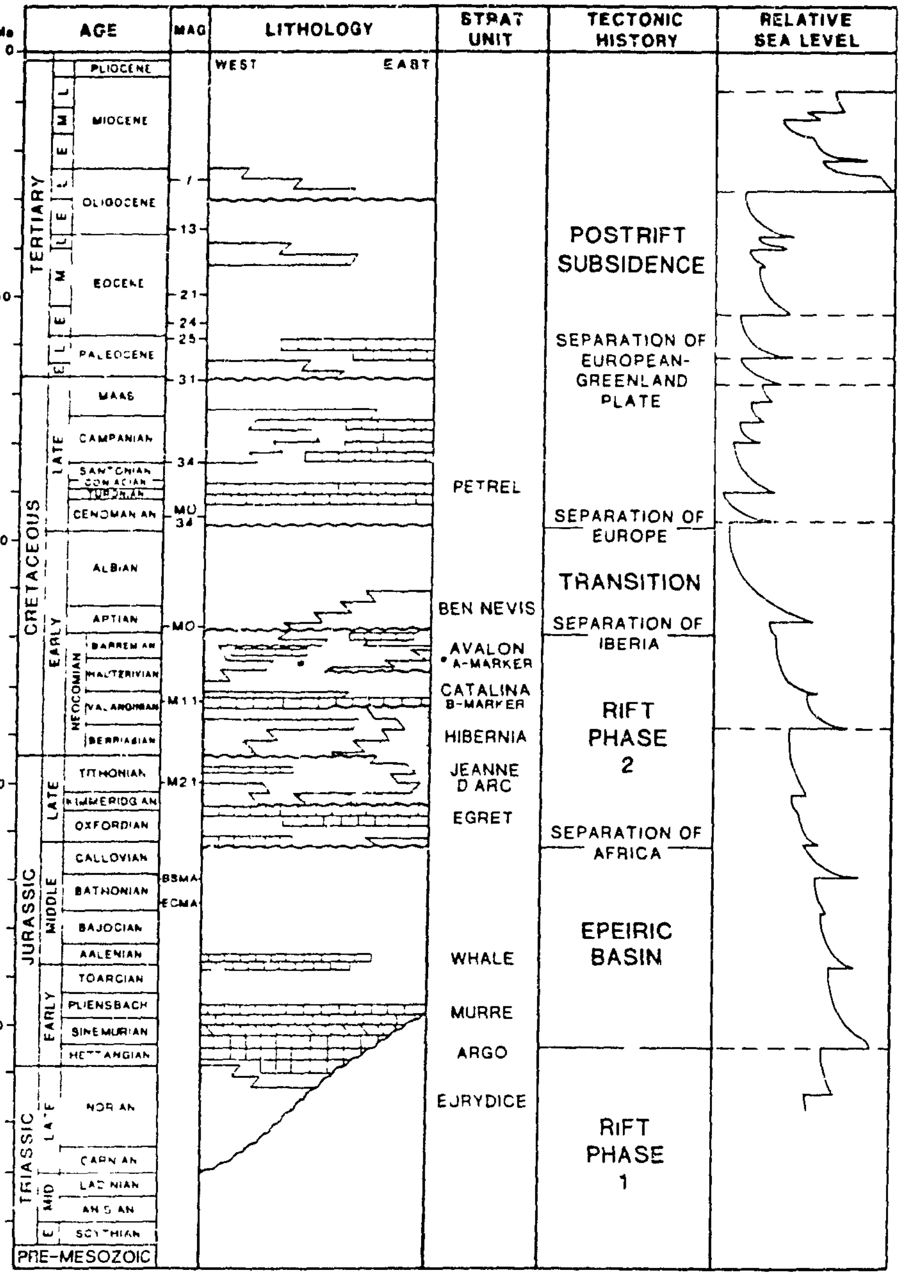


Figure 1.4 Tectonostratigraphic column for the Jeanne d'Arc basin showing the five major basin-forming stages. Uncomformity-bounded depositional sequences correspond to several episodes of continental separation. (From Tankard and Welsink, 1987).

information on fault activity. Conversion of time sections into depth sections was used to determine the detachment depths of the listric normal faults and burial depths of the source rocks.

Recognition of the extensional regime and structural styles of the Jeanne d'arc basin is the key to this research. A number of seismic profiles were interpreted to understand and illustrate the structural styles of the Jeanne d'Arc basin. In summary, the implication of the structural styles for petroleum exploration is the main concern of this research.

CHAPTER II.

METHODS OF STRUCTURAL ANALYSIS

II.1 BALANCING TECHNIQUES

During the interpretation of seismic profiles, section balancing techniques were used to determine the trajectories and detachment depths of the listric faults and the geometry of the hanging wall sequences. A section is said to be balanced when it can be reconstructed to its original geometry without cross-section area changes or bed-length changes. The section balancing techniques assume that all deformation is in the plane of the section (plane strain) and area changes due to compaction or sedimentary growth can be either ignored or measured and accounted for(Gibbs, 1983,1984).

Two main approaches to balance a section were used during the interpretation: 1) the line length balance, which checks the bed length on the section through the deformed rocks, and 2) the area balance, which compares the excess area during extension with a regional datum or a marker horizon before deformation.

In both approaches, a "regional line" and a "pin-line" are assumed (Figure 2.1). The "regional line" is in the position of the undeformed marker horizon. The "pin line" is a line in the foot wall perpendicular to the "regional line". Both

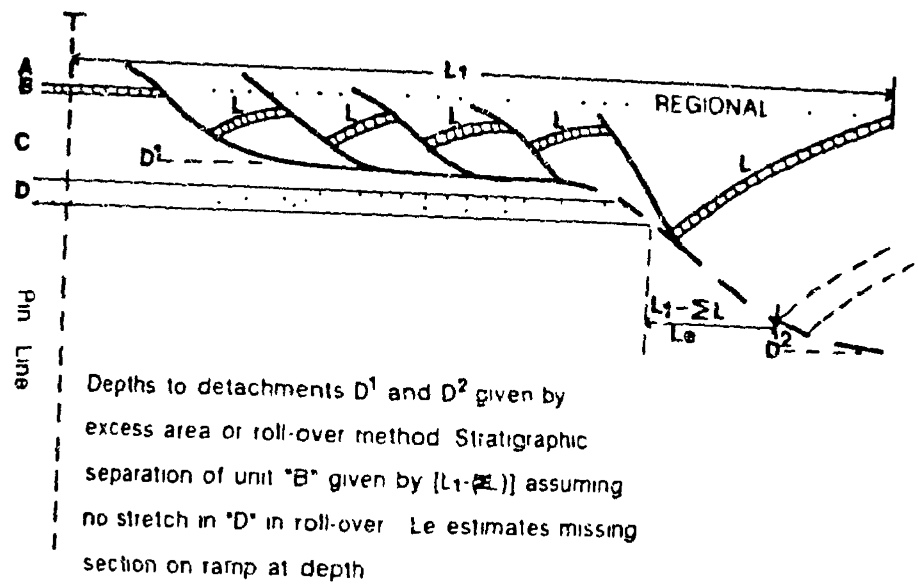


Figure 2.1 Calculation of separation of layer B and estimation of missing section (unit D) using balancing techniques.

techniques have to be used iteratively before it is possible to obtain a "satisfactory" result.

The depth to detachment can be calculated through the area balance for extended terrains, assuming constant cross-sectional area during extension. As shown in Figure 2.2, by measuring the area A, and calculating the extension e, the average detachment depth d can be calculated by the equation:

$$d = \frac{A}{e}$$

Extensional movement on a listric fault or detachment usually generates a roll-over anticline on the hanging wall. In the same fashion, complex hanging wall structures will be generated by movement along an irregular fault profile (Gibbs, 1983, 1984). The hanging wall geometry is a direct consequence of the shape of the foot wall and can be used to construct the trajectory of the listric fault or detachment.

The two most frequently used construction mehtods during the interpretation of seismic profiles are (i) the chevron construction (Gibbs, 1983, 1984; Verrall, 1982) and (ii) the modified chevron construction (Williams and Vann, 1987).

The chevron construction is commonly used for the construction of thrust faults. Verrall (1982) introduced this technique to the construction of extensional faults in the North Sea basin. The chevron construction was used to determine

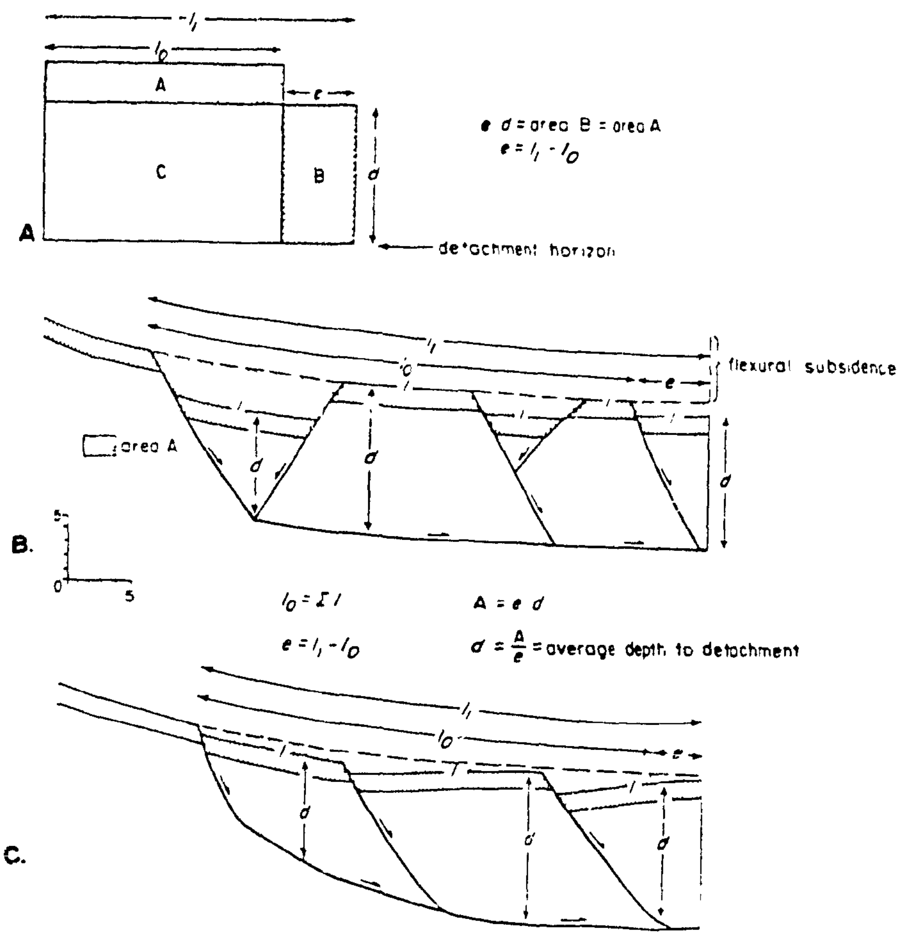


Figure 2.2 Area balance and calculation of average depth to detachment for extended terrains, assuming constant cross-sectional area during extension. A. Basic principle. B. Simplified extension by non-rotational planar faulting. C. More realistic extension by listric normal faulting. Area subsidence is entirely caused by faulting: flexural subsidence must not be included in this area. (Adapted from Gibbs, 1983).

the shape of listric fault from the roll-over profile assuming that all points in the hanging wall have moved an equal distance (constant heave). This assumption will satisfy area conservation but cause the change of bed thickness. This construction is graphically shown in Figure 2.3 and relies on the relationship that the fault dip O can be expressed as :

$$\tan O = t/H$$

where t is the throw and H the heave of the fault.

The modified chevron construction assumes that the hanging wall translates as a rigid block with little or no vertical thinning and with constant slip on the detachment fault. For the simple case in which there are no hanging wall antithetic and synthetic faults, the fault trajectory can be constructed graphically from the roll-over using the relationship (Figure 2.4):

$$\sin O = t/S$$

where S is the slip on the fault. To apply this method correctly to a linked fault array, slips on all of the faults must be summed up. So the overall slip along the detachment will be built-up rapidly. The interpretation of seismic line 71-32 in the Jeanne d'Arc basin shows an example of the modified chevron construction for a linked fault array (Figure

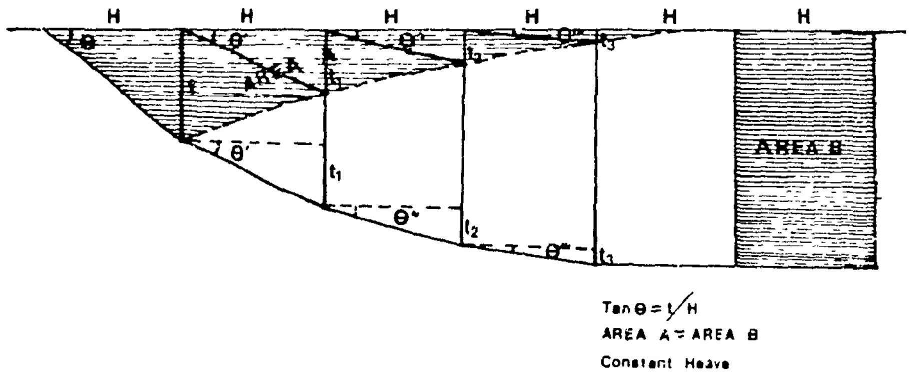


Figure 2.3 Detailed reconstruction of the shape of a listric fault using the chevron construction method (adapted from Gibbs, 1983).

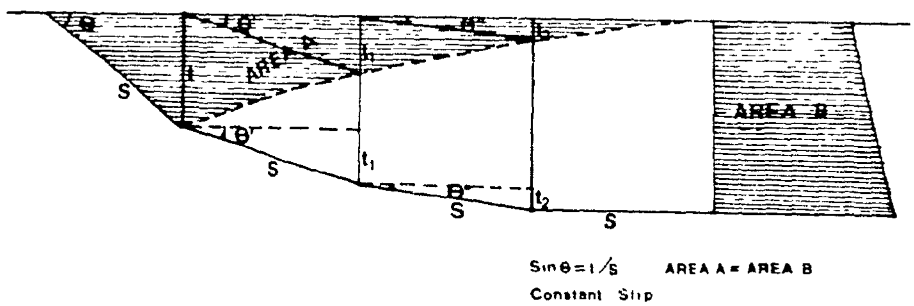
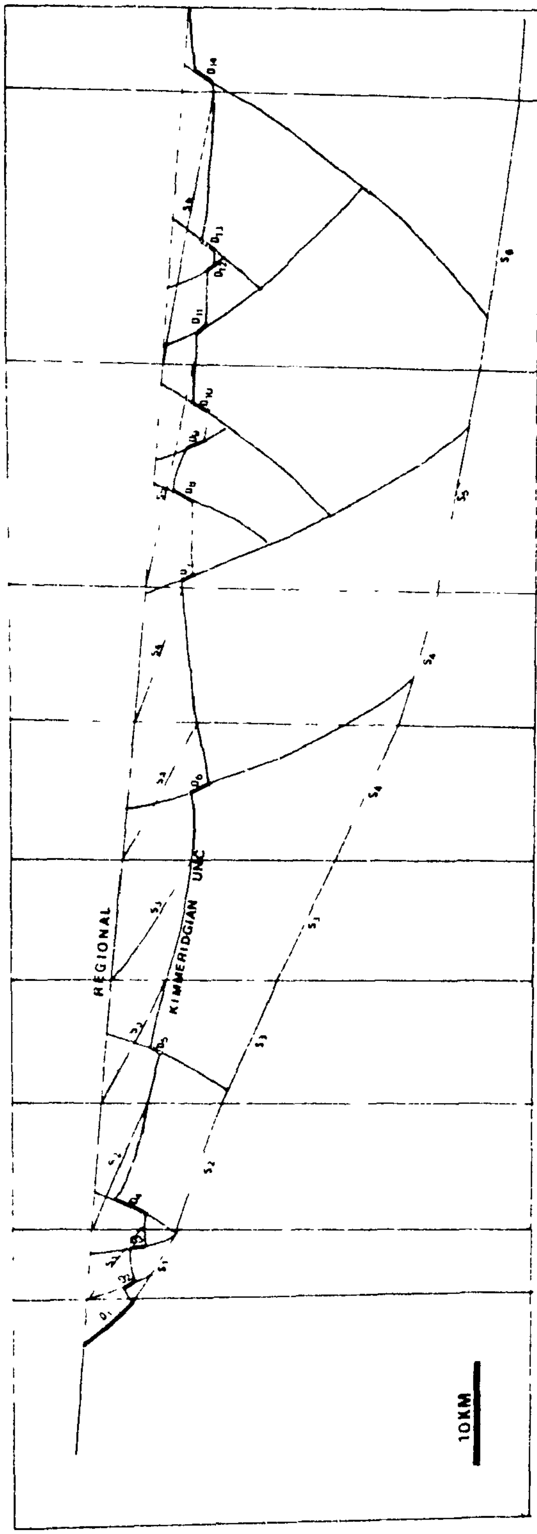


Figure 2.4 Detailed reconstruction for the shape of a listric fault using the modified chevron construction I (adapted from Williams and Vann, 1987).

Figure 2.5 Seismic line 71-32. A. showing the detailed procedure for the reconstruction of the detachment within the cover sequences using modified chevron construction I. B. Interpreted seismic section showing the detachment and associated Egret structure and Hebron-Ben Nevis structure complex. The estimated extension on this section during transition phase is about 13%. (See Figure 1.2 for location and Figure 1.3 for symbols).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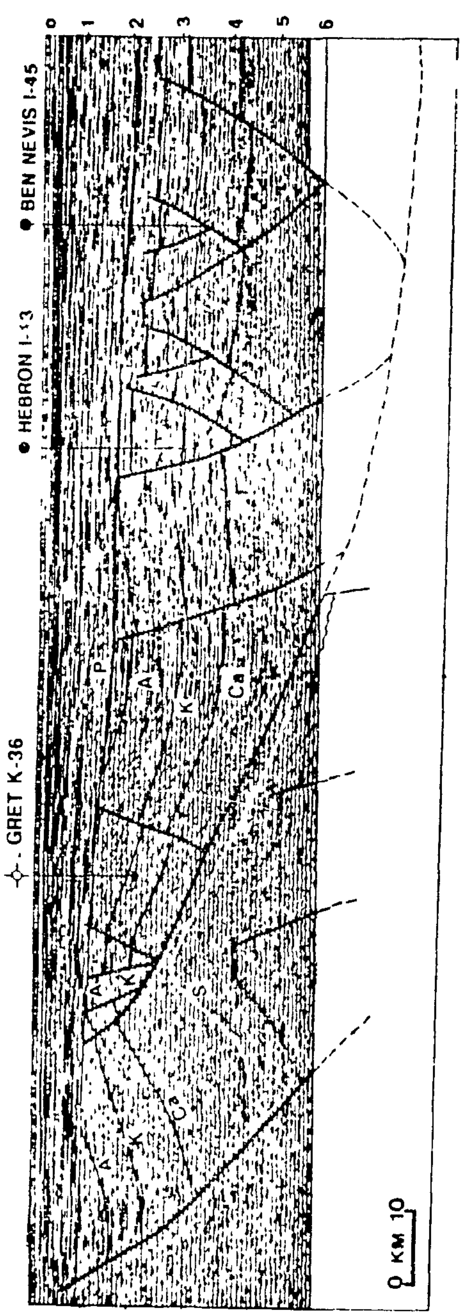
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2.5). This seismic line is approximately in the direction of the overall extension of the Jeanne d'Arc basin during the supracrustal detachment (Figure 2.6). So the deformation along seismic line 71-32 can be viewed as plane strain.

The effect of the two assumptions is that the depth to detachment is shallower using the modified chevron construction than using the Chevron construction. During the interpretation of the seismic profiles, these two approaches were generally used iteratively to arrive at a final solution.

These construction methods can also be used with well data to construct the roll-over shape of the stratigraphic markers encountered in the wells by back-calculation from the fault plane.

Although section balancing reconstructions are ideally carried out on geological sections with equal vertical and horizontal scales, seismic sections whose vertical scale is given in two-way travel time invariably contain geometric information which can be used to balance the section. The iterative application of balancing techniques and fault trajectories derived from the roll-over on the hanging wall of listric faults are essential parts of the primary interpretation of seismic lines. Although several solutions could result from using different balancing techniques, each result is valid under the assumptions for each balancing technique. The correct result should be both valid geometrically and realistic geologically. Unbalanced sections

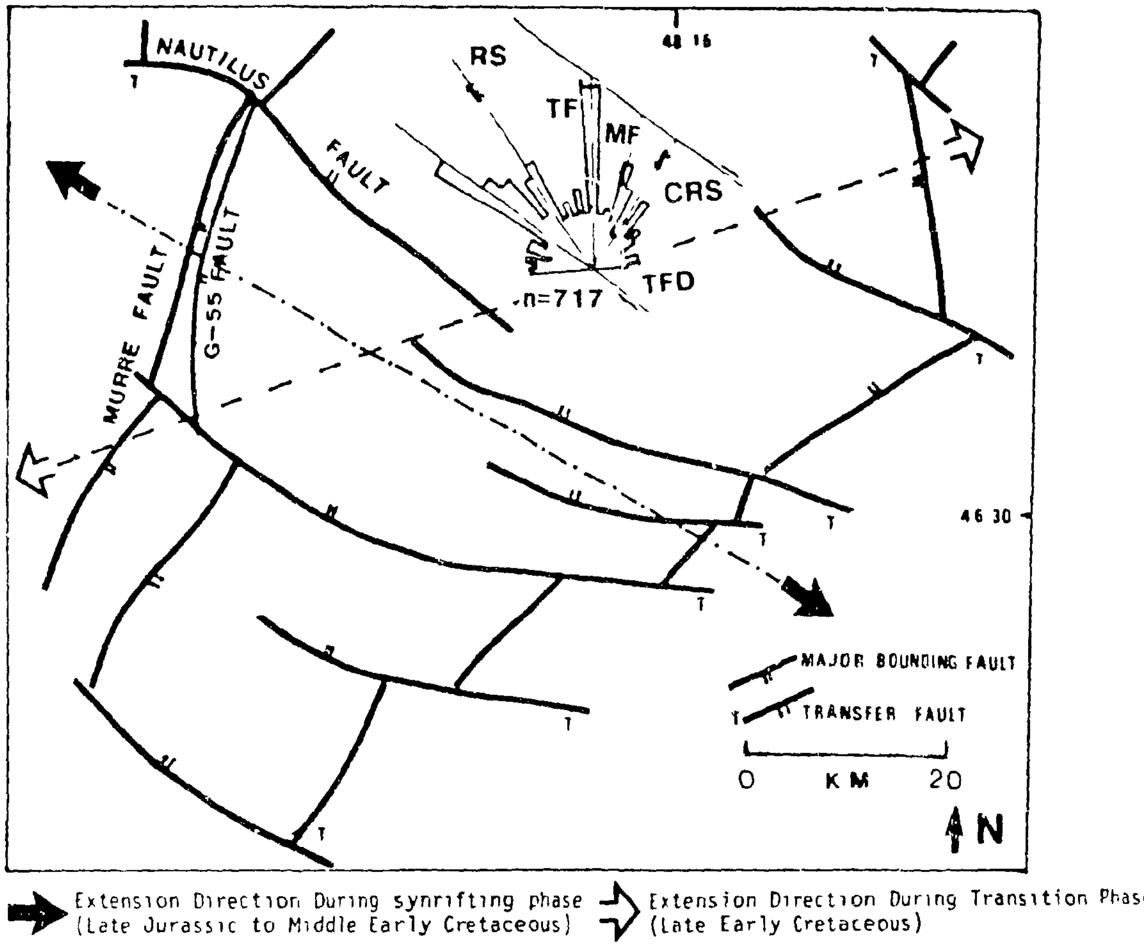


Figure 2.6 Extensional directions during synrift and transition phases. RS--Riedel shear; TF--Tension fracture; MF--Murre fault; CRS--Conjugate Riedel shear; TFD--Transfer fault direction. Rose diagram: from Tankard and Welsink, 1987.

are never correct.

The balancing test should only be carried out on sections that are parallel to the movement direction for all faults that intersect that section (Gibbs, 1983, 1984). For simple orthogonal extension, this means that the section should parallel transfer faults. For the more general case of oblique extension, the balancing should be carried out in three dimensions (See Gibbs, 1983 for details).

II.2 TIME-DEPTH CONVERSION

The key for the time-depth conversion is the determination of mean velocity. The velocity data usually come from sonic logs of wells on or near the seismic lines. In the case of absence of wells, stacking velocity data were used. However, the stacking velocity is usually 10%-20% higher than the mean velocity from sonic logs. So, the stacking velocity data were revised according to the sonic velocity data from nearby wells or by simply being multiplied by a factor of 0.85. Then the depths were determined by the simple equation:

$$D=V*T/2$$

where D is the depth, V is the mean velocity, and T the two way travel time.

During this study, the time-depth conversion was used to determine the burial depths of the source rocks and detachment depths of the listric faults in the Jeanne d'Arc basin.

II.3 DEPOSITIONAL SEQUENCE MAPPING TECHNIQUES

The depositional sequence mapping, whose final results are isopach maps, is a very important technique in the geological interpretation of seismic profiles (Hubbard et al, 1985). Depositional sequence mapping involves three steps:

1) Boundary reflectors must be correctly correlated and loop-tied throughout the grid of the seismic lines. In the Jeanne d'Arc basin, the B-marker limestone reflector can be correlated in most seismic sections over a large area and thus used as standard reflector for regional correlation. The other boundary reflectors are less recognizable than the B-marker limestone reflector. To make sure that the reflectors are loop-tied is important to obtain correct correlations. Well data are necessary to recognize certain reflectors and revise correlations, especially in structurally complicated areas. Because in some cases, the loop-tied reflectors may not be the correct reflectors, checking the correlation by using the well data is mandatory (Hubbard et al., 1985).

2) To extract thicknesses of the depositional sequences from the seismic sections, after they have been correctly correlated and loop-tied throughout the grid of seismic lines, is a relatively easy procedure.

3) From contouring thickness values within the grid of

seismic lines with the aid of a computer or manually, isochrone or isopach maps are prepared. This is the final result of depositional sequence mapping.

Isopach maps have great applications in geology and are extensively used in presenting the results of seismic interpretations. Some typical applications of isopach maps during my research are described below: 1) Isopach maps were used to describe the shape of a unit for which some depositional and/or structural features may be very diagnostic. 2) Isopach maps were used to predict facies, depositional environment, and so on. 3) Isopach maps were used to help unravel the geological history or make paleostructural reconstructions. To reveal early structural relationships, it is often necessary to produce isopach maps that effectively remove later tilting. 4) Isopach maps were used to determine the activity of major faults. Consequently, depositional sequence mapping through geological time can reveal the periods of fault activity.

CHAPTER III.

GEOLOGICAL SETTING

The Jeanne d'Arc basin is located in the Grand Banks, offshore Newfoundland. The Grand Banks underwent a complex geological history. Pre-rift basement comprises Precambrian and Paleozoic rocks of the Avalon terrane. The Avalon terrane was accreted to the Appalachian Orogen by oblique movement through transcurrent faults in the Mid-Paleozoic (Williams and Hatcher, 1983; King, et al., 1986). The basement fabrics had a profound effects on Mesozoic rifting, which is clearly reflected on regional gravity maps (Figure 3.1). The trends of structural elements of the basement correlate with the gravity gradient, which can be used to speculate on the basin boundaries and the positions of transfer faults.

The Early Cretaceous paleogeographic reconstruction for the Iberia, North American and European plates is shown in Figure 3.2. The Grand Banks were connected with the Galicia Bank through Flemish Cap before the break-up of the continents. The Grand Banks record about 225 m.y. of basin formation and subsidence. In the Jeanne d'Arc basin, at least 14 km of Triassic through Lower Cretaceous sedimentary rocks are preserved below the Aptian "break-up" unconformity (Tankard and Welsink, 1987; Figures 1.3 and 1.4). Several phases of plate tectonic motion were responsible for Mesozoic continental break-up and rifting around the Grand Banks:

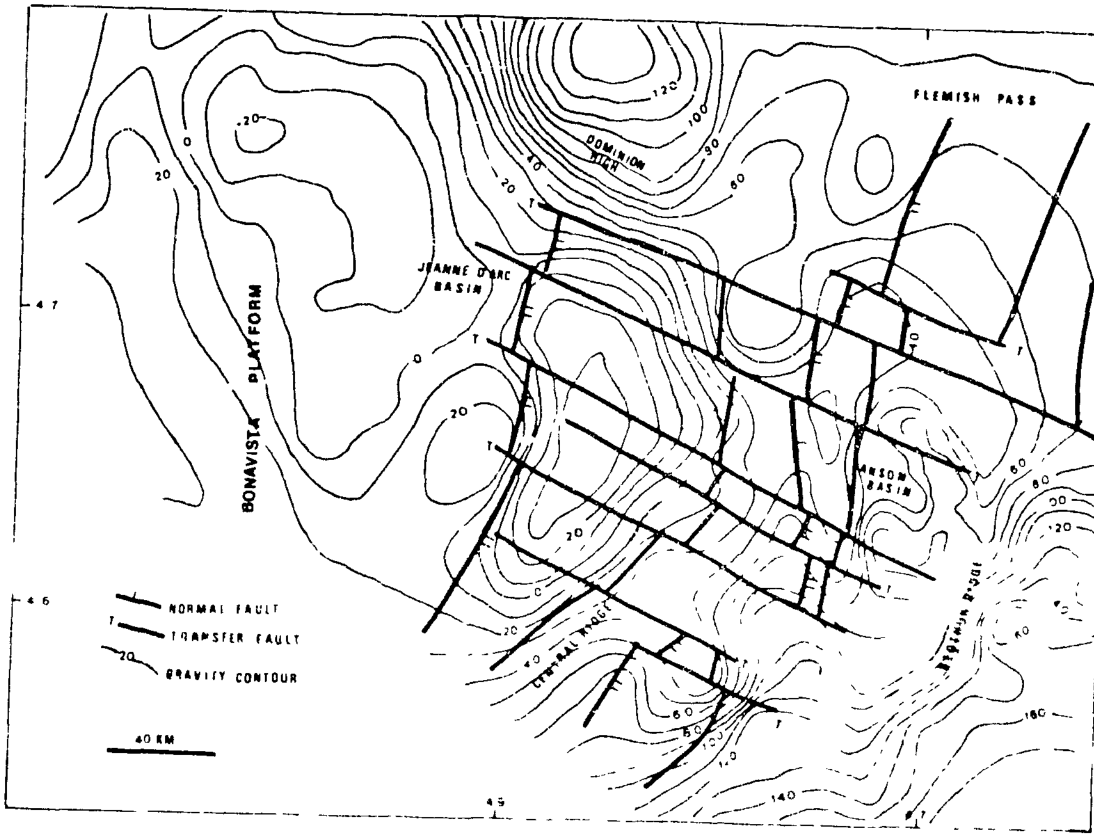


Figure 3.1 Regional Bouger gravity map for the central Grand Banks with superposed fault pattern showing the influence of basement fabrics on later rifting geometry.

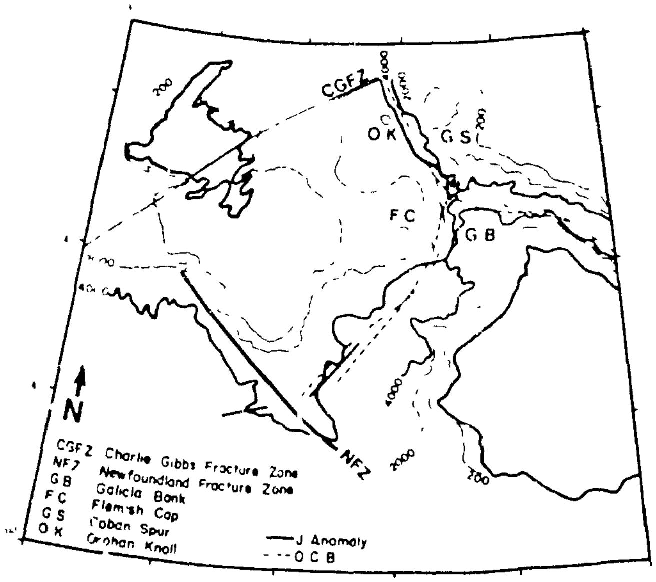


Figure 3.2 The reconstruction of Pangea in the entral North Atlantic (after Masson and Miles, 1984).

1) African-North American plate separation was responsible for the Triassic-Jurassic rifting on the Grand Banks (Wade, 1981). Post-rift subsidence resulted in a broad saucer-shaped, epeiric basin that straddled the Grand Banks, Galicia Bank and Celtic Sea platforms (Tankard and Welsink, 1987). In the Middle Jurassic, final continental break-up initiated the southern transform margin of the Grand Banks.

2) The separation and final break-up between Iberia and the Grand Banks resulted in Late Jurassic rifting and extended the overall rifting history of the Grand Banks into the Mid-Cretaceous (Masson and Miles, 1984).

3) The continental margin of northeast Newfoundland was formed as Europe separated from North America in Mid-Cretaceous time (Masson and Miles, 1984; Srivastava and Tapscott,1986). The separation of the Rockall Trough terminated rifting activity in this area and preceded sea-floor spreading of the Labrador Sea which started at 80 Ma (Srivastava, 1978).

The opening of the Atlantic Ocean around the Grand Banks is from south to north, and as a result, the continental margins in the Grand Banks developed progressively from south to north (Masson and Miles, 1984). The Grand Banks are divided into three extensional terrains by first-order transfer faults, each terrain being characterized by a distinctive basin style. Basins of the southern Grand Banks are shallow, narrow, and enlogate. The northern Grand Banks are dominated by broad

Orphan basin which is deeply buried under post-rift sediments of Late Cretaceous and younger ages (Keen et al., 1987b). The structural style of the central Grand Banks is simpler than that of the southern Grand Banks. Late Callovian-Aptian extension produced a series of half grabens including the Jeanne d'Arc basin. The Jeanne d'Arc basin contains up to 18 km of Mesozoic and Cenozoic sediments (Tankard and Welsink, 1987).

CHAPTER IV.

EXTENSIONAL MODEL FOR THE CENTRAL GRAND BANKS

Deep seismic profiles show that the continental crust and subcrustal lithosphere under the Grand Banks passive continental margins have been thinned progressively eastward, which suggests that the amount of extension increases progressively toward the separartion center and finally resulted in the break-up of the continents.

There are several interpretations for the evolution of passive continental margins. One is the pure shear (uniform stretching) model which assumes that: i) the lithospheric plate thins uniformly and in proportion to the amount of extension, ii) extension is in essence instaneous (less than 20 m.y.) (Mckenzie, 1978). Initial subsidence results from the brittle faulting and the replacement of lower density crust by high density asthenospheric material. Uplift caused by replacement of cold lithosphere by hot asthenosphere is believed to be subordinate. Post-rift thermal subsidence results from lithospheric cooling and contraction and is an exponential function of time. The Mesozoic rifting in the central Grand Banks lasted as long as 50 m.y.. The effect of a finite duration of an extensional event is that a significant amount of heat is lost during rifting, increasing the synrift subsidence at the expense of post-rift subsidence (Cochran, 1983). Ceophysical studies show that the lithosphere is layered and the rheological properties vary continuously with temperature and pressure. The lithosphere is unlikely to extend uniformly under stress (Royden and Keen, 1980; Beaumont et al., 1982). So the pure shear model is not applicable to the extension process in the Grand Banks.

Royden and Keen (1980) and Beaumont et al. (1982) proposed a discontinuous, non-uniform stretching model in which the amount of stretching in the upper lithosphere is not the same as that in the lower lithosphere and an intralithospheric discontinuity, usually placed at the base of the crust, is required. As shown in Figure 4.1B, Keen et al. (1987a) suggested that the Mohorovicic discontinuity ("Moho") acts as a decollement. The upper lithosphere generally deforms by brittle failure and the basin-bounding listric faults detach at the Moho, whereas the lower lithosphere extends by ductile flow (Keen, 1987a). Although this model is more realistic than the homogeneous stretching model, it does not easily explain the asymmetry of the extensional geometry in the central Grand Banks--Galicia Bank conjugate continental margins. This asymmetry includes: i) westward increase in the sole-out depth of the basin-bounding faults (9 km under Galicia Banks, 15-17 km beneath Flemish Cap, 26 km below the Jeanne d'Arc basin), ii) smaller fault-block spacing of the Galicia Bank margin (10-30 km width) as compared to that of the Grand Banks margin (40-100 km width), and iii) a westward decrease in the amount of extension from 45% to 20% (Tankard and Welsink, 1987).

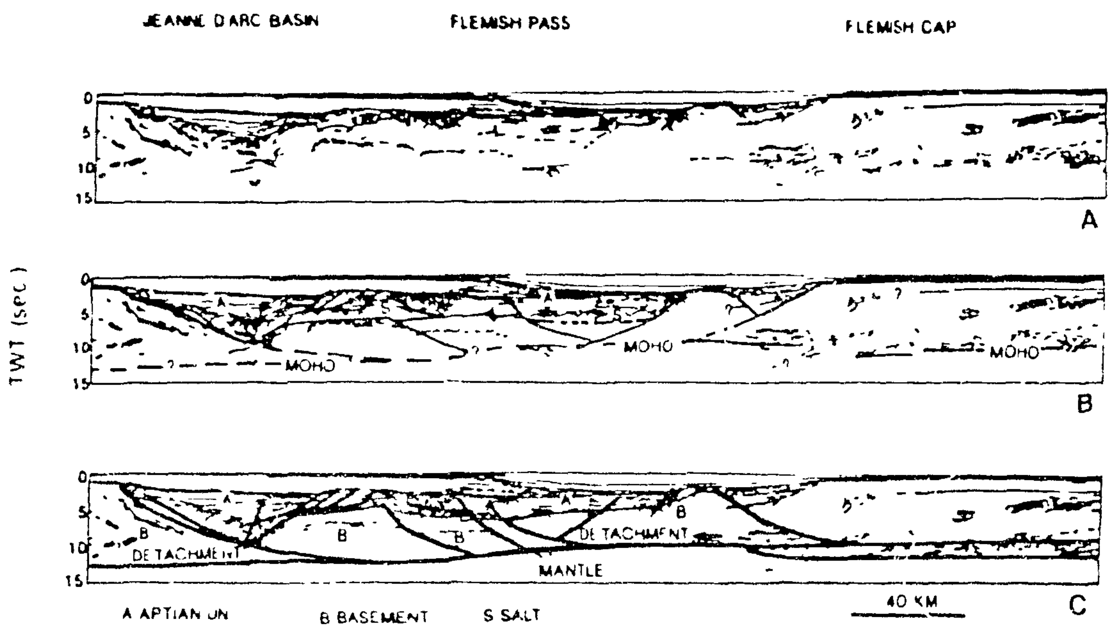


Figure 4.1 Reconstruction of extensional model for central Grand Banks using deep seismic profile 85-3. A. Trace of deep seismic profile without interrpetation. B. The same seismic profile interpreted by Keen (1987a). C. Reconstruction of present study. The estimated extension on this section is about 30%.

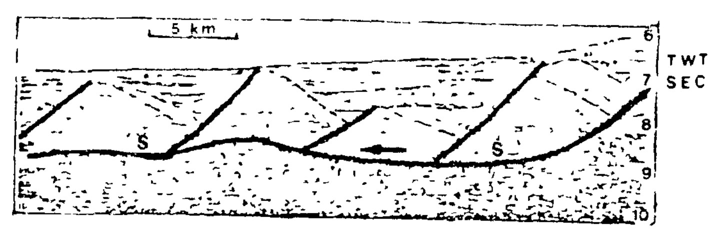


Figure 4.2 S reflection on Galicia Bank (from de Charpal et al., 1978) which may corrrelate with the low-angle detachment shown in Figure 4.1C. The estimated extension on this section is about 50%.

It is obvious that the Moho in Keen's (1988) interpretation dips gently westward not in accordance with her suggestion that the Moho is relatively horizontal (Figure 4.1B). In my opinion, the Moho in Keen's interpretation (from the middle to the left of the seismic section in Figure 4.1C) is part of the low-angle detachment dipping gently westward. Only on the right side of the seismic section, the Moho corresponds to the real Moho and the intracrustal detachment occurs a little above the Moho. This intracrustal detachment could be correlated to the S reflector on Galicia Bank (de Charpal et al., 1978; Manttret and Montadert, 1987; Figure 4.2). This confirms the suggestion of Tankard and Welsink (1987) that the extension of the central Grand Banks-Galicia Bank terrain probably occurred along a complex system of detachments dipping gently to the west. The basin-bounding faults sole out at this low-angle intracrustal detachment dipping gently westward. This low-angle intracrustal detachment is compatible with the asymmetry of the extensional geometry and has great significance for understanding the basin formation and subsidence history. However, it is more likely that the zones of upper and lower lithospheric stretching will be non-uniform. A model which combines the low-angle detachment and discontinuous, non-uniform stretching may therefore be preferable. Further discussion is beyond the scope of this study.

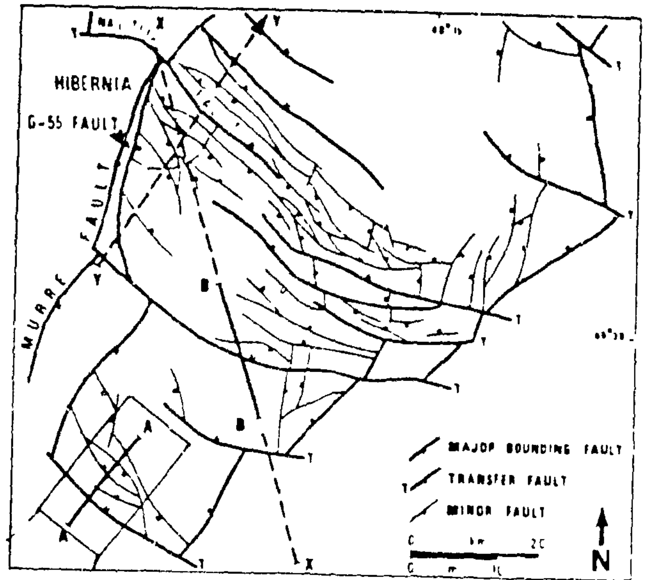
CHAPTER V.

STRUCTURAL STYLES OF THE JEANNE D'ARC BASIN

The Jeanne d'Arc basin has an asymmetric, funnel-shapped geometry. Extension was accommodated by southwest-northeast trending listric and planar fault sets (Figure 5.1). A suite of southeast-northwest trending transfer faults separates adjacent areas that extended by different amounts. The right-lateral strike-slip movement along the transfer faults also generated smaller scale Riedel shears and tension fractures within the cover sequences. The progressive increase of the extension in the Jeanne d'Arc basin northward produced the northward plunge of the basin floor. An isochrone of synrift sequences bounded by the Callovian unconformity and Valanginian unconformities in the southern apex of the Jeanne d'Arc basin reflects this paleogeography to some extent (Figure 5.2). Supracrustal detachment within the cover seqences toward the end of the rift phase at about Aptian time was caused by two factors: i) the gravitational instability of the cover sequences resulting from the northward plunge of the Jeanne d'Arc basin axis and ii) a new phase of extension in the northern Grand Banks (Orphan basin) (Figure 5.3).

There are number of distinct features characteristic of geological structures in the Jeanne d'Arc basin:

Roll-over anticline -- This is an anticline formed by



Figre 5.1 Fault patterns in the central Jeanne d'Arc basin (From Tankard and Welsink, 1987).

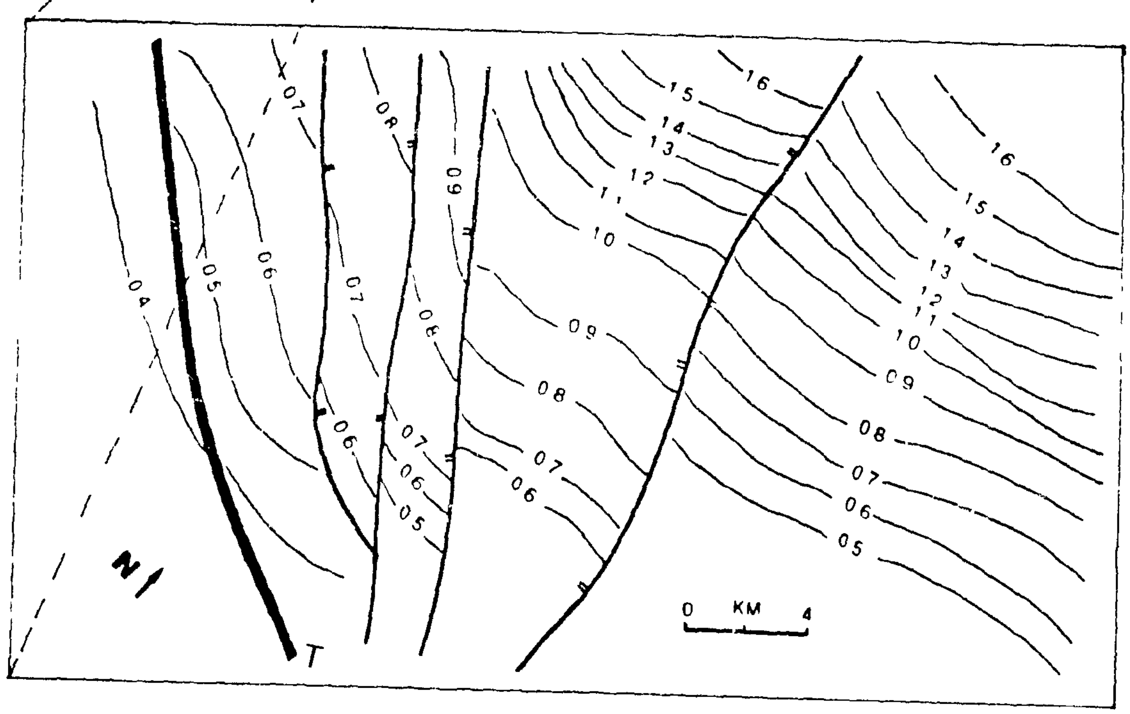


Figure 5.2 Isochron map (units in seconds) of synrift sequences in south Hibernia area.

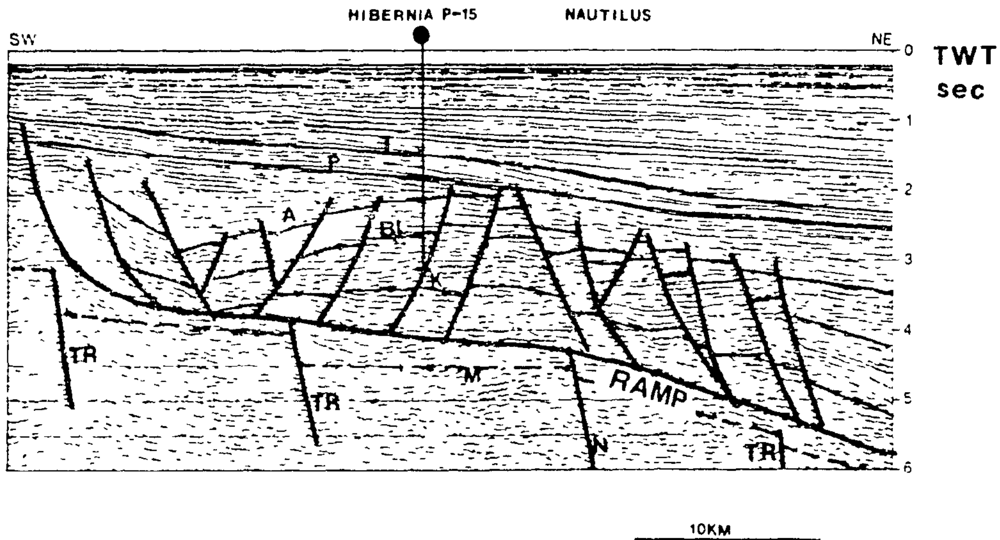


Figure 5.3 Seismic line NF-79-110 showing: (i)the supracrustal detachment within the cover sequences, (ii) the down stepping nature of basement transfer fault blocks, and (iii) the northward plunging floor of the Jeanne d'Arc basin. The Hibernia and Nautilus structures were formed as hanging wall anticlines. (See Figure 1.2 for location of profile and Figure 1.3 for symbols; from Tankard and Welsink, 1987).

gravity collapse and rotation of the hangiing wall along a normal listric fault, and subsequent infill by sediments of the surface depression produced by extension (Figure 1.3).

Intersections -- These are the configurations formed by structures which are repeated in multiple alignments over broad areas. These can combine to form zigzag or dogleg features. In the Jeanne d'Arc basin, the intersection of northeast-southwest trending normal listric faults and northwest-southeast trending transfer faults formed the zigzag boundaries seen in Figure 5.1.

Relay -- Inconsistently overlapping structural elements aligned parallel with one another and with the zone of deformation in which they occur are called relays. In the Jeanne d'Arc basin, the basin-bounding faults actually consist of a number of faults which are parallel with one another and connected by zones of deformation. Later, the transfer faults formed within the zones of deformation to accommodate the areas with different amounts of extension (Figures 5.1 and 5.4).

Trap-door blocks -- These are blocks formed by the intersection of normal listric faults and transfer faults with maximum relative uplift near the point of the intersection (Figure 5.5).

These distinctive structural features described above along with some other features constitute the unique structural styles of the Jeanne d'Arc basin. In the following, a more

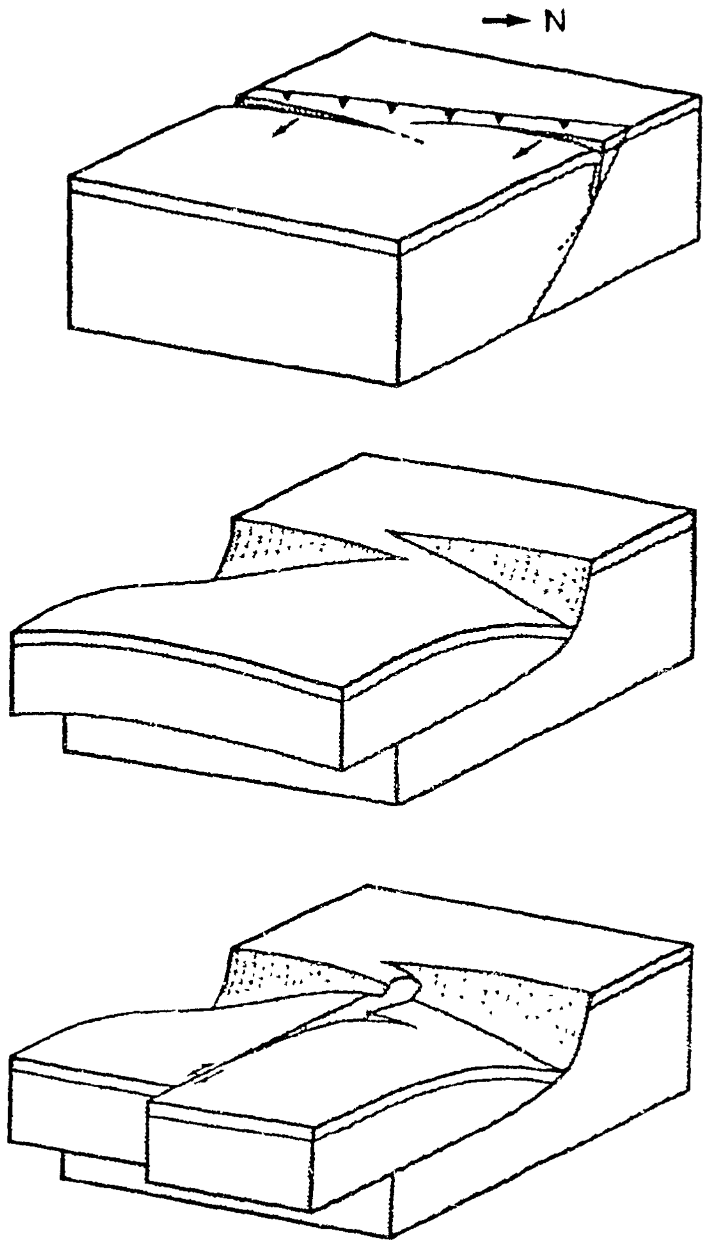


Figure 5.4 Block diagrams illustrating the formation of transfer faults and an associated relay structure (Courtesy H. Welsink).

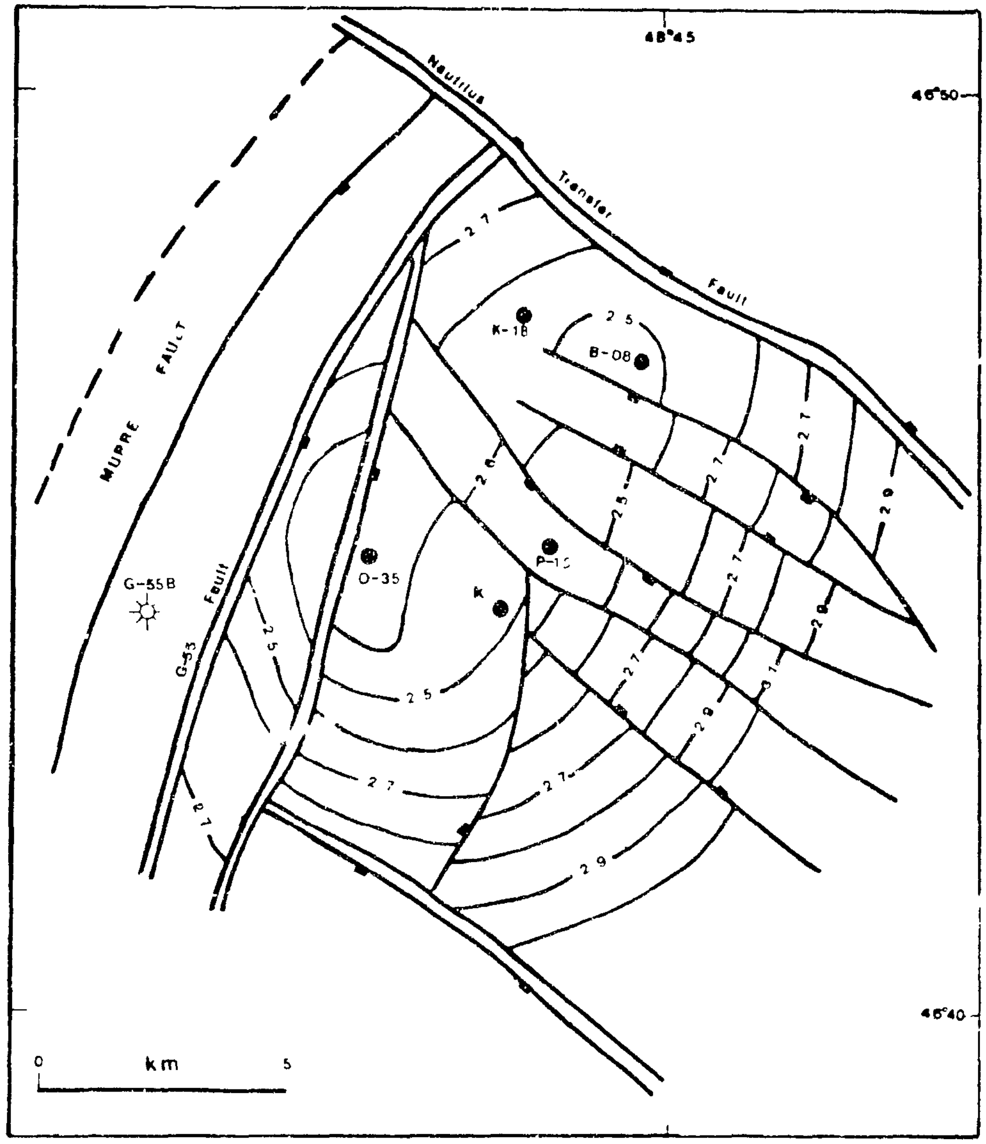


Figure 5.5 The isochron map (units in seconds) at the level of B-marker Limestone showing the shape of Hibernia anticline (from Arthur et al, 1982).

detailed disussion is presented.

The diagnostic feature of a listric normal fault or detachment is that a dip change occurs across the fault from the foot to hanging wall. For most listric faults or detachments, this involves a rotation or roll-over toward the foot wall of the pre-fault marker. The Murre Fault is the major basin-forming fault of the Jeanne d'Arc basin and characterized by a listric geometry and rotation of syn-rift sequences toward the fault plane (Figure 1.3). The Murre Fault involves basement and soles out along an intracrustal detachment surface (Figure 4.1). Figure 5.6 shows a listric fault detaching within the cover sequence in the South Hibernia area. The syn-rift sequences bounded by the Callovian and Aptian unconformities thin toward the transfer fault (T) (Figures 5.2 and 5.6). The thickness of the syn-rift sequences appears to bear little relation to this transfer fault. But the post-rift transitional sequences which are bounded by the Aptian and Cenomanian unconformities are mainly controlled by this fault. They progressively overstepped the fault plane of the transfer fault (T) and became thicker toward it (Figure 5.6), which may suggest that this transfer fault became reactivated at about the time of the Aptian unconformity and during the period of transition from the syn-rift to the post-rift phase.

The geometry of the hanging wall of a listric fault is a direct result of the trajectory of the listric fault plane (Gibbs, 1983, 1984). Figure 5.3 shows a listric detachment with

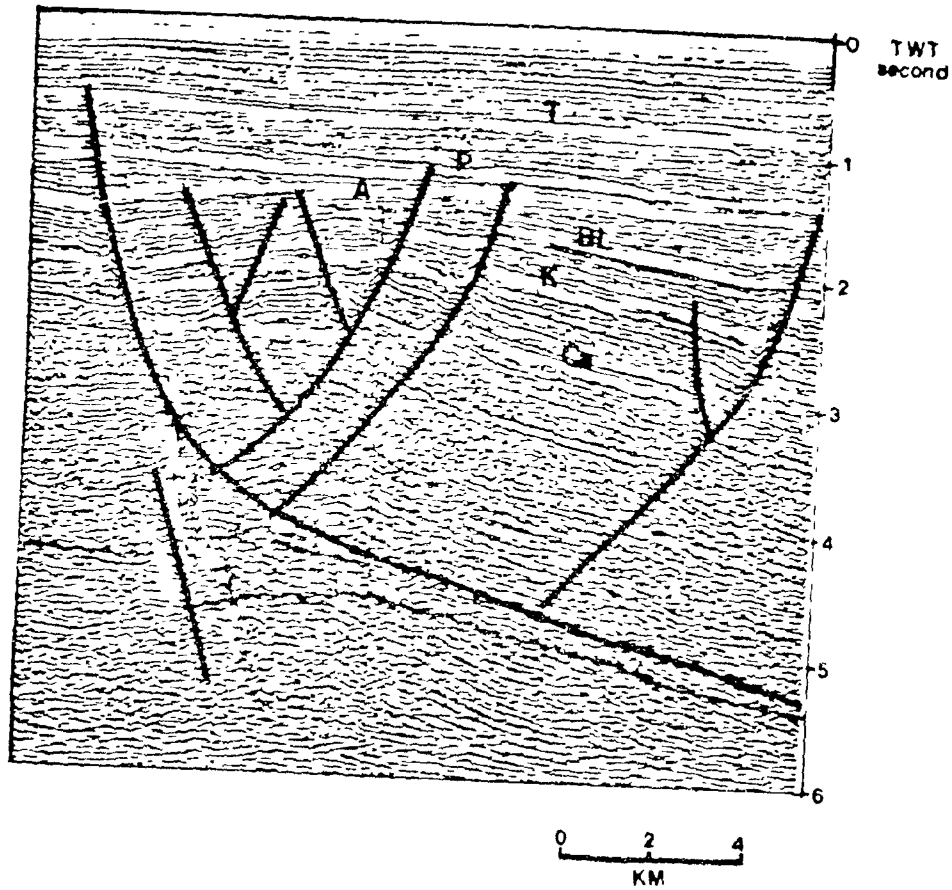


Figure 5.6 Seismic line 81-1305 showing the detachment within the cover sequence in south Hibernia. (See Figure 1.2 for location and Figure 1.3 for symbols).

a ramp. The movement of the hanging wall sequences along this detachment resulted in the formation of an anticline and a syncline in the hanging wall. A shortcut fault developed between the anticline and syncline. With further deformation, a complex of antithetic and synthetic faults developed. Figure 5.7 shows a listric detachment with two ramps above which two anticlines and two synclines were formed as a result of the movement of the hanging wall sequences along the detachment.

Transfer faults formed shortly after the formation of normal basin-bounding faults because of the need to accommodate the different amounts or different rates of extension. They developed because, in the early stage of extension, normal faults nucleate independently in a number of locations along the embryonic rift (Figure 5.4). As these normal faults propagate along the strike toward each other, offsets and/or difference in dips between them must be accommodated by the deformation of the rock mass. The listric normal faults and the deformation zone between them form the so-called relay structures referred to earlier. With increase of the displacement along the normal faults, this deformation will become concentrated into narrow zones or faults (transfer faults) in order to minimize the work done by the extension. The relay structures have significant control on the depositional facies and the thickness of the depositional sequences. First, basin draining rivers can enter a half-graben basin along the deformation zone or transfer fault between the

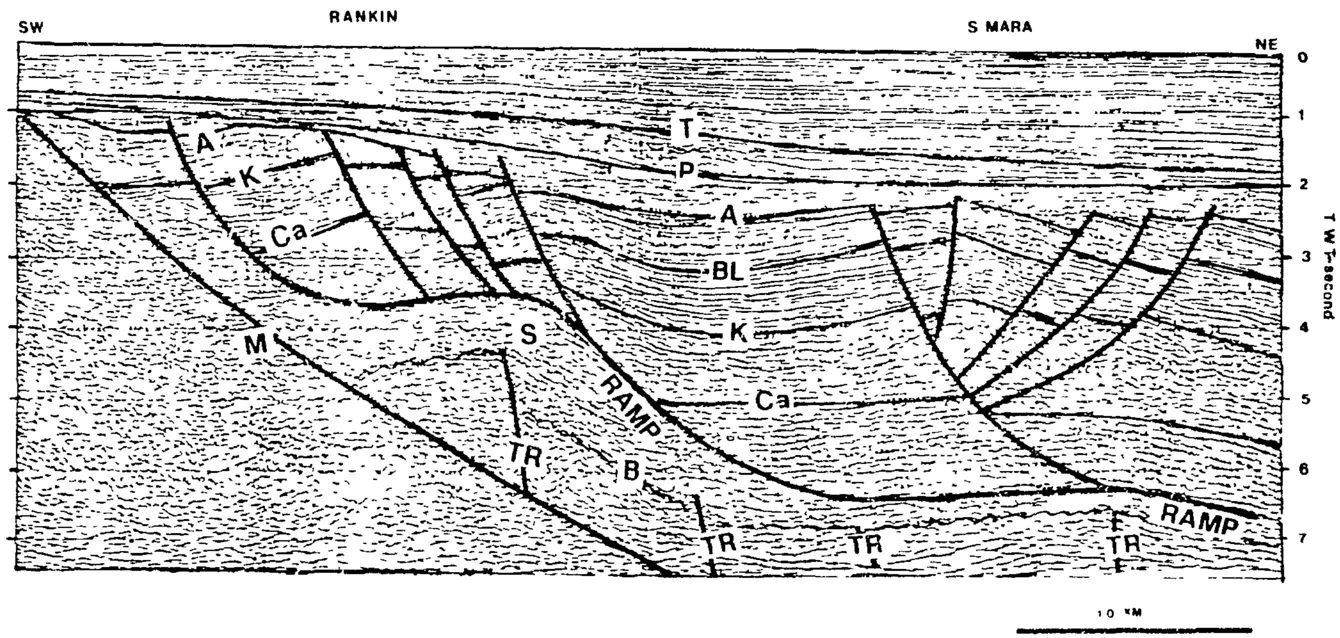


Figure 5.7 Seismic line NF-82-12 showing the detachment within the cover sequences and the formation of the Rankin structure and South Mara structure. (See Figure 1.2 for location and Figure 1.3 for symbols).

the areas with different amounts of extension, although the drainage is usually away from the basin in the foot wall because of isostatic uplift (Figure 5.8). A system of fan-delta complexes is formed in an area such as the Hibernia oil field where the Nautilus transfer fault intersected with the Murre basin-bounding fault and formed a relay structure. The configuration of depositional sequences mimics the shape of the surface on which they were laid. Seismic line NF-79-108 runs through one of the relay structures. The depositional sequences thicken northward as result of the shape of the basement (Figure 5.9). A supracrustal detachment within the cover sequences formed because of gravity instability at about Aptian time.

Transfer faults are kinematically analogous to oceanic transform faults. Transfer faults are ubiquitous in continental extensional terrains just as transform faults are in the oceanic crust. In the Jeanne d'Arc basin, the transfer faults are orthogonal or oblique at high angle to the basin forming normal faults. The oblique relationship may have been produced by oblique extension (Gibbs, 1983, 1984) and/or the influence of basement structure. The regional gravity map shows good correlation between gravity gradients on the one hand and the basin boundaries and transfer fault trends on the other (Figure 3.1), suggesting that basement structural fabrics had a profound effect on Mesozoic extension and structural development (Amoco and Imperial, 1973; Williams, 1984; Tankard

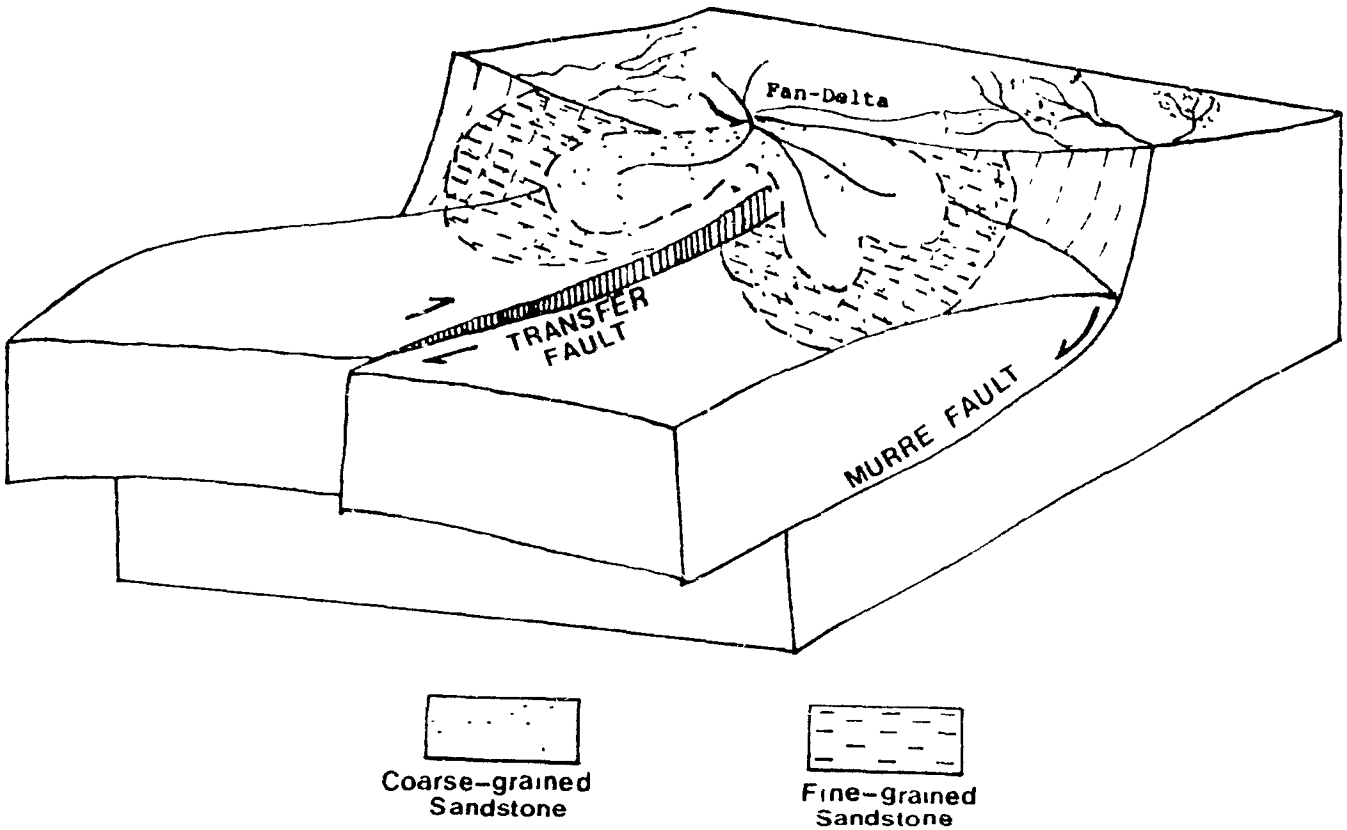


Figure 5.8 Association of fan-delta complexes with deformation zone or transfer fault of a relay structure.

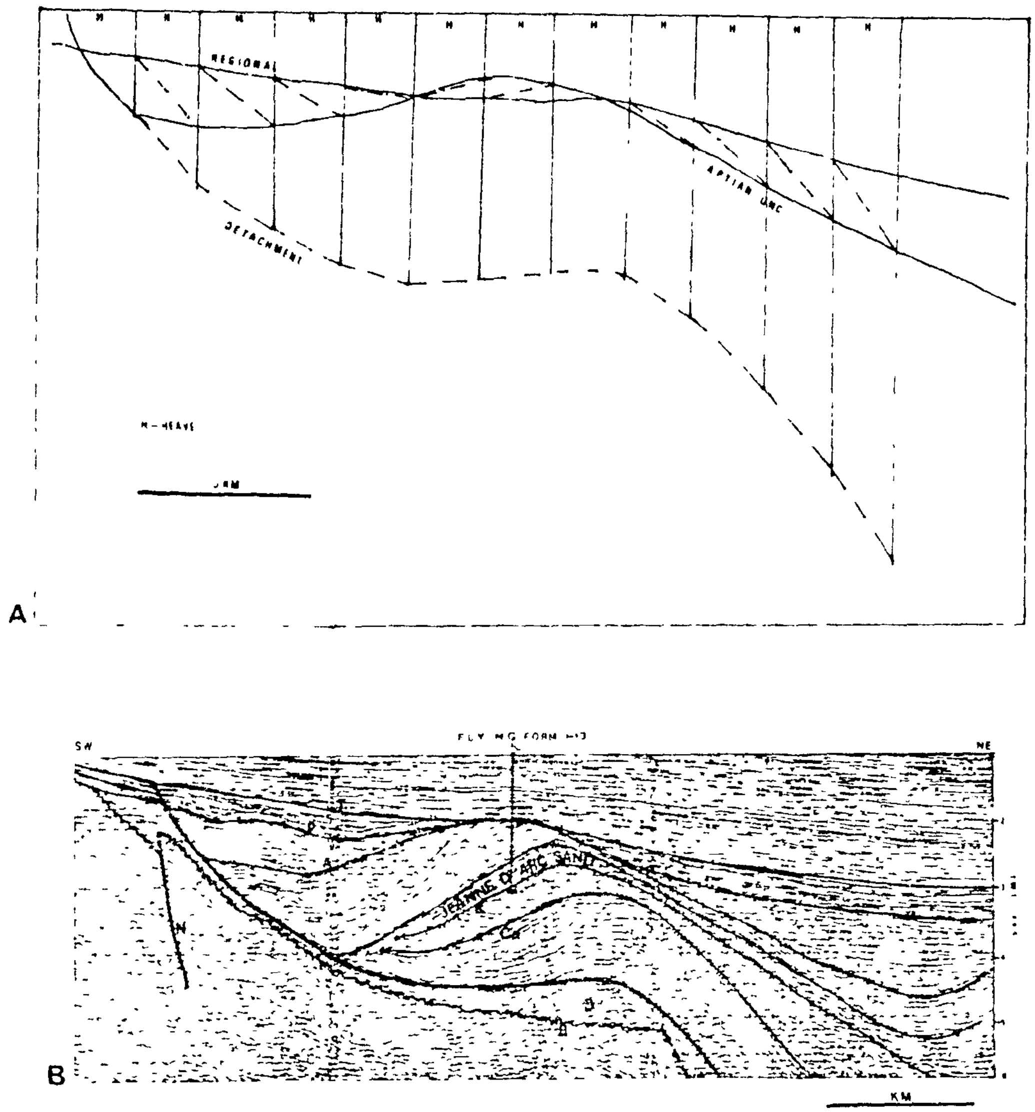


Figure 5.9 Seismic line NF-79-108. A. The detailed procedure for the reconstruction of the detachemnt within the cover sequences using chevron construction. B. Interpreted seismic section. (See Figure 1.2 for location and Figure 1.3 for symbols).

and Welsink, 1987). So the gravity data can be used to identify the positions of transfer faults.

On seismic cross-sections, the transfer faults appear as moderately to very steeply dipping normal faults and rarely as reverse faults (Figures 1.3, 5.3 and 5.10). The rotation of transfer faults along strike forms so-called scissor structures (Figure 5.11). These transfer faults commonly splay upward as they propagate up into the sedimentary fills, resulting in so-called flower structures. Transpressional flower structures are called positive flower structures and transtensional flower structures are called negative flower structures (Figure 5.10). In the Jeanne d'Arc basin , most flower structures are negative, although some parts of the flower structures may have a reverse sense. Reverse faults may be caused by either the later rotation of normal faults or locally compressive stress in the hanging wall of a larger-scale listric fault (Gibbs, 1983).

The transfer faults were reactivated in a normal sense from Late Barremian onward and caused further deepening of the Jeanne d'Arc basin toward north-northeast for two reasons: 1) the northward plunging axis of the Jeanne d'Arc basin caused gravity instability of the sedimentary fill; 2) a new phase of rifting with a northwest trend developed in the northern Grand Banks. The increasing plunge of the basin created a new set of normal faults that detached the Mesozoic succession above the basement (Figures 2.5, 5.3, 5.9). The hanging wall geometry

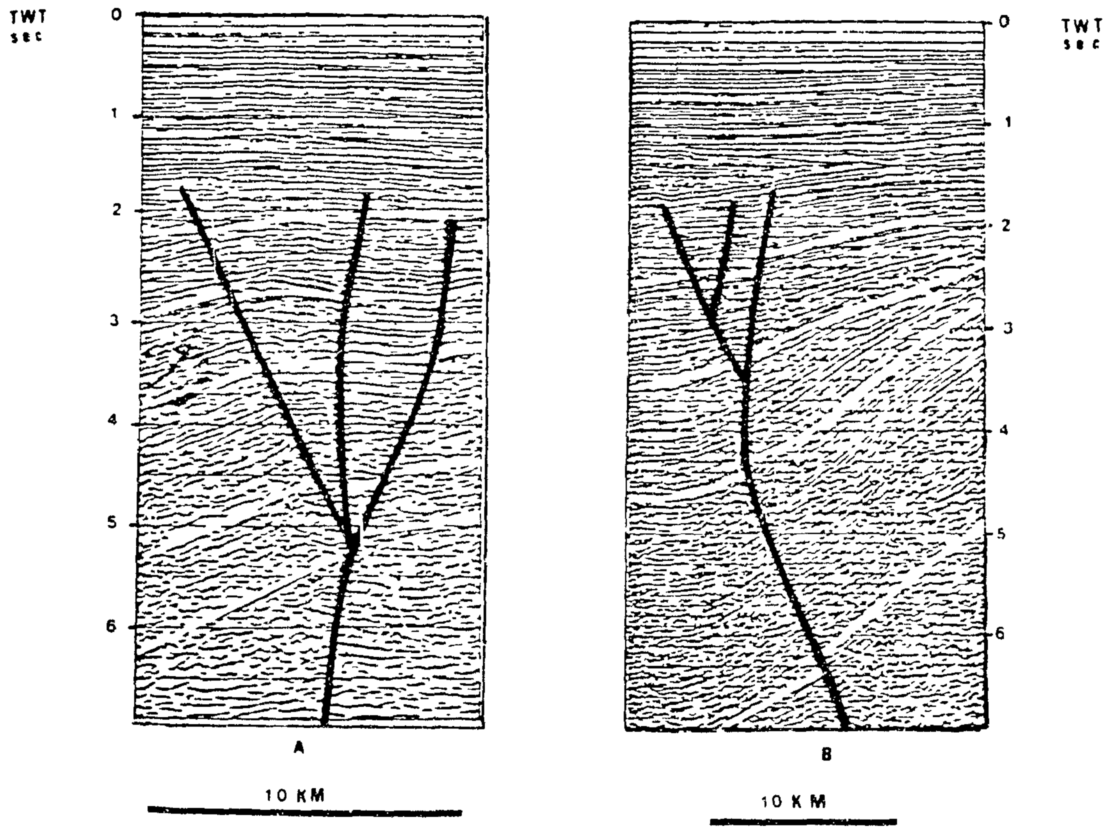


Figure 5.10 Negative flower structures (see text for explanation) from portions of seismic lines NF-79-108 (A) and NF-79-103 (B). Notice that the structure (B) on the right changes from normal faults in the upper part to a reverse fault in the lower part because of later rotation. (see Figure 1.2 for location and Figure 1.3 for symbols).

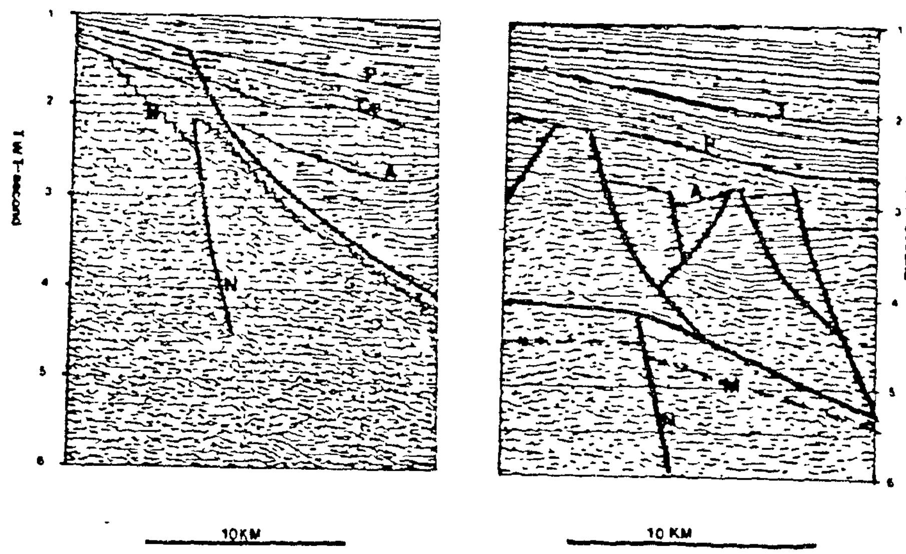


Figure 5.11 The rotation of Nautilus transfer fault formed a Scissor structure. A: Portion of sesmic line NF-79-108, showing the Nautilus fault (N) as a reverse fault. B: portion of seismic line NF-79-110, showing the Nautilus fault (N) as a normal fault (See Figure 1.2 for location and Figure 1.3 for symbols).

reflected the geometry of the foot wall which was characterized by the down-stepping nature of the basement transfer faults (Figure 5.3). These supracrustal detachments occurred principally above the Lower Jurassic salts. The movement of the hanging wall was essentially gravity driven. These supracrustal detachments resulted in another set of anticlines and synclines which were superimposed above the old set of anticlines and synclines related to the Murre basin forming fault. The Avalon sequence was deeply eroded and thinned in structurally high regions and redeposited in the synclinal area.

Differential extension as well as fault block rotation in the Jeanne d'Arc basin resulted in differential subsidence rates, producing differential gravity loading of the syn-rift depositional sequences on the salt strata, which in turn initiated the salt movement. Salt accummulation within the anticlines and withdrawal from synclines accentuated the configuration of the syn-rift sequences. Numerous salt-cored structures and diapirs were formed in the Jeanne d'Arc basin (Figures 1.3, 5.9, 5.12, 5.13). The Callovian and younger sequences thin toward the salt structures and few faults or diapirs extended into the post-rift sequences, suggesting that the salt structures developed during the Callovian-Aptian syn-rift phase.

In order to resolve the stress field of the Jeanne d'Arc basin, Tankard and Welsink (1987) constructed a rose diagram to show the main trends of the faults (Figure 2.6). There are

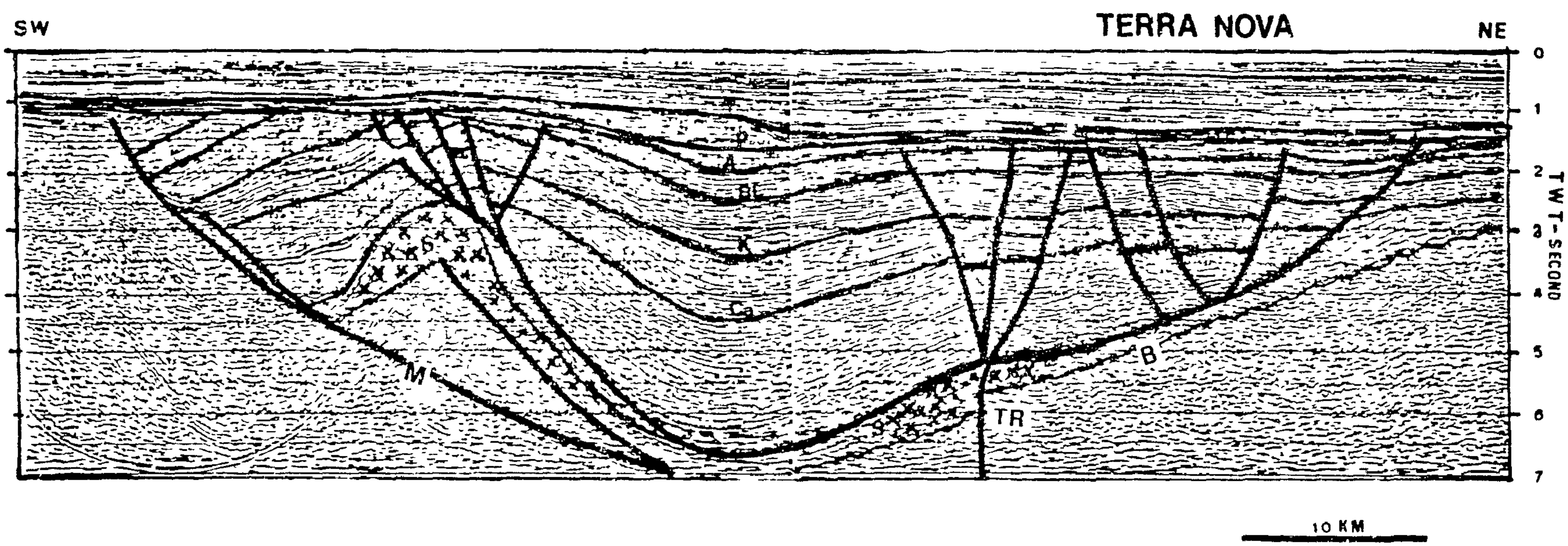


Figure 5.12 Seismic line NF-82-12 showing Terra Nova structure and the salt structure. The salt withdrew from the syncline area and accumulated in the anticline region (See Figure 1.2 for location and Figure 1.3 for symbols).

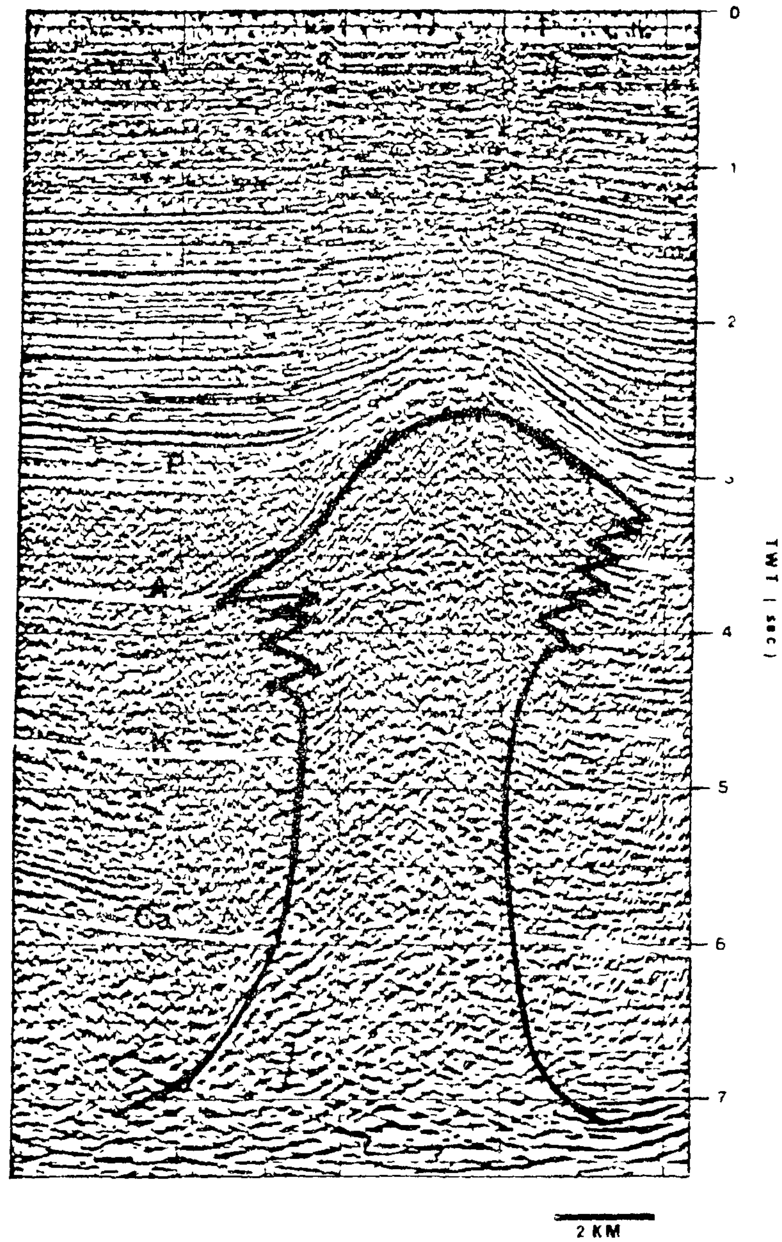


Figure 5.13 Seismic line 82-10 showing Adolphus salt diapir (See Figure 1.2 for location and Figure 1.3 for symbols).

two fault trends in the basin involving basement: 1) extensional basin-forming faults such as the Murre Fault, and 2) transfer faults such as the Nautilus transfer fault. The basin-forming faults and transfer faults were formed at the early stage of basin formation. Although these two sets of faults are not quite perpendicular to each other, the Jeanne d'Arc basin can be viewed as being formed approximately by orthogonal extension. So the extensional stress during rifting should be approximately parallel to the overall trend of the transfer faults, that is, directed southeast-northwest (Figure 2.6).

The remaining faults have a smaller scale and only involve the cover sequences. Their distribution appears to be related kinematically to right-lateral strike-slip motion of the transfer faults (Tankard and Welsink, 1987). However, these faults have less control on the thickness of the syn-rift sediments than on that of the sediments deposited during the transition period from syn-rift to post-rift, as suggested by Figures 5.3 and 5.6. The formation of these faults appears to be related to the reactivation of the transfer faults and the development of the supracrustal detachment during the transition time.

It can be inferred that the activity of the transfer faults was not intense after the early stage of basin formation until the transition time (Early Aptian) when the transfer faults were reactivated in a normal sense. Movement of the transfer faults is oblique-slip during the transition time. The dip-slip fraction of movement of the transfer faults caused the down-stepping nature of the transfer faults, which at last resulted in supracrustal detachments. The strike-slip movement of the transfer faults kinematically controlled the formation and distribution of small scale faults. Unfortunately, the exact displacement in the two directions (dip-slip and strike-slip) can not be accurately determined because of inadequate information. However, it is certain that the overall extensional direction during the transition time is oblique to the transfer faults and directed northeast-southwest in late Early Cretaceous time (Figure 2.6). The extension due to this extensional event estimated on sesmic section 71-32 is about 13%. As mentioned earlier, the reactivation of the transfer faults and development of the supracrustal detachment may be related to the new phase of rifting in the Orphan basin in the northern Grand Banks. Therefore, the stress field in the Jeanne d'Arc basin could be similar to that in the Orphan basin during the transition time. At this stage, movement of both the basin-forming faults and the transfer faults is oblique slip. As a result, the movement of the transfer fault has a normal sense, and the rotation was translated into large amounts of strike-slip movement along the older basin-bounding extensional faults. The G-55 fault formed at this stage by detachment within the cover sequences and the northward translation of the Mesozoic succession (Figure 2.6).

CHAPTER VI.

SUBSIDENCE HISTORY OF THE JEANNE D'ARC BASIN

The Jeanne d'Arc basin contains a stratigraphic succession up to 18 km thick, resulting from 225 m.y. of basin formation and subsidence. The present configuration of the Jeanne d'Arc basin is the result of four episodes of basin formation: 1) Triassic-Early Jurassic rift phase, 2) Middle Jurassic epeiric basin phase, 3) Late Jurassic-Early Cretaceous rift phase, and 4) Early Cretaceous-Tertiary post-rift phase (Figures 1.3 and 1.4). The episodic subsidence history is clearly shown in the subsidence curve of Figure 6.1.

VI.1 TRIASSIC-EARLY JURASSIC RIFT AND POST-RIFT EPEIRIC BASIN PHASES

The earliest episode of rifting occured in Late Triassic with a span of about 20 m.y. This rifting event is documented by a thick sequence of terrestrial red beds and overlying evaporites. Post-rift thermal subsidence resulted in a broad, saucer-shaped, epeiric basin that straddled the Grand Banks, Galicia Bank, and Celtic Sea Platforms (Tankard and Welsink, 1987). Seismic data show little evidence of fault-controlled subsidence or disruption by unconformities.

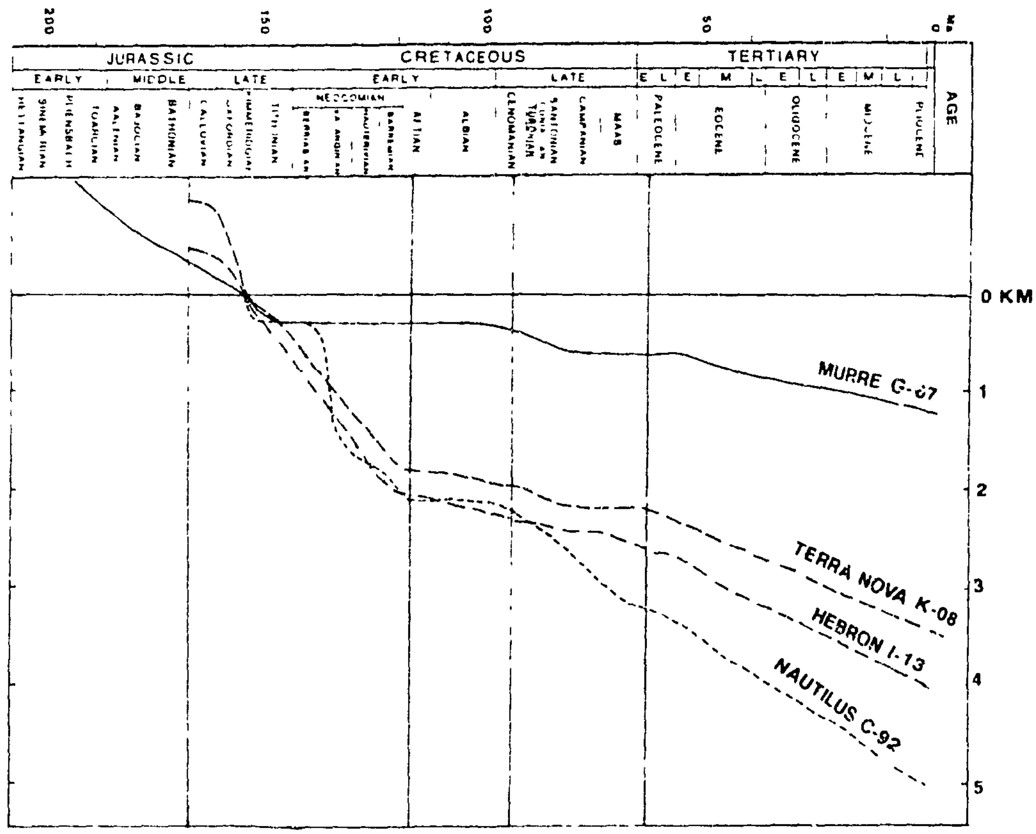


Figure 6.1 Subsidence curves showing the episodic nature of subsidence which is related to episodic tectonic movement. Present burial depths increase northward (i.e. from Murre G-67 to Nautilus C-92) and are directly related to the extensional history and structural styles of the Jeanne d'Arc basin. Kimmeridgian unconformity was used as reference level. (See Figure 1.2 for the location of wells).

VI.2 LATE JURASSIC-EARLY CRETACEOUS EXTENSION

The Late Calllovian-Aptian time was the dominant period of rifting and basin formation in the Jeanne d'Arc basin. The amount of subsidence in the Jeanne d'Arc basin is different in different areas (Figure 6.1) and directly related to structural style. In cross-section, the rotation of the syn-rift wedge along the listric basin-bounding Murre fault produced several anticlines and synclines on the hanging wall (Figure 1.3). The highest subsidence rates are within the synclines. Salt tends to migrate to the anticlines and withdraw from the synclines, which accentuated the differential subsidence pattern of the Jeanne d'Arc basin. The listric fault margin of the Jeanne d'Arc basin is characterized by fast stacking of terrigenous sediments and lateral facies variations. In the monoclinal western margin of the Jeanne d'Arc basin the stratigraphic units are gradually wedging-out westward due to depositional and erosional thinning.

The Jeanne d'Arc basin recorded three stages of Late Jurassic-Early Cretaceous subsidence (Figure 6.1): 1) Late Callovian-Middle Kimmeridgian rift-related subsidence, 2) Late Kimmeridgian-Valanginian fault-controlled subsidence, and 3) Late Valanginan-Early Aptian late-stage extensional subsidence.

VI.2.1 LATE CALLOVIAN-KIMMERIDGIAN RIFT-RELATED SUBSIDENCE

Late Callovian-Middle Kimmeridgian subsidence corresponds to the onset of rifting, and formed the main hydrocarbon source rocks which are organic-matter rich limestones and calcareous mudstones. These fine-grained calcareous and argillaceous sediments onlap the basal unconformity and appear to blanket the entire basin (Figure 1.3). The fine-grained nature of the sediments suggests that faulting activity was not intense. This subsidence style agrees with the low angle detachment extensional model in which substantial movement along an intracrustal detachment may occur before significant brittle deformation affects the upper crust (Wernicke, 1985). However, the transfer faults appear to have controlled the topography of the southern extent of the Jeanne d'Arc basin. The thickness, organic carbon content and source rock quality of the Late Oxfordian-Kimmeridgian sediments increase northward from the southern margin along the axis of the rift (Powell, 1985) and across the transfer faults (Tankard and Welsink, 1987).

VI.2.2 LATE KIMMERIDGIAN-VALANGINIAN FAULT-CONTROLLED SUBSIDENCE

Late Kimmeridgian-Valanginian subsidence marked the climax of rifting. Fault activity was very intense, as suggested by the coarse, poorly sorted, fast-stacked sediments near listric faults and the existence of numerous depocenters within the Jeanne d'Arc basin. Listric normal faults and transfer faults divided the Jeanne d'Arc basin into numerous fault blocks with different subsidence rates and depocenters. At this stage, the sediment dispersal system consisted of a network of channels and valleys originating from the southern apex of the Jeanne d'Arc basin (Figure 6.2). These channels trend longitudinally down the axis of the basin and die out in the depocenter of the Terra Nova field. The dispersal systems formed complexes of fan-deltas at the intersection of transfer faults and listric normal faults or at the deformation zones of the relay structures (Figure 5.8). Intense faulting activity, rapid subsidence rates associated with the rotation of the fault blocks resulted in coarse-grained, poorly sorted, proximally sourced fluvial rocks, as well as restricted and shallow marine deposits. The floor of the basin in the west (faulted margin) is the plane of the listric Murre fault. Formation of synthetic fault sets which merge with the sole fault created a synthetic fault fan, imparting a ramp-flat geometry to the floor of the Jeanne d'Arc basin (Figures 1.3, 2.5). As mentioned earlier, this geometry of the basin floor significantly influnced the later deformation of the cover sequences, forming series of anticlines and synclines.

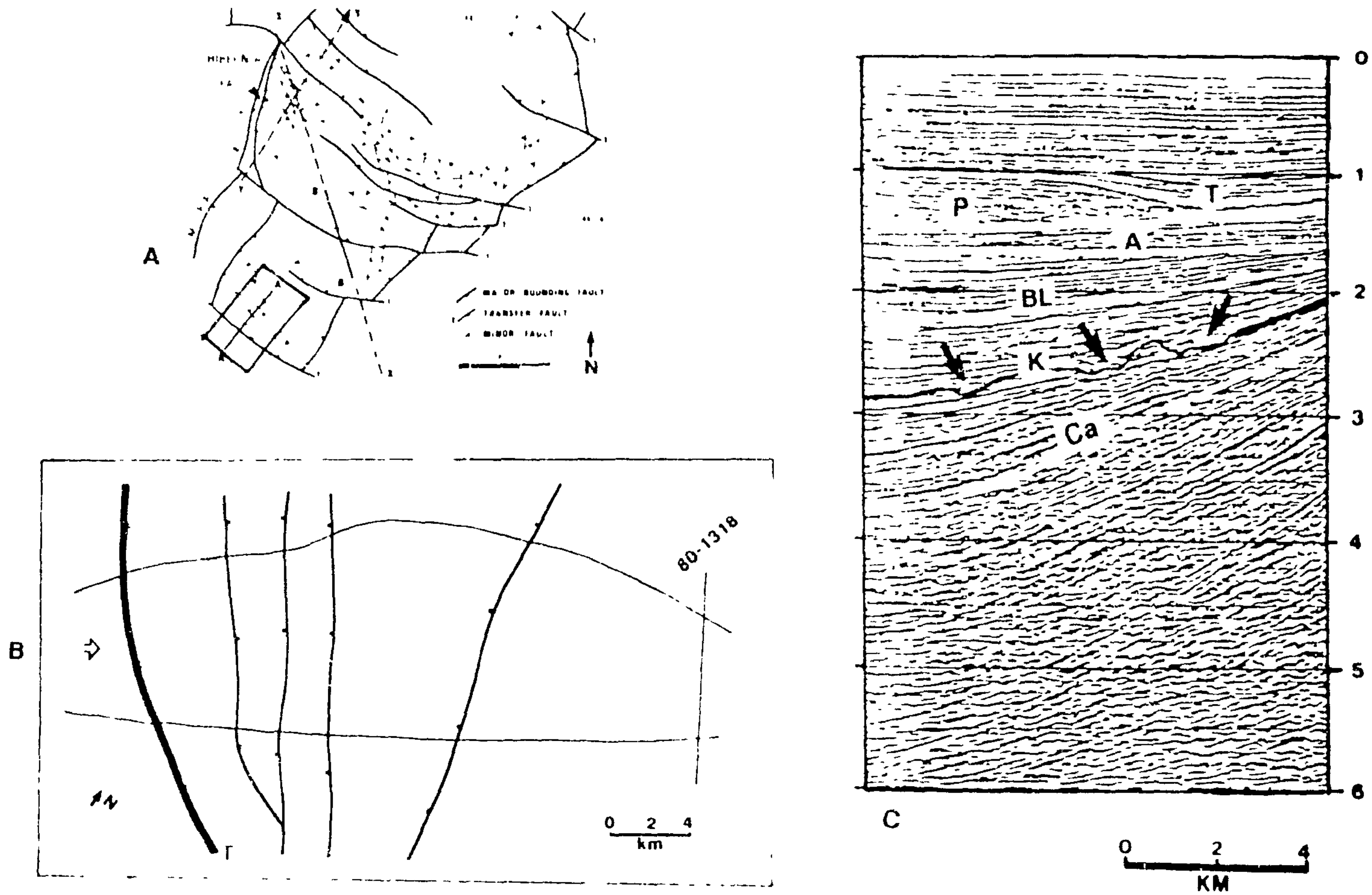


Figure 6.2 A. Index map. B. Position of a complex of channels identified on 15 different seismic lines in the south Hibernia area. C. Seismic line 80-1318 showing some of the channels (marked by arrows).

VI.2.3 LATE VALANGINIAN-EARLY APTIAN SUBSIDENCE

The end of the cycle of intense fault-controlled subsidence is recorded by the B-marker limestone about 32 m.y. after the beginning of mid-Mesozoic rifting. Late Valanginian-Early Aptian basin development significantly changed the depositional patterns. Faulting activity was not intense at this time, and as a result, the sediments were dominantly fine-grained and argillaceous deppositional sequences overlapped the rift shoulders. Subsidence rate was greatest in the centre of the basin. Movement of transfer faults had a normal sense and caused the down-stepping northward of the transfer fault blocks. Subsidence rates increased toward the north across the transfer faults (Figure 6.1). Late Valanginian-Early Aptian paleogeography was characterized by shallow marine deposition along the basin margins. Water depth was somewhat greater than that during the deposition of pre-B-marker horizons, and circulation was open marine (Tankard and Welsink, 1987). The composite Catalina and Avalon sandstones are the principal reservoir levels formed during this interval. The intervening A-marker limestone consists of a series of limestone and calcareous sandstone lenses with an en-echelon arrangement. It shows distinct lithological and thickness changes across faults.

VI.3 LATE APTIAN-EARLY CENOMANIAN POST-RIFT TRANSITION

The old transfer faults were reactivated in a normal sense about the time of the Aptian unconformity and during the transitional period to the post-rift stage, probably because of the influence of the new phase of extension in the Orphan basin of the northern Grand Banks. A supracrustal detachment formed within the cover sequence as a result of the gravity instability of the sedimentary fill (Figures 2.5, 5.3, 6.3). The subsidence along the southwest-northeast set of extensional faults was insignificant at this stage. Another set of anticlines and synclines associated with the supracrustal detachment was superimposed on the old set of anticlines and synclines which was related to the basin-forming listric Murre fault. So the overall subsidence pattern of the Jeanne d'Arc basin is related to three factors: 1) the overall northward plunging axis of the Jeanne d'Arc basin, 2)the hanging-wall anticlines and synclines related to the basin-forming listric Murre fault, and 3) the hanging-wall anticlines and synclines associated with later supracrustal detachment.

VI.4 POST-RIFT THERMAL SUBSIDENCE

The post-rift thermal subsidence can be divided into two stages. The first stage (late Cenomanian to Palaeocene) displays a differential subsidence pattern which is related to

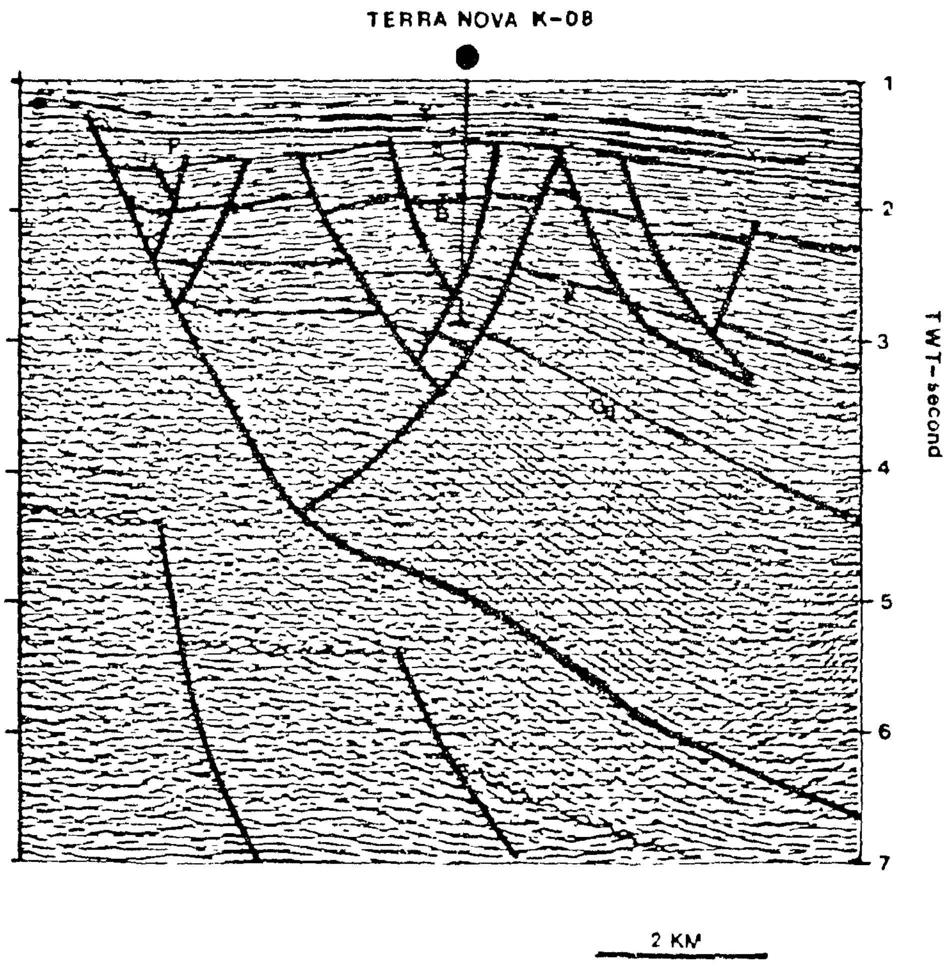


Figure 6.3 Seismic line 81-1366 showing the Terra Nova structure (See Figure 1.2 for location and Figure .3 for symbols).

the position of a given area within the Jeanne d'Arc basin (Figures 1.3, 2,5, 5.12). Broad flexures dominated the structural styles at this stage. They are believed to be the result of passive draping by sediments and differential compaction above the buried topography. Numerous fan-deltas, sourcing from the Bonavista Platform, formed at this stage. The second stage (post-Palaeocene) shows an integrated subsidence pattern of the Jeanne d'Arc basin as a single , unsegmented downwarp.

CHAPTER VII.

IMPLICATIONS FOR PETROLEUM EXPLORATION

The tectonic and structural framework and subsidence history of the Jeanne d'Arc basin largely controlled the distribution and properties of source and reservoir rocks, and the maturation, migration , and entrapment of hydrocarbons. The implication of the structural styles of the Jeanne d'Arc basin for petroleum exploration is very important for further exploration in the basin and other basins with similar structural styles.

VII.1 DISTRIBUTION OF SOURCE ROCKS

The Jeanne d'Arc basin is unique in the Canadian East Coast offshore in containing thick, rich, oil-prone Upper Jurassic source beds. Geochemical studies in other areas of the Canadian East Coast offshore (Scotian Shelf--Powell, 1982; Labrador Shelf--Rachid et al., 1980; Powell, 1979) and drilling results provided evidence for gas-prone source rocks only.

The Upper Jurassic (Oxfordian-Kimmeridgian) source rocks have been shown to be the main source rocks for the Hibernia oil and other oil discoveries in the Jeanne d'Arc basin (Arthur et al., 1982; Powell, 1985). There is a clear tectonic control on the distribution of source rock facies in the Jeanne d'Arc basin (Tankard and Welsink, 1987). Deposition of the source rocks occurred during the initial rifting phase associated with the separation of Iberia from the Grand Banks. The relatively rapid deepening of the Jeanne d'Arc basin coincided with a relatively high sea-level stand in the Kimmeridgian, resulting in the formation of a deep anoxic basin that favored the formation of organic-matter rich source rocks (Demaison and Moore, 1980). Dominantly argillaceous and chemical sedimentation suggests that fault activity was not intense at this time. However, the transfer faults appear to have controlled the topography of the southern part of the Jeanne d'Arc basin and affected source rock thickness. Sediments thicken and prograde northward across the transfer faults in the southern half of the basin. The thickness, organic carbon content, and source rock quality of the Kimmeridgian-Late Oxfordian sediments increase from the southern margin northward along the rift (Powell, 1985) and across the transfer faults (Figure 7.1).

The offset rift basins to the south of the Jeanne d'Arc basin contain thick Kimmeridgian sediments but with low concentrations of organic matter of non-source quality, suggesting a relatively open environment. So it can be inferred that differential uplift and subsidence during the initial rifting phase may have formed a barrier between the Jeanne d'Arc basin and those other basins to the south. The deposition and distribution of the Kimmeridgian source rocks fit the low

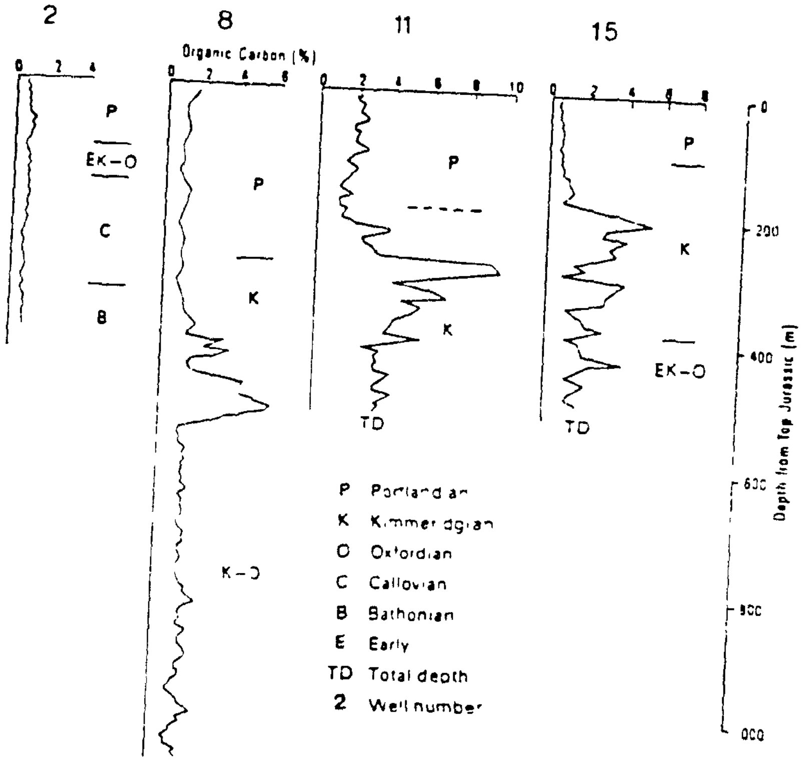


Figure 7.1 Distribution of organic carbon and thickness of Upper Jurassic sediments of the Jeanne d'Arc basin (from Powell, 1985). Well numbers refer to those in Figure 1.2.

angle detachment model. According to the intracrustal detachemnt model, at the beginig of extension, substantial movement and subsidence along an intracrustal detachment my occur without significant brittle deformation in the upper crust. This process could form a relatively restricted and poorly oxygenated environment which favors the formation of source rocks. Further extension, in the Jeanne d'Arc basin, would cause intense brittle faulting, which would destroy this restricted environment. This stage is characterized by the deposition of coarse-grained, poorly sorted sandstones near the faults and rapid facies variation, which is discussed in detail in the following paragraph.

VII.2 DISTRIBUTION OF RESERVOIR ROCKS

In the Jeanne d'Arc basin, hydrocarbon accumulation is restricted to Upper Jurassic-Lower Cretaceous reservoir rocks mainly including the Jeanne d'Arc Sandstone, the Hibernia Sandstone, and the composite Catalina and Avalon sandstones. Extensional structures play a major part in determining the styles of clastic syn-rift deposition, both regional and locally, and thus control the distribution of the reservoir rocks.

VII.2.1 JEANNE D'ARC SANDSTONE

The Tithonian Jeanne d'Arc sequence was deposited during an intense rifting phase. The northward plunging axis of the Jeanne d'Arc basin resulted in a prominent dispersal system (fluvial plain) that developed on the southern apex of the basin (Figure 6.2). A sand fan-delta complex is expected to have been deposited at the end of the channel system (Figure 7.2). The Jeanne d'Arc and Hibernia sequences together constitute the mega-sequence which spans the interval from the regressional Kimmeridgian unconformity to the transgressional Valanginian unconformity which is a product of the same tectonic regime. The isochron map of this unit in the southern apex of the Jeanne d'Arc basin shows a northward thickening wedge, reflecting the northward deepening basin floor (Figure 7.3). Along the fault-bounded margins of the Jeanne d'Arc half-graben, the drainage was away from the basin because of isostatic uplift of the basin shoulder during extension. However, streams were able to flow into the basin through the deformation zones of the relay structures or the transfer faults which offset the fault-bounded margin (Figure 5.8). This means that the depositional sites of the clastic sediment can be predicted from structural models before detailed lithologic studies are undertaken. The Jeanne d'Arc sequence of the Hibernia oil field was deposited as a marginal alluvial fan complex at the intersection of the basin-forming Murre fault

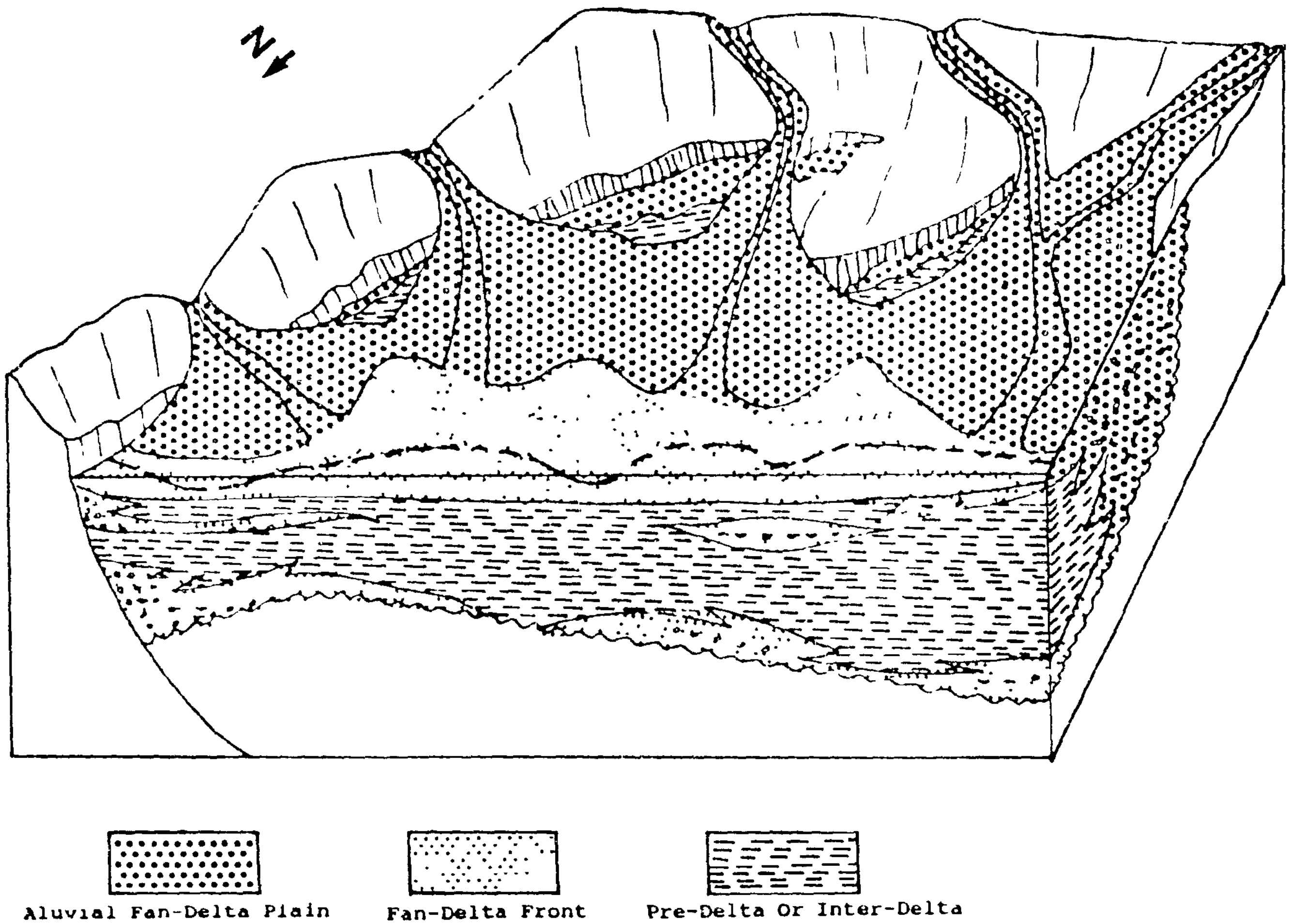


Figure 7.2 Schematic depositional model for the south and southeast margins of the Jeanne d'Arc basin (from Dwyer, et al., 1986).

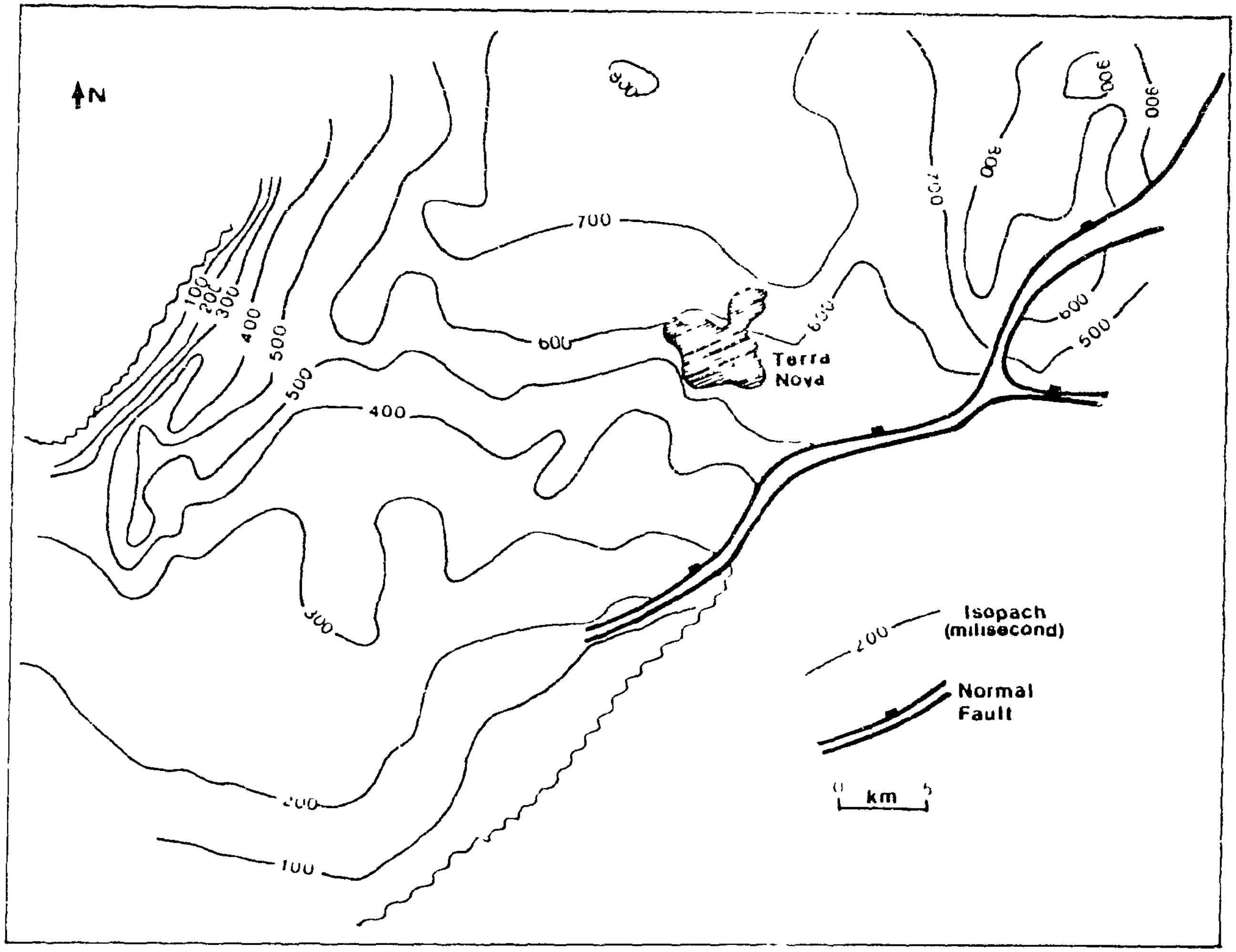


Figure 7.3 Isochron map for the Jeanne d'Arc and Hibernia sandstones in southern and southeastern parts of the Jeanne d'Arc basin (from Dwyer, et al., 1986).

and the Nautilus transfer fault. On the eastern monoclinal margin of the Jeanne d'Arc basin, a system of alluvial fans and fan-deltas is expected to have formed, preferably in areas where the transfer faults cut through the basin margin. In Malawi rift of the East African rift system, sedimentation of this type is quite extensive (Crossley, 1984).

VII.2.2 HIBERNIA SANDSTONE

The Valanginian Hibernia Sandstone is fine to medium-grained, and poorly to fairly well sorted. The distribution pattern of the Hibernia Sandstone is similar to the Jeanne d'Arc Sandstone and controlled by the structural styles of the Jeanne d'Arc basin. In the area of the Hibernia oil field, the dispersal system draining the Bonavista platform deposited a suite of sandy fan-deltas near the intersection of the basin-bounding Murre Fault and the Nautilus transfer fault. Rifting at this stage was not as intense as that at the time of the Jeanne d'Arc sequence. The relatively fine-grained nature of the sandstones and the absence of conglomeratic facies equivalent to the Jeanne d'Arc Sandstone suggest that the topographic relief and gradients were more gentle.

VII.2.3 COMPOSITE CATALINA AND AVALON SANDSONES

The Catalina and Avalon sandstones formed during the late stage of rifting. Fault-controlled subsidence gradually decreased in intensity. Gradients were gentle. As a result, the sandstones were fine to very fine-grained. No terrestrial facies are recognized in the half-graben fill. The depositional facies are characteristic of shoreface environments. The Avalon stratigraphy was also affected by supracrustal detachment. At the crest of the hanging wall anticlines the sediments were eroded and redeposited in nearby synclines.

VII.3 POROSITY EVOLUTION IN SANDSTONES

Sediments undergo various diagenetic processes (mechanical compaction, dissolution, alternation, precipitation) from the time of deposition until metamorphism. These processes can significantly modify the reservoir porosity and permeability with incresing burial time and depth. Abid (1988) studied the mineral diagenesis and porosity evolution in the Hibernia oil field. In the following sections, his results are discussed as far as they are relevant to the problems of hydrocarbon migration and entrapment related to structural evolution.

VII.3.1 MECHANICAL COMPACTION

The major result of mechanical compaction is the decrease in primary porosity. However, significant porosity changes occurred between 2500-3000 m depth in the Hibernia oil field

(Abid, 1988). Above 2500 m, mechanical compaction is relatively minor, which is indicated by loosely packed framework of sandstones. Fromework grains have point contact with one another. Below 3000 m, concavo-convex grain contacts and stylolites due to pressure solution (chemical compaction) prevail. The degree of mechanical compaction in reservoir rocks of the Hibernia field at different depth varies, from minor in the Avalon Sandstone through moderate in the Catalina Sandstone ("B" Sandstone) to advanced in the Hibernia and Jeanne d'Arc sandstones.

VII.3.2 CHEMICAL DIAGENESIS

In the Hibernia oil field, the most important diagenetic processes, which influenced the sandstone porosity besides mechanical compactin, are: i) the precipitation of early ferroan calcite cements, ii) quartz overgrowth, iii) dissolution of calcite cements, iv) precipitation of late ferroan calcite/ferroann dolomite cements. The early ferroan calcite cementation is very important for the formation of secodary porosity in sandstones. Where early ferroan calcite cements occupied the pore space in sandstones, they prevented further mechanical compaction as well as quartz overgrowth. Later dissolution of the calcite cements resulted in widespread secondary porosity developemnt. Where early ferroan calcite cementation was not significant, porosity decreased continuously due to mechanical compaction and quartz overgrowth and could not be recovered by later dissolution. Late ferroan calcite/ferroan dolomite cementation destroyed the secondary porosity to some extent but not significantly. This may be because hydrocarbon migration occurred shortly after the formation of secondary porosity, which prevented further cementation. However, if the interval between the generation of secondary porosity and hydrocarbon migration was too long, cementation and additional compaction would have destroyed the newly formed secondary porosity to a large extent. The ratio of secondary porosity to total porosity increases with burial depth from 20% in the Avalon Sandstone (2100-2660 m) to >80% in the diagenetically mature Hibernia Sandstone (3480-4100 m) (Figure 7.4). On the basis of isotopic analyses, Abid (1988) suggested that most materials required for the precipitation of early calcite cements, late calcite cements as well as quartz overgrowth came from both interbedded and deeper level shales through dissolution of fossil fragments, and alteration of clay and other minerals.

VII.3.3 SOME PRIMARY CONTROLLING FACTORS ON THE GENERATION OF SECONDARY POROSITY

VII.3.3.1 PRIMARY POROSITY AND PERMEABILITY

The flow of fluids tends to choose the easiest paths first,

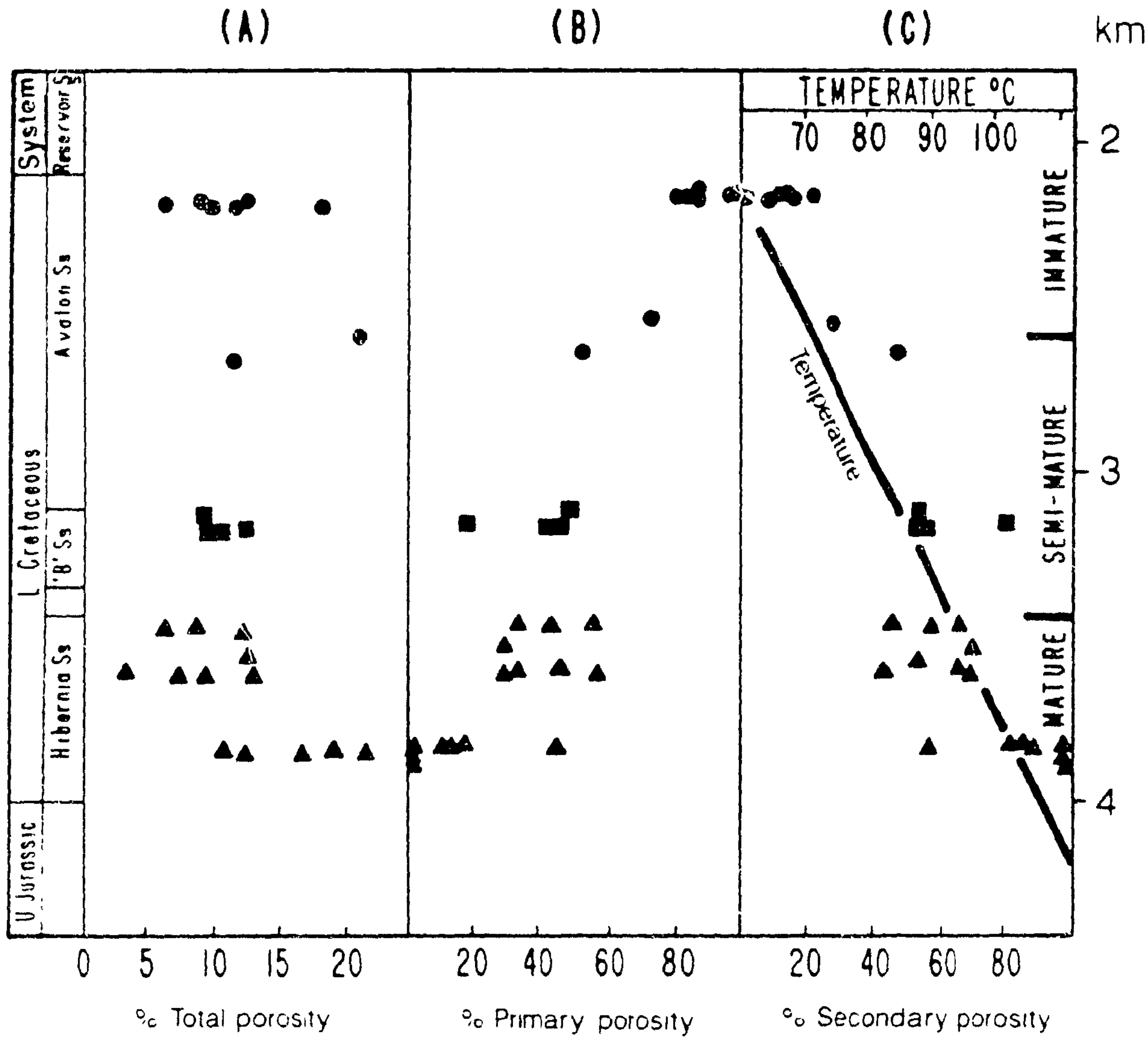


Figure 7.4 (A) Percent total porosity and (B) percent primary and (C) secondary porosity versus burial depth, Hibernia oil field (from Abid, 1988).

Avalon Ss ● "B" Ss ■ Hibernia Ss ▲

that is, the most porous and permeable sandstones as well as faults and fractures. Faults and fractures will be discussed later. When other factors are the same, sandstones with high porosity and permeability tend to have high secondary porosity in comparison with tight sandstones at the same depth.

VII.3.3.2 THICKNESS OF SANDSTONES AND SHALES

Under the assumption that the materials required for chemical diagenesis came mainly from interbeded and deeper level shales, thin, porous sandstone beds interbeded with shales are more likely to have undergone early ferroan calcite cementation and have abundant secondary porosity due to later dissolution of calcite cements. Thick sandstone beds with low primary porosity and permeability will be less affected by early calcite cementation and show more advanced mechanical compaction compared to thinner sandstones. This may be true for the Hibernia oilfield (Abid, 1988). As disussed earlier, the Jeanne d'Arc and Hibernia sandstones were deposited as complexes of fan-deltas. Sandstone beds in different parts of the fan-deltas may have undergone different diagenetic histories. Sandstone beds in the middle of fan-delta complex are relatively porous and permeable and interbeded with shales. The presence of large volumes of shales will provide large amounts of fluids for cenmentation and dissolution processes. In the rear part of the fan-delta complex, sandstone beds are thick and little shale exists. The fluids required for cementation and dissolution were not available. In the front of the fan-delta complex, the sandsones are fine-grained and contain abundant detrital clay, and thus have low porosity and permeability. Consequently, there was little early calcite cement in the sandstones. Therefore, only in the middle of the fan-delta, sandstones underwent early calcite cementation, and porosity was recovered through later dissolution of the calcite cements. While in the rear and front of the fan-delta complex, no early calcite cements were precipitated in the sandstone beds, mechanical and chemical compaction decreased the porosity substantially.

VII.3.3.3 FAULTS AND FRACTURES

Faults and fractures are the major paths for fluids to migrate vertically in the Jeanne d'Arc basin (Powell, 1985). Sandstones near faults zones thus may have a high percentage of secondary porosity. Fault activity could have large effects on the formation of secondary porosity. The later detachment within cover sequences and the reactivation of the transfer faults occurred in Early Aptian time. This faulting activity may have triggered the migration of fluids within pore space, which may mark the time of the generation of widespread secondary porosity.

VII.3.3.4 ACIDIC WATER ASSOCIATED WITH MATURATION OF ORGANIC MATTER

Along with the maturation of organic matter, large amounts of organic acids will be released into pore water. These acidic fluids can flow laterally along sandstone beds or vertically along faults and fractures, which will result in widespread secondary porosity development. Therefore, the acids associated with and perhaps moving ahead of the hydrocarbons could create a substantial part of reservoir porosity for the accumulation of the hydro-`rbons that trail the acids in their migration. (Surdam and C.ossey, 1987)

VII.4 TYPES OF HYDROCARBON TRAPS

With the knowledge of the structural styles of the Jeanne d'Arc basin, we can anticipate the types of hydrocarbon traps to be encountered in the basin, excluding stratigraphic traps (Harding and Lowell, 1979). First, the hanging wall anticlines can form important closures, especially when they formed at the junction of normal extensional faults and transfer faults such as Hibernia anticline structure. At this location, important "trap-door" closure may occur, where regional dip, block rotation drape and flexure focus the maximum structural relief, forming numerous structural and stratigraphic traps. The floor of the Jeanne d'Arc basin has a flat-ramp geometry which significantly influenced the later deformation of the cover sequences. A series of anticlines and synclines in the hanging wall were formed with movement of the cover sequences along the listric basin-bounding Murre fault. The Terra Nova anticline structure is in the same fault block as the Hibernia structure and was originally associated with the listric basin-bounding Murre fault (Figures 2.6 and 5.12). Late detachment within the cover sequences produced the final configuration of this anticline (Figure 6.3). The negative flower structure associated with a transfer fault (Figure 5.10) can also form structural traps. Transfer fault zones, as long-lived zones of movement, are likely to be preferred fluid flow paths along which hydrocarbons migrate from deeply buried source rocks to higher level structural and stratigraphic traps. Salt-cored structures, including domes and penetrative diapirs, are numerous in the Jeanne d'Arc basin. Hydrocarbon traps of these types were the focus of early exploration in the southern Grand Banks.

VII.5 THE MATURITY OF THE SOURCE ROCKS

There is a linear relationship between maturity and present depth (Creaney and Allison, 1987):

$$LOM = 2.38D-0.50$$

where LOM is the level of organic maturation, and D the depth (km). The burial depths were obtained by time-depth conversion of seismic sections. The maturity state at the present time is directly related to the structural framework and subsidence history of the Jeanne d'Arc basin (Figure 7.5). The source rocks are thermally immature in the southern part of the Jeanne d'Arc basin, but become mature rapidly northward, corresponding to the northward deepening of the Jeanne d'Arc basin. The central and northern parts of the Jeanne d'Arc basin are overmature. The maturity state of the source rocks is also affected by the hanging wall geometry of the listric basin-bounding fault. Source rocks became mature earlier within synclines than within anticlines. In addition, thermal maturation of the source rocks was influenced by the supracrustal detachment. Displacement and rotation of the Mesozoic cover above the supracrustal detachment resulted in overdeepening in the hanging wall synclines. As a result, source rocks in the hanging wall synclines became mature earlier. Peak oil generation was reached in the deepest part of the Jeanne d'Arc basin by Barremian time (122-116 Ma; Creaney and Allison, 1987). Under the Hibernia structure, peak oil generation occurred somewhat later during Cenomanian time (100-92 Ma) and after the Petrel Limestone was in place as an effective top seal.

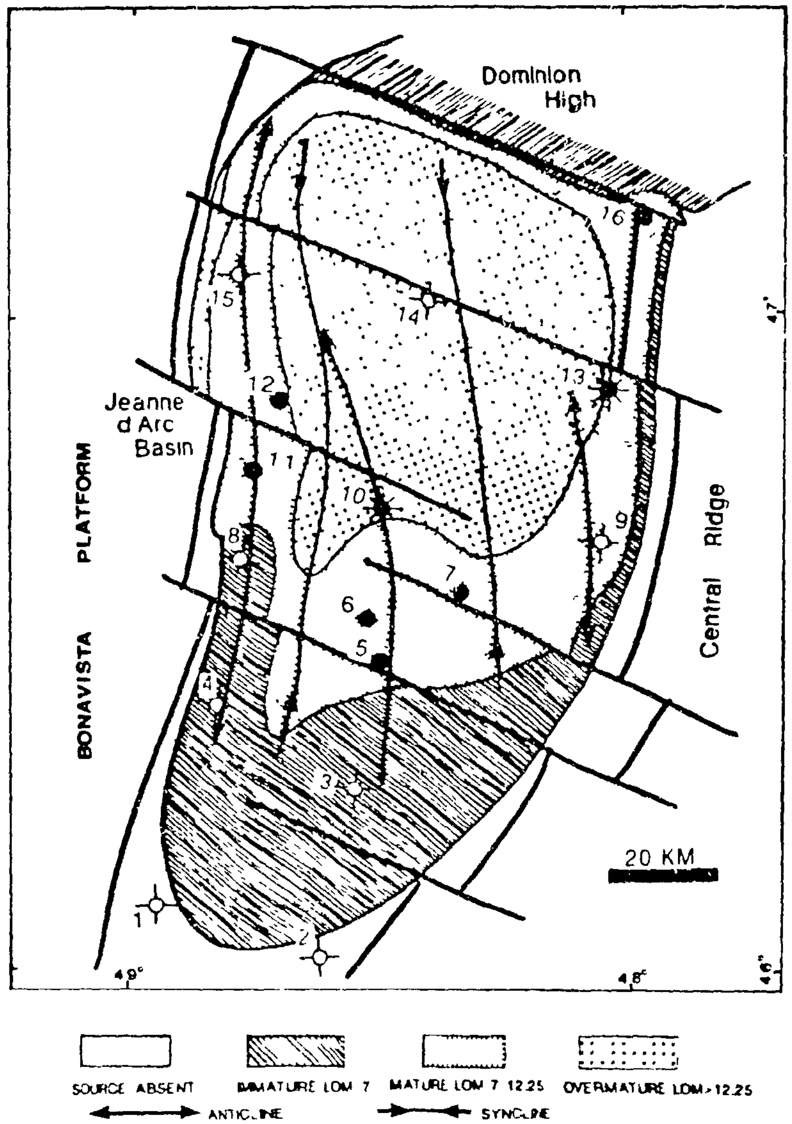


Figure 7.5 The maturity state of source rocks at the present time in the Jeanne d'Arc basin. Well numbers refer to those in Figure 1.2. (Modified from Creaney and Allison, 1987)

VII.6 THE MIGRATION AND ENTRAPMENT OF HYDROCARBONS

So far, the majority of the oil discoveries in the Jeanne d'Arc basin has been within or near the present mature zone (Figure 7.5), although it is possible that the hydrocarbons could migrate upward to less mature reservoir rocks before thermal destruction within the present overmature zone. This distribution pattern of oil discoveries suggests that hydrocarbons are mainly locally sourced in the Jeanne d'Arc basin. Possible reasons for this are (i) the relatively frequent facies changes as a result of the intense fault activity, and (ii) the separation of fault blocks by faults preventing long-distance lateral migration of hydrocarbons. More or less vertical migration along faults and fractures has been the main mechanism of trap fill in the Hibernia area, and this has been confirmed by geochemical evidence (Creaney and Allison, 1987). The transfer faults were reactivated at late Barremian time to Early Aptian. The supracrustal detachment and its associated antithetic and synthetic faults in Early Aptian time modified the pre-existing rift-related hydrocarbon traps and developed the migration paths. These events could have triggered the migration of fluids. As mentioned earlier, peak oil generation was reached in the deepest part of the Jeanne d'Arc basin by Barremian time (122-116 Ma). In the Hibernia area, the peak oil generation (at about 100 Ma) occurred about 20 Ma after the time of the supracrustal detachment (at about

120 Ma). Acidic pore water assosiated with the hydrocarbons may have created significant amounts of secondary porosity. Oil gas chromatograms of six oil samples taken from a vertical interval of 1.7 km from the Hibernia P-15 well appear identical, suggesting that they are derived from the same Kimmeridgian source (Creaney and Allison, 1987). The timing of hydrocarbon migration relative to the formation of the secondary porosity is very important to the occurrence of hydrocarbons in reservoirs which is a result of a number of factors. Other important factors include: i) the distribution of source rocks and reservoir rocks, ii) the maturity of the source rocks, iii) migration paths, iv) the development of structural and stratigraphic closures, v) availability of cap rocks as seals, and vi) the preservation of hydrocarbons etc. In the following, several hydrocarbon structural closures or potenntial structures of the Jeanne D'Arc basin are discussed. Because of lack of information, secondary porosity was only discussed for the Hibernia oilfield.

The **giant Hibernia oilfield** (Figure 5.5) is located in a mature source rock area (Figure 7.5). The drainage system along the Nautilus transfer fault deposited extensive reservoir rocks within the Hibernia area. The hanging wall anticline formed the critical closure and existed before the time of peak oil generation (Creaney and Allison, 1987). Late supracrustal detachment associated with a set of antithetic and synthetic faults modified the Hibernia anticline structure and improved the migration paths. The Petrel Limestone formed an effective top seal after the supracrustal detachment but before peak oil generation. As mentioned earlier, secondary porosity takes a large portion of total porosity, especially in Hibernia Sandstone (>80%) and lower Catalina Sandstone (about 60%). Hydrocarbon migration in the Hibernia ocurred shortly after the generation of secondary porosity in the Hibernia Sandstone, which prevented the destruction of newly-formed secondary porosity by cementation and compaction (Abid, 1988). The Cenomanian unconformity is a marker of relatively intense tectonic activity. Migration of the hydrocarbons usually occurred at the time of the first intense tectonic movement after peak oil generation. The acids associated with and moving ahead of the hydrocarbons may have created substantial porosity. So the entrapment of the hydrocarbons within the Hibernia structure could have occurred in Early Cenomanian time when Europe separated from North America (Figure 1.4). In the Hibernia oil field, the major reservoir rocks for the hydrocarbon accumulation are Hibernia Sandstone, Catalina Sandstone, and Avalon Sandstone. The Jeanne d'Arc Sandtone is not a good reservoir rock, because it is thick, poorly-sorted and contains lots of detrital clay matrix, and thus has low permeability. These properties do not favor the formation of secondary porosity. Mechanical and chemical compaction may be advanced and have reduced porosity substantially.

The **Terra Nova structure** is a northward plunging rollover anticline (Figures 5.12 and 6.3) situated in the same segment of the Jeanne d'Arc basin as the Hibernia structure (Figure 2.6). Both structures are related to the basin-bounding Murre fault and modified by late supracrustal detachment in Aptian time. The isopach map of the Jeanne d'Arc and Hibernia sequences is a good guide to the basin paleogeography. The eastern basin margin south of Terra Nova is a ramp which leads down to the northeast plunging trough (Figure 7.3). The drainage system from the south and east margins of the Jeanne d'Arc basin is marked by a network of channels and valleys and deposited a complex array of fan-deltas at the Terra Nova depocenter (Figure 7.2). The Jeanne d'Arc Sandstone is the major reservoir rock unlike in the Hibernia oil field (Dwyer et al, 1986). Sourced from the underlying Kimmeridgian organic-matter rich limestone and calcareous shales, oil migrated vertically into the reservoir, and was traped in this structure.

The **Nautilus structure** is separated from the Hibernia structure by a shortcut fault (Figure 5.3). It is also a roll-over anticline (Figure 7.6) which is located in a different fault block than the Hibernia structure (Figure 2.6). This structure occurs also in the area of mature source rocks. Well Nautilus C-92 confirmed that hydrocarbons are trapped in this structure. However, reserves in this structure are much less than those in the Hibernia structure as a result of poor-

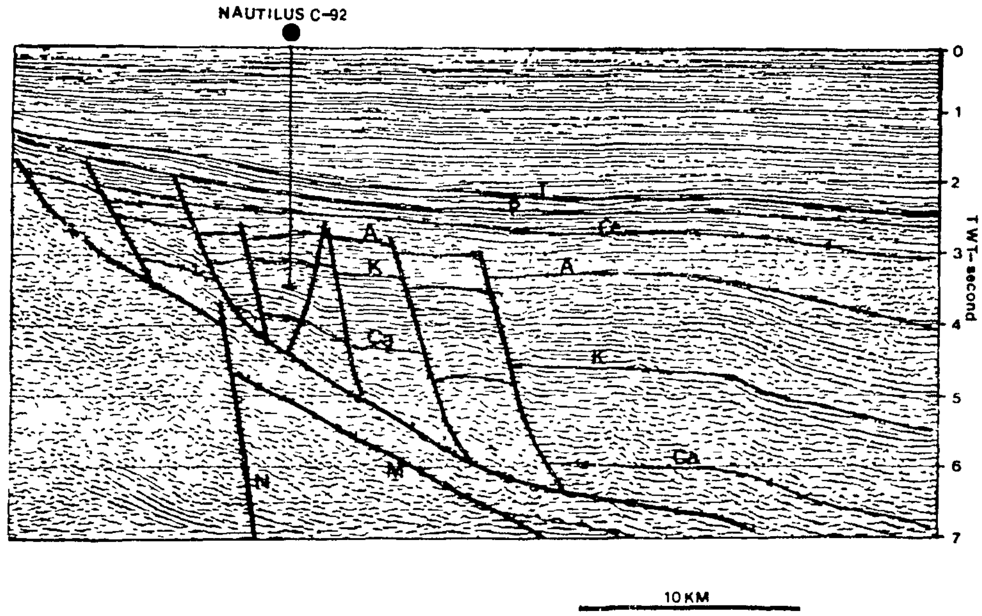


Figure 7.6 Seismic line 81-122 showing the Nautilus structure. (See Figure 1.2 for location and Figure 1.3 for symbols).

quality source rocks.

The **Egret structure** is a salt-cored roll-over anticline (Figure 2.5). Rotation along the basin-forming Murre fault, salt accumulation within the anticline, and supracrustal detachment within the cover sequences resulted in frequent erosion on the crest of the Egret anticline structure. Organic matter was oxidized and destroyed to some extent. At the present time, the source rocks are still immature due to shallow burial. Even though the hydrocarbons may have migrated from adjacent mature source rock areas, frequent erosion and faulting may have destroyed the traps. As a result, there is no accumulation of hydrocarbons in this structure. (Egret K-36 is a dry well).

In contrast, **Hebron-Ben Nevis structure complex** trapped hydrocarbons. Relatively greater burial depth resulted in the formation of mature source rocks (Figure 6.1). Hydrocarbons migrated vertically from the source rocks to the overlying reservoir rocks through fault planes and fractures. Interbeded shales formed an effective seal. Consequently, hydrocarbon accumulation occurred in the Hebron-Ben-Nevis complex (Hebron I-13 and Ben Nevis I-45 wells).

Figure 5.7 shows the Rankin and the South Mara structures in cross section. There are no hydrocarbons trapped in the **Rankin structure** due to immature source rocks as well as destruction of the organic matter and the hydrocarbon traps by erosion and faulting. The **South Mara structure**, on the other hand, trapped both oil and gas. The South Mara structure is located in the overmature source rock area, but near mature source rocks. The hydrocarbons within this structure may have migrated upward to the less mature reservoir rocks from the underlying source rocks before thermal destruction or laterally from the mature source rocks area through faults, fractures and unconformities.

The **Flying Form structure** (Figure 5.7) is located in the mature source rock area (Figure 7.5). However, no hydrocarbons were found in this trap (Flying Form I-13 well). This may be because: 1) the exposure of Kimmeridgian source rocks resulted in their oxidation and erosion, and 2) later erosion and faulting may have destroyed and/or released the hydrocarbons within this structure, if there were any.

The **Adolphus structure** (Figure 5.13) is a penetrative salt diapir. Although this structure is within the overmature source rock area, oil show occurred in well Adolphus 2K-41. The explanation for this is that the hydrocarbons migrated upward to less mature reservoir rocks before thermal destruction.

CHAPTER VIII.

CONCLUSIONS

The tectonic extension of the Grand Banks--Galicia Bank terrain probably occurred along a low-angle intracrustal detachment dipping gently westward. This low-angle detachment model fits the conspicuous characteristics which include their asymmetry, greater amounts of extension in proximal regions (Galicia Bank margin), and increasing basin sizes distally.

The extension of the Grand Banks was influenced by several continental separation events: 1) the separation of North America from Africa in the Jurassic, 2) the separation of North Ameria from Iberia in the Early Cretaceous, 3) the separation of North America from continental Europe in the Late Cretaceous. There are several episodes of basin formation and subsidence recorded in the central Grand Banks. Late Triassic extension marked the first rifting event. This rift appears to have inherited the trend of basement structures and was aborted later without the formation of oceanic crust. Late Jurassic-Aptian rifting is the major extensional event in the central Grand Banks which lasted 50 m.y. and formed the final configuration of the Jeanne d'Arc basin. The subsidence history of the Jeanne d'Arc basin is episodic due to the episodic nature of the extensional tectonic movements.

The extension in the Jeanne d'Arc basin was accommodated by a set of northeast-southwest trending listric and planar normal faults. A set of transfer faults with a northwest-southeast trend transects the normal faults at high angles and accommodated the areas with different amounts of extension. The extensional direction at the early stage of the rifting phase is northwest-southeast approximately along the transfer faults. The transfer faults were reactivated in a normal sense and reinforced the northward plunge of the Jeanne d'Arc basin at about Aptian time. Supracrustal detachment occurred because of the gravity instability and a new phase of extension in the northern Grand Banks. The extensional direction is northeast-southwest at this time.

Several factors influenced the subsidence pattern of the Jeanne D'Arc basin: 1) the northward plunge of the basin floor as a result of northward increase of extension, 2) the synthetic fault fan along the listric basin-bounding faults which have significant influence on the configuration of the cover sequence and caused several hanging wall anticlines and synclines, 3) the supracrustal detachment which produced another set of hanging wall anticlines and synclines and caused numerous structural and stratigraphic modifications.

The main source rocks in the Jeanne d'Arc basin is the Kimmeridgian organic-matter rich calcareous shale which formed in a deep anoxic basin during the onset of the Late Jurassic-Aptian rifting. The formation of the source rocks agrees with the low-angle detachment model in which substantial movement and subsidence may occur before significant brittle deformation affects the upper crust (Wernicke, 1985). The thermal maturity of the source rocks is directly related to the subsidence history. In the Jeanne d'Arc basin, there is a linear relationship between thermal maturity of the source rocks and burial depth.

The distribution of the reservoir rocks in the Jeanne d'Arc basin was controlled by structural style. First, drainage systems entered the Jeanne d'Arc basin and deposited fan-delta complexes along the deformation zones or transfer faults of relay structures in the listric fault boundary of the basin. Second, the streams cut a network of channels and valleys in the southern apex and the east monoclinal margin of the Jeanne d'Arc basin and formed a series of fan-delta complexes in a number of depocenters.

The main hydrocarbon traps are hanging wall anticlines such as the giant Hibernia oil field and the Terra Nova oil field. The petroleum potential of each structural closure is determined by several aspects: 1) the distribution, the quality and the volume of the source rocks, 2) the distribution of the reservoir rocks, 3) the generation of secondary porosity, 4) the maturity of the source rocks, 5) the migration paths, 6) the cap rocks, 7) the preservation of the hydrocarbon traps. Each of these aspects is directly related to the tectonic framework and structural styles of the Jeanne d'Arc basin and the extensional history.

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APPENDIX

SEISMIC LINES USED IN THIS STUDY

72-32, 80-1301, 80-1303, 80-1305, 80-1306, 80-1307, 80-1308, 80-1309, 80-1310, 80-1311, 80-1312, 80-1314, 80-1316, 80-1318, 80-1320, 80-1322, 80-1324, 81-120, 81-122, 81-1366, 82-10, 82-12, NF-79-103, NF-79-104, NF-79-105, NF-79-106, NF-79-107, NF-79-108, NF-79-109, NF-79-110, Nf-79-111, NF-79-112, NF-79-113, NF-79-114, NF-79-115, NF-79-116, NF-79-117, NF-79-118, NF-79-119.