EVOLUTION OF THE JEANNE D’ARC BASIN, OFFSHORE NEWFOUNDLAND, CANADA: 3D SEISMIC EVIDENCE FOR >100 MILLION YEARS OF RIFTING

by

BEATRIZ ELENA SERRANO SUAREZ

A thesis submitted to the

Graduate School – New Brunswick

Rutgers, The State University of New Jersey

in partial fulfillment of the requirements

for the degree of

Master of Science

Graduate program in Geological Sciences

written under the direction of

Dr. Martha O. Withjack

Dr. Roy W. Schlische

and approved by

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New Brunswick, New Jersey

January 2013
ABSTRACT OF THE THESIS

Evolution of the Jeanne d’Arc basin, offshore Newfoundland, Canada: 3D seismic evidence for >100 million years of rifting

by BEATRIZ ELENA SERRANO-SUAREZ

Thesis Directors:

Dr. Martha O. Withjack and Dr. Roy W. Schlische

The Jeanne d’Arc rift basin formed during the breakup of Pangea from Late Triassic through Early Cretaceous time. Previous studies concluded that rifting was episodic, occurring during two or three distinct events with intervening periods of thermal subsidence. To test these conclusions, I used 3D seismic-reflection data, well data, and restoration techniques to determine the spatial and temporal evolution of the Flying Foam region in the northwestern part of the Jeanne d’Arc rift basin. The Flying Foam region lies between the NNE-striking, E-dipping Mercury and Murre border faults of the basin. In the southern Flying Foam region, a series of basement-involved faults are present between the Mercury and Murre faults. In the north, a major anticline (the Flying Foam structure) overlies the Murre fault. I have identified three syn-rift tectonostratigraphic packages, none of which are present in the footwall of the Mercury fault. Strata within the basal Late Triassic/Early Jurassic syn-rift package thicken toward basement-involved faults. This package contains salt of the Argo Formation, which decouples the basement-involved faults from shallow structures. The overlying Jurassic package lacks evident fanning toward the Murre and Mercury faults. However, changes in thickness across the
Murre fault and along-strike thickness variations in the hanging-wall of the Mercury fault reflect displacement on the faults during deposition. The overlying Early Cretaceous package thins toward the Flying Foam anticline, a structure produced by a combination of forced folding above the Murre fault and fault-bend folding associated with a listric fault that detaches within the Argo salt. Thus, the Early Cretaceous package is also a syn-rift unit. In conclusion, my work indicates that the tectonic process of rifting in the Jeanne d’Arc basin was not episodic but rather was persistent, occurring from the Late Triassic through the Early Cretaceous. However, the intensity and the direction of the extension could have changed through time.
ACKNOWLEDGMENTS

I would like to especially thank my advisors, Dr. Martha Withjack and Dr. Roy Schlische, for their incredible patience and dedication and also for their unconditional support and contribution to this work. I would also like to thank Dr. Karen Bemis and Dr. Kevin Lyons for their continuous feedback and follow up. Additional thanks to WesternGeco for providing the seismic data, the Canada-Newfoundland offshore Petroleum Board for providing the well data, and the National Science Foundation, Husky Energy, and the Department of Earth and Planetary Sciences of Rutgers University for their financial support. I would like to thank Schlumberger and Energy Information, Software & Solutions for providing the Petrel and SMT seismic interpretation software, respectively. My gratitude also goes to my husband Andres and my parents and family for all the support to finish my studies at Rutgers. I also thank my friends and faculty from the Earth and Planetary Science Department who supported me during this time.
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1. Introduction

The Jeanne d’Arc rift basin is located on the Grand Banks of Canada, offshore Newfoundland (Figs. 1 and 2). This basin is one of the most important oil provinces of Canada with four oil-producing fields: Hibernia, Whiterose, Terra Nova and North Amethyst (Appendix 1, www.cnlopb.nl.ca). The basin developed during the breakup of the supercontinent Pangea during the Mesozoic (e.g. Louden, 2002; Seton et al., 2012; Withjack et al., 2012a), and it is part of the more extensive eastern North American rift system (Fig. 1).

The onset of rifting in this rift system was relatively synchronous and began by the Late Triassic, but the cessation of rifting and onset of seafloor spreading was diachronous, ranging from latest Triassic in the southern segment (southeastern United States), to Early Jurassic in the central segment (northeastern United States and southern Canada) and Late Cretaceous in the northern segment (eastern Grand Banks of Canada) (Withjack et al., 1998; Schlische et al., 2002; Withjack and Schlische, 2005; Withjack et al., 2012a). In the Jeanne d’Arc basin, some authors suggest that rifting occurred in two or three distinct episodes with intervening periods of thermal subsidence (e.g. Hubbard et al., 1985; Tankard and Welsink, 1987; Hubbard, 1988; Sinclair, 1988; Grant and McAlpine, 1990; McAlpine, 1990; Sinclair and Riley, 1995; Sinclair et al., 1999) (Fig. 3). My goal is to study the rift evolution of the Jeanne d’Arc basin using 3D seismic and well data from the Flying Foam area, in the northwestern corner of the basin, and to address the following questions:

• Are structures detached or basement-involved?
2. Geologic and structural background

The Jeanne d’Arc basin is a funnel-shaped, 25-80 km wide, half graben that deepens and widens northward (Tankard and Welsink, 1987) (Fig. 2). The NNE-striking, E-dipping Murre fault in the south and Mercury fault in the north bound the basin on the west (e.g. Enachescu, 1987; Tankard and Welsink, 1987). Intrabasinal faults generally strike NW-SE and detach on salt (e.g. Tankard and Welsink, 1987; Withjack and Schlische, 2005). The study area, in the northwestern corner of the basin, lies between the Mercury and the Murre faults. The Flying Foam anticline overlies the Murre fault in the north; in contrast, in the south, several basement-involved faults occur between the Mercury and the Murre faults.

Pre-rift rocks consist of Paleozoic igneous and metamorphic rocks from the Avalon and/or Meguma terrains (Tankard and Balkwill, 1989) (Fig. 3). Several orogenies (Ordovician Taconic, Devonian Acadian and Carboniferous-Permian Alleghanian) preceded rifting (Naylor, 1971; Rodgers, 1971; Murphy and Keppie, 1998; Williams, 1999; Cocks and Torsvik, 2011). The overlying sedimentary section (Fig. 3) consists of
Late Triassic – Early Jurassic siliciclastic rocks from the Eurydice Formation and salt from the Argo Formation (e.g. Jansa and Wade, 1975; McAlpine, 1990). The overlying Early Jurassic to Late Jurassic section consists of dolomites, limestones, calcareous shales and some sandstones from the Iroquois, Downing, Voyager and Rankin formations (e.g. McAlpine, 1990; Sinclair et al., 1999). Within the Rankin Formation, an organic-rich shale (the Egret Member) sources the hydrocarbons of the Jeanne d’Arc basin (e.g. Magoon et al., 2005). The overlying latest Jurassic – Early Cretaceous section consists of sandstones, shales and some limestones from the Jeanne d’Arc, Avalon, Whiterose, Catalina, Hibernia, Nautilus and Ben Nevis formations (e.g. McAlpine, 1990; Sinclair, et al., 1999). Sandstones from the Hibernia and Avalon formations are the main reservoir rocks in the Jeanne d’Arc basin (e.g. Magoon et al., 2005). Finally, the Late Cretaceous – Cenozoic section consists of shales and some sandstones from the Dawson Canyon and Banquerau formations (e.g. Deptuck et al., 2003). In general, studies suggest that the Late Triassic – Early Jurassic and the latest Jurassic – Early Cretaceous sections correspond to periods of active rifting, whereas the Early Jurassic to Late Jurassic section represents a period of tectonic quiescence (e.g. Hubbard et al., 1985; Tankard and Welsink, 1987; Hubbard, 1988; Sinclair, 1988; Grant and McAlpine, 1990; McAlpine, 1990; Grant and McAlpine, 1990; McAlpine, 1990; Sinclair and Riley, 1995; Sinclair et al., 1999; Welsink and Tankard, 2012). The Late Cretaceous – Cenozoic section corresponds to post-rift rocks that accumulated during the thermal subsidence of the basin (e.g. McAlpine, 1990; Sinclair, et al., 1999). This study focuses on the Late Triassic to Early Cretaceous sections.
3. Data and methodology

3.1 Seismic data

This study involves the interpretation of 3D seismic data from the Flying Foam area in the Jeanne d’Arc basin. The digital data, provided by WesternGeco, were acquired in 1995 and consist of 1532 E-W inlines, 3150 N-S crosslines, and 2250 time-slices (Table 1). Inlines and crosslines are generic names given to sequentially numbered orthogonal seismic profiles for 3D seismic surveys (Hart, 1999). An inline is a seismic line that parallels the movement direction of the ship acquiring the data. Crosslines are perpendicular to the inlines. A time-slice is a horizontal plane through a 3D-seismic volume at a given TWT (two-way time). Each inline and crossline is 39 km long, but the interpretable length is ~30 km for the inlines and ~36 km for the crosslines, yielding a total interpretable area of 1080 km². Table 1 lists the main seismic-acquisition parameters, and Appendix 2 gives the seismic processing report (Schlumberger and Geco-Prakla, 1996). The data quality is good, but the presence of peg-leg multiples commonly masks the true geometry of the reflections (Figs. 4 and 5). The displays of inlines and crosslines in this thesis have a vertical exaggeration of 1:1 assuming an average velocity of 4.0 km/s (an average velocity supported by velocity surveys from Line HBV83-195; Appendices 2 and 3).

3.2 Seismic interpretation

Tectonostratigraphic packaging (Fig. 6) provides information about the relative timing of events and the structural style of a region, and therefore, is an appropriate method to study the evolution of the Flying Foam area. The first step consists of identifying
unconformity-bounded packages. For example, the rift-onset unconformity separates the pre-rift and the syn-rift packages, and the post-rift unconformity separates the syn-rift and the post-rift packages (e.g. Withjack et al., 2002). Differences in the characteristics of the reflections define other packages. For example, high-ductility units lack internal reflections and decouple the deeper and shallow deformation. Fault-related growth beds thicken toward a fault on the downthrown side of a fault or exhibit differences in thickness of correlative strata on each side of a fault (e.g. Withjack et al., 2002). Fold-related growth beds thin toward the crest of antiforms and thicken toward the troughs of synforms (e.g. Withjack et al., 2002). The tie between inlines, crosslines and time-slices helped defined the 3D geometry of packages, horizons and structures in the study area. The interpretation also included the mapping of major and some minor structures (e.g., detached faults).

3.3 Well data and correlation with seismic data

Formation tops and unconformities from five wells in the study area are available from the Canada-Newfoundland Labrador Offshore Petroleum Board (CNLOPB) website (www.cnlopb.nl.ca/well_alpha.shtml) (Table 2 and Appendix 5) and the BASIN database website (http://basin.gdr.nrcan.gc.ca/wells/index_e.php). To tie the well data (in depth) to the seismic data (in two-way time), I used the velocity information from 2D seismic line HBV83-195 (Appendices 3 and 6). This line is close to the West Flying Foam L-23 and Flying Foam I-23 wells. For the other wells in the study area, I also used the velocity surveys from line HBV83-195 because they have the same lithologic formations as the West Flying Foam L-23 and Flying Foam I-23 wells.
4. Structural framework

The N-striking, E-dipping Mercury fault bounds the Flying Foam region in the west (e.g. Enachescu, 1987; Driscoll et al., 1995) (Figs. 7 to 9). The Murre fault is to the east of the Mercury fault and also dips to the east (e.g. Enachescu, 1987; Tankard and Welsink, 1987). My interpretation indicates that the distance between these faults decreases to the north (Fig. 8). The zone between the Mercury and the Murre fault corresponds to a relay ramp, which is an inclined zone between two normal fault segments that overstep in map view and that have the same dip direction (Peacock and Sanderson, 1994; Peacock, 2002). This kind of structure connects the footwall of a fault segment with the hanging wall of a contiguous fault segment (Peacock, 2002). In the southern part of the study area, other N-striking, E-dipping basement-involved faults lie between the Mercury and Murre faults (Figs. 7 and 8). These faults are less well imaged in the central and northern parts of the study area. Basement-involved faults have normal separation, a listric geometry in cross section and link at depth. Part of the listric geometry of the faults could be due to the increase of stratal velocities with depth. Synthetic seismic sections made by Withjack and Pollock (1984) showed that planar normal faults appear in seismic as listric faults because each second of two-way traveltime in the seismic section represents a greater distance than the preceding second.

The Flying Foam anticline, in the central and northern parts of the study area, is a doubly-plunging anticline (Fig. 10) with a N-striking, E-dipping axial plane (Fig. 11). West of the Flying Foam anticline, a doubly-plunging syncline with a N-striking, E-dipping axial plane exists (Figs. 10 and 11). East of the Flying Foam anticline, a NE-plunging syncline is present (Fig. 10). Other minor folds are present in the central
western and southeastern parts of the study area (Fig. 7). Several faults with normal separation detach within a ductile package and affect some of the overlying packages (Figs. 7, 10, 12 to 19).

The structural framework proposed in this study shows the geometry of the structures and its spatial variability in map view (Fig. 7) along-strike (Fig. 8) and along-dip (Fig. 9), whereas other studies (e.g. Hubbard et al., 1985; Enachescu, 1987; Tankard et al., 1989; Edwards, 1990; Driscoll et al., 1995; Withjack and Callaway, 2000) were only able to show single 2D lines to interpret the structures in the Flying Foam area. Differences in the interpretation of the basin-bounding faults and the top of the ductile package also exist. In Enachescu (1987), for example, the ductile package does not parallel the Mercury fault and the position of the Murre fault in the Flying Foam area is not clear. In Edwards (1990) the Murre fault is not present and most of what in this study corresponds to a ductile package corresponds to basement in his work. Driscoll et al. (1995) do not interpret a ductile package and the geometry of the Mercury fault corresponds to what in this study is the geometry of the top of the ductile package. The interpretation of this study mostly agrees with the one in Withjack and Callaway (2000). Finally, previous works were not able to map the multiple detached faults shown in this study.

5. Tectonostratigraphic packages - observations

The Flying Foam area has five tectonostratigraphic packages, labeled from A to E, bounded by four horizons, labeled H1 to H4. Package A is the oldest package, and Package E to the youngest. Horizon H1 is the oldest boundary, and Horizon H4 is the
youngest. Table 3 summarizes the seismic characteristics of the packages and horizons and also includes formation names, lithologies and ages. The following sections describe the packages and the horizons in detail.

5.1 Package A

Package A has a few E-dipping reflections that gradually converge at depth. These reflections are subparallel to interpreted basement-involved faults, including the Mercury and the Murre faults. Peg-leg multiples parallel to these reflections are common in Package A (Fig. 5). Horizon 1, the top of Package A (Figs. 12 to 18), is well imaged in the footwall of the Mercury fault and reasonably well imaged in the hanging-wall in the southern part of the study area (Fig. 16); elsewhere, it is not well imaged. Horizon 1 is structurally higher in the southern part of the study area and deepens toward the north (Figs. 8, 12 to 16). No well has reached Horizon 1 within the study area.

5.2 Package B

Many reflections in Package B are chaotic, but some reflections are continuous (Figs. 16 to 18). These continuous reflections subtly diverge toward the basement-involved faults (Figs. 20 and 21). Faults above and below package B terminate within it. Horizon 2, the top of Package B, is irregular with steeply dipping segments parallel to the basin-bounding faults and gently dipping segments between them (Figs. 12 and 13). Horizon 2 is best imaged in the southeastern part of the study area (Figs. 15 and 16); elsewhere, imaging of this horizon is poor. Horizon 2 is structurally higher in the southern part of the study area and deepens toward the north (Figs. 8, 12 to 16). No well has reached Horizon 2 within the study area.
5.3 Package C

Package C has sub-parallel reflections, and its thickness varies throughout the study area. In the northern part of the study area, Package C is thick (Figs. 12 and 13). In the central western part of the study area, Package C is thinner (Fig. 14); in the central eastern part of the study area, Package C is thick (Fig. 14). In the southwestern part of the study area, Package C is absent or very thin (Figs. 15 and 16); in the southeastern part of the study area, Package C is thick (Figs. 15 and 16). Horizon 3 bounds the top of Package C. In the northwestern part of the study area, Horizon 3 separates dipping sub-parallel reflections in Package C from overlying diverging reflections in Package D (Figs. 12 and 22). In the northeastern part of the study area, a zone of chaotic reflections commonly exists between Packages C and D (Figs. 12, 13 and 23); Horizon 3 is not well defined here. In the central western part of the study area, Horizon 3 separates sub-parallel reflections in both Packages C and D (Figs. 13 and 24). In the central eastern part of the study area, Horizon 3 is not well defined. It lies somewhere between diverging reflections from Package D and dipping sub-parallel reflections from Package C (Figs. 14 and 25). In the southwestern part of the study area, Horizon 3 is not present (Figs. 15 and 16). In the southeastern part of the study area, Horizon 3 is not well defined; it lies somewhere between sub-parallel reflections from both Packages C and D (Figs. 15, 16 and 26). In strike view in the western part of the study area, Horizon 3 separates reflections that diverge toward the north in Package C from sub-parallel reflections in Package D (Figs. 18 and 27). In the eastern part of the study area, Horizon 3 is not well defined (Fig. 19). Only the Flying Foam I-13 well reached Horizon 3, which coincides with an unconformity with a missing section of Tithonian (Jurassic) age (CNLOPB, 2012).
5.4 Package D

Package D is present only in the hanging-wall of the Mercury fault and consists of sub-parallel and diverging reflections. In the northwestern part of the study area, reflections from Package D diverge toward the west (Figs. 12 and 22). In the northeastern part of the study area, flat-lying reflections from Package D lap onto a zone of chaotic reflections that commonly exists between Packages C and D (Figs. 12, 13 and 23). In the central western part of the study area, older strata are sub-parallel, whereas younger strata diverge toward the west (Figs. 13, 14 and 24). In the central eastern part of the study area, reflections diverge toward the east (Figs. 14 and 25). In the southwestern part of the study area, all reflections from Package D are sub-parallel (Figs. 15 and 16). In the southeastern part of the study area, Package D has a variety of geometries. For example, on Line D (Figs. 15 and 26), basal reflections from Package D are sub-parallel and folded. Upper reflections from Package D lap onto the eastern limb of the fold and diverge toward a detached fault to the west. On Line E (Fig. 16), reflections from Package D are sub-parallel. Horizon 4 bounds the top of Package D. Onlap, toplap and some downlap terminations mark this horizon (Fig. 28). The Mercury K-76, Nautilus C-92 and Thorvald P-24 wells (CNLOPB, 2012) reached Horizon 4, which coincides with an unconformity with a missing section of Cenomanian age (CNLOPB, 2012). Toward the top of the Flying Foam anticline, the Flying Foam I-13 and West Flying Foam L-23 wells reached Horizon 4, which coincides with an unconformity with a missing section of early Paleogene age (CNLOPB, 2012).

5.5 Package E

Package E consists of continuous reflections that dip gently to the east; these
reflections are generally undeformed (Figs. 12 to 16). In the northern part of the study area, reflections are sub-parallel (Figs. 12 to 14). In the southern part of the study area, some basal reflections are sigmoidal, whereas overlying reflections are sub-parallel (Figs. 15 and 16).

6. Tectonostratigraphic packages - interpretation

6.1 Package A

Package A likely corresponds to pre-rift rocks (Table 3) because primary reflections related to stratification are absent. Basement-involved faults with normal separation offset this package. Rocks in Package A are likely igneous or metamorphic rocks because: 1) the Murre G-67 well in the southern Jeanne d’Arc basin encountered metasedimentary rocks of Middle to Late Devonian age (McAlpine, 1990) (Fig. 29, Appendix 1). The Spoonbill C-30 and Hibernia G-55 wells (Appendix 1) encountered low-grade metasedimentary rocks and metamorphic basement, respectively (McAlpine, 1990). 2) Onshore studies in Newfoundland indicate that the eastern part of the island corresponds to the Avalon terrain, which consists of upper Precambrian metasedimentary and volcanic rocks and associated intrusions and overlying Cambrian-Ordovician shales and sandstones (Keen et al., 1990; Williams, 1999). In the south in Nova Scotia, rocks assigned to the Meguma terrain correspond to latest Neoproterozoic or Early Ordovician siliciclastic rocks overlain by volcanic rocks and granitic plutons (Keen et al., 1990; Williams, 1999; Cocks and Torsvik, 2011). Horizon 1 is an unconformity, according to data from the Murre G-67 well (Appendix 1), with Devonian rocks below the
unconformity and Triassic rocks above it.

6.2 Package B

Thickening of strata from Package B toward basement-involved faults indicates that Package B is a syn-rift unit (Fig. 21). Additionally, Package B is a highly ductile unit because: 1) the upper and lower boundaries commonly have very different geometries, 2) faults above and below Package B terminate within it, and 3) Package B decouples the deep from the shallow deformation (Figs. 12 to 19) as evidenced by the differences in the structural geometries above and below Package B. Specifically, few basement-involved faults offset Package A (Fig. 14), whereas several detached faults offset Packages C and D (Figs. 14, 17 to 19). No folding occurs in Package A, whereas several folds deform strata from Packages C and D (Figs 12 to 14).

Based on these observations, Package B likely corresponds to sedimentary rocks of the Eurydice and Argo formations, the oldest syn-rift rocks encountered in the Jeanne d’Arc basin. The Murre G-67 well in the southern Jeanne d’Arc basin encountered siliciclastic rocks from the Eurydice Formation unconformably overlying metasedimentary rocks from Package A (see section 6.1, McAlpine, 1990). The Spoonbill C-30 and Cormorant N-83 wells (Appendix 1), also in the southern Jeanne d’Arc basin, encountered salt-rich rocks from the Argo Formation overlying rocks from the Eurydice Formation (McAlpine, 1990). The ductile behavior of Package B agrees with the presence of salt in the Argo Formation. Palynomorphs from the Eurydice Formation, recovered in the Cormorant N-83 and Spoonbill C-30 wells, indicate ages from Carnian-Norian to Rhaetian. For the Argo salt, samples in the Spoonbill C-30 well indicate ages from Rhaetian -Early
Hettangian to late Hettangian-early Sinemurian (McAlpine, 1990). Therefore, the age of Package B is Late Triassic – Early Jurassic.

6.3 Package C

The following stratigraphic patterns characterize Package C: 1) absence of Package C in the footwall of the Mercury fault and, in the southwestern part of the study area, absence of Package C in the footwall of the Murre fault (Fig. 8); 2) thickness changes in the hanging-wall of the Mercury fault; specifically strata diverging toward the north (Figs. 8, 9 and 18). These patterns suggest that Package C is a syn-rift unit because: 1) Movement along the Mercury fault explains the absence of Package C in the footwall of the Mercury fault and in the southwestern part of the study area. 2) Thickening of strata toward the north (Figs. 18 and 27) indicates differential movement along the Mercury fault because displacement along normal faults typically increases from the tips toward the center (e.g. Barnett et al., 1987; Schlische and Anders, 1996; Kim and Sanderson, 2005). As a consequence, the syndepositional packages are thicker in the center and thinner toward the tips of the fault-bounded basin (Fig. 30) (e.g. Schlische and Anders, 1996; Withjack et al., 2002). Also, an increased displacement on the Mercury fault to the north explains the northward thickening of Package C (Fig. 27).

Alternatively, faulting and later erosion of Package C in the footwall of the Mercury fault, and salt mobilization could explain the stratigraphic patterns of Package C.

However, strata from Package C are sub-parallel in dip sections (Figs. 12 to 16), which suggests little or no salt movement. Also, in the southern Jeanne d’Arc basin (Fig. 29), published seismic profiles indicate that strata equivalent to Package C thicken toward
basement-involved faults. This thickening is not evident in the Flying Foam area because thickening of syn-rift strata toward the basin-bounding faults is subtle during the latter stages of rifting in many of the rift basins of eastern North America. For example, in the Newark basin, Withjack et al. (2012b) determined that the change in bedding dip of some of the syn-rift packages is ~3° from top to bottom. This difference in dip is only apparent in regional transects.

Only one well reached the top of Package C in the study area; the Flying Foam I-13 well encountered rocks from the Rankin Formation (CNLOPB, 2012). Studies from the southern Jeanne d’Arc basin and the Hibernia oilfield report that the Voyager, Downing and Iroquois formations underlie the Rankin Formation (McAlpine, 1990; Sinclair et al., 1999). McAlpine (1990) indicates that these formations range in age from Late Triassic to Late Jurassic.

6.4 Package D

Package D consists of diverging and sub-parallel strata. In the northwestern part of the study area, strata thin toward the crest of the Flying Foam anticline and thicken toward Horizon 2, which locally parallels the Mercury fault (Figs. 12 and 22). Horizon 2 is a lithologic contact and a fault contact. The ductile rocks (Argo salt) of Package B underlie Horizon 2. This contact acted as a detachment fault with a ramp-flat-ramp geometry. The ramps are parallel to the Mercury and the Murre faults and the flat is between them (Fig. 31). Strata thickening toward this fault indicate syn-faulting deposition, and strata thinning toward the crest of the Flying Foam anticline indicate growth during folding (see section 7.1 for a complete explanation). In the central western part of the study area,
younger strata thicken toward the detachment fault and thin toward the Flying Foam anticline, whereas older strata are sub-parallel (Figs. 13, 14 and 24). Therefore, folding and movement along the detachment fault started in the north and propagated later to the south. The boundary between diverging reflections and flat-lying reflections on Line B (Fig. 24) coincides with an unconformity with a missing section of Aptian age (West Flying Foam L-23 well; CNLOPB, 2012). Above this unconformity, the West Flying Foam L-23 well encountered rocks from the Nautilus and Ben Nevis formations, and below this unconformity, it encountered rocks from the Avalon, Whiterose, Catalina and Hibernia formations (CNLOPB, 2012; Appendix 4). The Fortune Bay and Jeanne d’Arc basin underlie the Hibernia Formation (McAlpine, 1990; Fig. 3). The formations that conform Package D range in age from Latest Jurassic to Early Cretaceous (McAlpine, 1990).

In the southwestern part of the study area, all strata from Package D are sub-parallel (Figs. 15, 16 and 28). The Mercury K-76 well encountered rocks from the Nautilus and Ben Nevis formations (CNLOPB, 2012; Appendix 4), therefore, the oldest strata from Package D did not accumulate; alternatively, they accumulated but were later eroded away. The discussion section describes in more detail other stratigraphic patterns in Package D and their tectonic significance.

6.5 Package E

Package E is present in the entire area. The Mercury fault cuts part of strata of Package E, but, in general, no significant faulting or folding deforms this package. Strata do not thicken toward the border fault, but rather thicken gradually to the east. Therefore,
Package E is a post-rift unit. All wells in the study area encountered Package E. The Mercury K-72, Nautilus C-92 and Thorvald P-24 wells drilled the basal part of this package, which corresponds to the Wyandot and Dawson Canyon formations (Appendix 4). All other wells in the study area drilled the upper part of Package E, which corresponds to the Banquereau Formation (Appendix 2). The age of the oldest rocks in Package E is Late Cretaceous (Grant and McAlpine, 1990; Sinclair et al., 1999; Deptuck, 2003).

7. Discussion

7.1 Are structures detached or basement-involved?

Both types of structures are present in the Flying Foam area. This is because Package B, which contains salt (Argo Formation), behaves ductilely and decouples the deeper deformation from the shallower deformation. As a consequence, the style of deformation of the cover is different than the style of deformation of the basement. Specifically, a few basement-involved faults offset Package A, whereas several detached faults affect Packages C and D. Also, no major folding occurs in Package A, whereas major and minor folds deform Packages C and D. The Flying Foam structure is the main fold in the study area. This structure is a forced fold (Withjack and Callaway, 2000) and a fault-bend fold (Tankard et al., 1989) that deforms rocks from Package C (see discussion below). The forced fold forms because of flexure of the sedimentary cover above the Murre fault, which is a basement-involved fault with normal separation (e.g. Withjack et al., 1990; Schlische, 1995). The fault-bend fold (e.g. Xiao and Suppe, 1992; Schlische, 1995) forms
because of movement on the non-planar detachment fault associated with Horizon 2 and with displacement on the Murre fault (see section 6.4 and discussion below).

Experimental and geometric models provide additional insights into the development of the Flying Foam structure. Experimental models from Withjack and Callaway (2000) simulated forced folding using a precut metal base to represent a basement-involved normal fault and wet clay and silicone polymer to represent the sedimentary cover and a ductile salt layer, respectively. The models show that in the presence of a ductile layer, a basement-involved fault does not propagate to the surface, but rather produces a forced-fold in the strata above the ductile layer (Fig. 32). Growth beds in the model reflect syn-faulting and syn-folding deposition during movement along the basement-involved fault and during the folding of the package above the ductile layer. Similarly, in the Flying Foam area, the Murre fault does not propagate through Package B (Argo salt) but produces a forced fold in Package C. Growth beds from Package D reflect syn-faulting and syn-folding deposition during movement along the Murre fault and during folding of Package C, therefore, Package D is a syn-rift unit. The experimental models differ from the Flying Foam area in details and complexity. In the models, both the ductile layer and the package above it are pre-rift. In the study area, Packages B and C are syn-rift. However, during the accumulation of Package D and the corresponding displacement of the Murre fault, Package C is a pre-kinematic package, just like the pre-kinematic package of the model.

Additionally, the experimental models show that, as displacement increases on the basement-involved fault, displacement also increases on the detached fault in the footwall of the master fault. One or more of those detached faults achieves a ramp-flat-ramp fault
geometry, movement on which produces a fault-bend fold anticline (Fig. 32). A geometric model from Withjack and Schlische (2006) illustrates how displacement on a ramp-flat-ramp fault produces an anticlinal fault-bend fold and a dipping diachronous unconformity. The model assumes that the hanging-wall deforms by inclined simple shear, that the footwall remains rigid, that compaction is not significant and that growth beds fill depressions developed during faulting up to a prescribed datum. The inclined-shear direction dips 70° toward the main normal fault. Their results show that syndepositional strata diverge toward the fault near the upper ramp and lap onto a diachronous unconformity above the lower ramp (Fig. 33). In the Flying Foam area, strata from Package D diverge toward the detachment fault in the *northwestern* and *central western* parts of the study area (Figs. 12, 13, 22, 24 and 31). In the *northeastern* part of the study area, strata in Package D are parallel and lap onto a zone of chaotic strata that probably correspond to the diachronous unconformity observed in the geometric model (Figs. 12, 13, 23, 25 and 31). The geometric model differs from the study area in the complexity of the Flying Foam area. In the study area, the ramp-flat-ramp fault geometry of the detachment fault results from the interaction between the Mercury and the Murre faults in the presence of a ductile layer, whereas in the geometric model only one fault exists (see following section). In the study area, changes in the stratigraphic patterns occur along strike, and the structures represent a final stage of deformation, whereas the model shows the evolution of the structure and changes only in one cross section.
7.2 When did the deformation occur?

To illustrate the evolution of the Flying Foam area, I restored the cross section of Line B (Fig. 34) using inclined shear and rigid-body rotation. I assumed plane-strain conditions, negligible compaction and negligible deformation in the footwall, that all packages have constant area through time, and that growth beds completely fill any spaces created during faulting up to a prescribed regional datum. The footwall remains fixed. Despite these simplifying assumptions, the restoration schematically shows the evolution of the Flying Foam region in the northern part of the study area. The restoration indicates 25 km of extension equivalent to a stretch of 60%. This is a minimum estimate because the restoration does not take into account deformation accommodated by small-scale structures or footwall deformation.

7.2.1 Paleozoic (Package A)

Several orogenies (Taconic, Acadian and Alleghanian) related to the amalgamation of the supercontinent Pangea occurred during this period (Keen et al., 1990; Williams, 1999; Cocks and Torsvik, 2011). Structures include low-angle thrust faults. Erosion likely removed rocks from this package.

7.2.2 Late Triassic (Package B)

Rifting started with the accumulation of siliclastic rocks of the Eurydice Formation and salt of the Argo Formation (Package B). In the southern part of the study area, the Mercury and other basement-involved faults were active. The Murre fault was active in the rest of the Jeanne d’Arc basin (Sinclair, 1995), but it is unclear if it was active in the Flying Foam area. In the rest of the study area, only the Mercury fault was active. All
faults had normal separation.

7.2.3 Early to Late Jurassic (Package C)

Displacement on the Mercury fault continued, but it was greater in the north as evidenced by the absence of Package C in the southwestern part of the study area and by strata thickening toward the north in the western part of the study area. Strata do not obviously thicken toward the Mercury fault likely because, in the Flying Foam region, the basin was very wide, and differences in dip between the layers are very subtle (see section 6.3). The Murre fault was only active in the southeastern part of the study area, as evidenced by the absence of Package C in the footwall of the Murre fault and by the apparent lack of thickness changes in the central and northeastern parts of the study area (Fig. 35).

7.2.4 Latest Jurassic to Early Cretaceous (Package D)

The structural complexity increased during this period in the study area. The stratigraphic patterns in Package D indicate differences in the deformation style between Tithonian and Aptian times and between Aptian and Cenomanian times. Differences also exist between the eastern and western parts of the study area. For clarity the discussion starts with the western part of the study area.

From Tithonian through Aptian times, strata from Package D diverge toward a detachment fault in the northwestern part of the study area (section 6.4, Figs. 12, 20 and 32), whereas in the central western and southwestern parts of the study area, strata from Package D are sub-parallel (Figs. 13 to 16, 22 and 26). From Aptian through Cenomanian times, strata from Package D diverge toward the detachment fault in the northwestern and
central western parts of the study area, whereas in the southwestern part of the study area, strata from Package D are sub-parallel. Differences in the displacement direction on the detachment fault in space and through time could explain the heterogeneous stratigraphic patterns observed. However, this subject requires further study.

Displacement on the detachment fault produced fault-bend folding and displacement on the Murre fault produced forced folding. As a consequence, along-strike differences in the Flying Foam anticline are the result of differences in the degree of fault-bend folding vs. forced folding. In the northeastern part of the study area (Figs. 12, 13 and 21), strata from Package D are parallel. This stratigraphic pattern is similar to the one in the geometric model of Figure 33. Therefore, the detachment fault was active, and fault-bend folding was greater than forced folding. In the central eastern part of the study area (Fig. 14 and 25), strata from Package D diverge toward the east. Displacement on the detachment decreased or was oblique and, therefore, forced folding was greater than fault-bend folding in the E-W direction. In the southeastern part of the study area, two stratigraphic patterns exist. On Line D (Figs. 15 and 26), displacement on the detachment occurred only on the ramp parallel to the Murre fault and along the overlying detached fault. Therefore, displacement on the detachment and fault-bend folding was minimal. Forced folding predominates. On Line E (Fig. 16), no folding occurred; therefore the Murre fault was not active. Alternatively, the Murre fault was at the surface, and thus, no forced folding occurred.

7.2.5 Late Cretaceous – Cenozoic (Package E)

A period of erosion occurred, as evidenced by toplap terminations (Fig. 28). Then,
during the Paleogene and Neogene, post-rift sedimentation occurred with accumulation of Package E. Differential subsidence occurred gently tilting strata to the east. Additionally, the Mercury fault offsets the strata at the base of Package E. This could be related to either slight reactivation of the Mercury fault or differential compaction of strata of Package E.

7.3 Is rifting episodic or persistent?

The stratigraphic patterns interpreted in the Flying Foam area suggest that rifting in the Jeanne d’Arc basin lasted from the Late Triassic through the Early Cretaceous; that is, rifting lasted more than 100 m.y. (Figs. 35 and 36). In contrast, previous workers (e.g. Hubbard et al., 1985; Tankard and Welsink, 1987; Hubbard, 1988; Tankard et al., 1989; Grant and McAlpine, 1990; Sinclair, 1995; Sinclair and Riley, 1995; Sinclair et al., 1999) suggested that rifting in the Jeanne d’Arc basin occurred in two or three different episodes with intervening periods of thermal subsidence, and that each rifting episode lasted tens of millions of years. In other words, previous studies more or less consider that Packages B and D are syn-rift units, whereas Package C is a post-rift unit.

Consensus exists about the syn-rift nature of Package B (e.g. Tankard and Welsink, 1987; McAlpine, 1990; Sinclair, 1995), despite the fact that most studies do not identify thickening of strata toward the basin-bounding faults. Consensus also exists about the post-rift nature of Package C. Grant and McAlpine (1990), for example, indicated that the presence of gradational and conformable contacts of formations within Package C indicate no syndepositional growth, even though they noted that the Egret Member from the Rankin Formation thickens northeastward in the basin. Package D, in contrast, has
several unconformities within it and marked thickening of strata toward the Mercury and the Murre faults, and thus previous workers (e.g. Tankard and Welsink, 1987; Edwards, 1990; Sinclair et al., 1999) consider that Package D corresponds to a period of rift reactivation in the Jeanne d’Arc basin.

This study shows that strata from Package B thicken toward basement-involved faults, and thus confirms the syn-rift nature of this package. This study also shows that Package C is a syn-rift unit, and not a post-rift unit as previous studies suggest, because of the spatial distribution of the strata and thickening of strata toward the north. Finally, this study agrees with previous studies about the syn-rift nature of Package D, but identifies and describes in more detail the complex stratigraphic patterns and the deformation associated with this package. Specifically, Package D exhibits two different stratigraphic patterns: diverging strata and sub-parallel strata. These patterns are related to displacement on the Mercury and the Murre faults and a detached fault that coincides with the top of Package B (top of the Argo salt). Displacement on the Murre fault and the detachment fault caused forced folding and fault-bend folding, which are responsible for the Flying Foam anticline.

The differences in the spatial distribution of the packages and the variety of orientation of the detached structures (folds and faults) (Figs. 7, 10 and 35) suggest that the intensity of rifting and extension direction could have changed through time. However, the prediction of the extension direction in a basin is difficult. For instance, experimental clay models with multiple episodes of extension (Henza, 2009; Henza, et al. 2010, 2011) show that, in areas with multiple deformational episodes, fault orientation may not reflect the direction or relative magnitude of each event. In the Jeanne d’Arc basin, several
authors suggest that the border faults correspond to reactivated thrust faults (e.g. Enachescu, 1987; Tankard and Welsink, 1989; Withjack and Schlische, 2005). Therefore, a complete analysis of the extension direction and intensity of rifting needs a detailed study and falls beyond the scope of this study.

The syn-rift nature of Package C implies potential reservoir rocks near basement-involved faults, because coarser rocks accumulate close to border faults (e.g. Withjack et al., 2002). The Voyayer Formation within Package C contains thermally mature source rocks (e.g. Fowler and Brooks, 1990; McAlpine, 1990; Magoon et al., 2005) and fine-grained sandstones (McAlpine, 1990) that could be reservoir rocks. Therefore, Package C could contain important hydrocarbon accumulations that might have been overlooked because of the assumption that this package was post-rift. Additionally, persistent rifting in the Jeanne d’Arc basin implies persistent heat flow for hydrocarbon maturation and generation. That persistent heat flow could explain the existence of mature rocks in the Voyayer Formation, and the likely occurrence of deeper reservoirs not explored yet.

8. Summary and conclusions

The interpretation of 3D seismic data from the Flying Foam area indicates that rifting in the Jeanne d’Arc basin was not episodic (as previous studies suggested), but persistent from the Late Triassic through the Early Cretaceous. Persistent rifting resulted in three different packages. Strata from the basal salt-rich Package B gradually thicken toward basement-involved faults. Strata from overlying Package C do not obviously thicken toward basement-involved faults, but strata thickening toward the north indicate
differential displacement on the Mercury and Murre faults. Strata from the uppermost Package D have a variety of geometries that reflect differences in displacement on the basin-bounding faults and displacement on a detachment fault (top of the Argo salt in Package B).

Folding and detached faulting occurred during the Late Jurassic-Early Cretaceous in the study area. A combination of fault-bend folding and forced folding produced the Flying Foam anticline. Forced folding occurred above the Murre fault, and fault-bend folding resulted from displacement on the detachment fault with a ramp-flat-ramp geometry on top of the Argo salt. This geometry resulted because the top of Package B (Argo salt) parallels the Mercury and the Murre faults, forming ramps and a flat between them. Along-strike differences in the displacement on the basin-bounding faults and temporal differences in the activity of these faults account for the different stratigraphic patterns observed in Package D.
References


Murphy, J. B., and Keppie, J. D. (1998), Late Devonian palinspastic reconstruction of the Avalon-Meguma terrane boundary: implications for terrane accretion and basin development in the Appalachian orogen, *Tectonophysics*, 284(3-4), 221-231.


Table 1. Main parameters of the 3D seismic data set from the Flying Foam area.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Number of inlines (E-W orientation)</td>
<td>1532</td>
</tr>
<tr>
<td>Number of crosslines (N-S orientation)</td>
<td>3150</td>
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<tr>
<td>Inline spacing</td>
<td>25 m</td>
</tr>
<tr>
<td>Crossline spacing</td>
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</tr>
<tr>
<td>Processing record length</td>
<td>9 s</td>
</tr>
<tr>
<td>Processing sample interval</td>
<td>4 ms</td>
</tr>
<tr>
<td>Nominal fold</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 2. Basic information from wells inside the area of study.

<table>
<thead>
<tr>
<th>Well name</th>
<th>Spud date</th>
<th>Well class</th>
<th>TD* (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Flying Foam L-23</td>
<td>07-Nov-1981</td>
<td>Exploratory</td>
<td>4554</td>
</tr>
<tr>
<td>Flying Foam I-13</td>
<td>26-Sep-1973</td>
<td>Exploratory</td>
<td>3683.2</td>
</tr>
<tr>
<td>Nautilus C-92</td>
<td>29-Sep-1981</td>
<td>Exploratory</td>
<td>5117</td>
</tr>
<tr>
<td>Mercury K-76</td>
<td>19-May-1985</td>
<td>Exploratory</td>
<td>5212</td>
</tr>
<tr>
<td>Thorvald P-24</td>
<td>24-Jun-1991</td>
<td>Exploratory</td>
<td>3810</td>
</tr>
</tbody>
</table>

* TD: Total Depth
Table 3. Summary of the tectonostratigraphic units present in the Flying Foam area, Jeanne d’Arc basin, offshore eastern Canada

<table>
<thead>
<tr>
<th>Packages and horizons</th>
<th>Seismic-reflection geometries</th>
<th>Name, lithology and age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Package E</td>
<td>Continuous, sub-parallel, low- to high-amplitude reflections</td>
<td>Banquereau Fm. (shales), Dawson Canyon Fm. (shales, limestones), Wyandot Fm. (chalks and marlstones) and Otter Bay Fm. (sandstones); Early Cretaceous – Recent (?) (CNLOPB, 2012; Deptuck, et al., 2003)</td>
</tr>
<tr>
<td>Horizon 4</td>
<td>Erosional truncation surface</td>
<td>Base of Paleogene unconformity</td>
</tr>
<tr>
<td>Package D</td>
<td>Continuous, low- to high-amplitude reflections; the geometry of the reflections vary from north to south and from west to east.</td>
<td>Ben Nevis Fm. (shales and some sandstones), Nautilus Fm. (calcareous shales). Avalon Fm. (sandstones), Whiterose Fm. (shales and limestones), Catalina Mb. (sandstones), Hibernia Fm. (sandstones), Fortune Bay Fm. (shales) and Jeanne d’Arc Fm. (sandstones); Late Jurassic – Early Cretaceous (CNLOPB, 2012; McAlpine, 1990; Sinclair et al., 1999)</td>
</tr>
<tr>
<td>Horizon 3</td>
<td>Inferred unconformity</td>
<td>Late Jurassic (Tithonian) unconformity</td>
</tr>
<tr>
<td>Package C</td>
<td>Continuous, mostly sub-parallel, low- to high-amplitude reflections</td>
<td>Rankin Fm. (limestones), Downing Fm. (shales with interbedded limestones) and Iroquois Fm. (dolomites and limestones); Early to Late Jurassic (?) (McAlpine, 1990; Sinclair et al., 1999)</td>
</tr>
<tr>
<td>Horizon 2</td>
<td>Top of salt</td>
<td></td>
</tr>
<tr>
<td>Package B</td>
<td>Chaotic and locally grading to low- to moderate-amplitude parallel reflections</td>
<td>Eurydice Fm. (continental red beds) and Argo Fm. (mainly salt); Late Triassic – Early Jurassic (?) (McAlpine, 1990; Sinclair et al., 1999)</td>
</tr>
<tr>
<td>Horizon 1</td>
<td>Inferred angular unconformity; poorly imaged</td>
<td>Late Triassic</td>
</tr>
<tr>
<td>Package A</td>
<td>No primary reflections</td>
<td>Pre-Triassic strata and basement (Sinclair et al., 1999)</td>
</tr>
</tbody>
</table>
Figure 1. a) Map of the eastern North America rift system showing location of the Jeanne d’Arc basin (blue polygon) and key tectonic features. Inset shows position of the rift system relative to Pangea during Late Triassic time. b) Regional transect from offshore Canada (location given by dashed line in a) showing key tectonostratigraphic features. Modified from Withjack et al. (2012).
Figure 2. a) Map of the Jeanne d’Arc basin highlighting the study area. Southern half of map shows faults cutting prominent Middle Jurassic reflection, and northern half shows faults cutting Aptian/Albian sequence (modified from Withjack and Schlische, 2005).

b) Regional cross section (location given by red line in a) showing tectonostratigraphic packages (capital letters and colors) and main structural features. Dashed lines and gradational colors show uncertainty. Regional cross section is based on seismic line HBV83-195 (Appendix 3), modified from Withjack and Schlische, (2005), and line B, this study. See location of line B in Figure 7 and interpreted line in Figure 13.
Figure 3. Lithostratigraphic chart of the Jeanne d’Arc basin highlighting tectonostratigraphic packages interpreted in this study (capital letters) and tectonic stages interpreted in previous studies. Modified from Sinclair et al. (1999) and Magoon et al. (2005). Results from my thesis work will show that Packages B, C and D are all syn-rift units.
Figure 4: a) Uninterpreted time-slice at 2.720 s. Box shows location of enlargement in b. b) Uninterpreted part of time-slice. c) Interpreted part of time-slice showing true reflections (green lines) and peg-leg multiples (dashed red lines).
Figure 5: (a) Part of seismic line C. (b) Interpreted line showing primary reflections (green lines), multiples (dashed red lines) and migration artifacts (black lines). Capital letters are tectonostratigraphic packages. See line location on Figure 7 and complete line in Figure 14.
Figure 6. Interpreted seismic line B (see location of line on Figure 7) showing key features. Colors represent tectonostratigraphic packages. Detached faults dip away from the cross section. Differences in the stratigraphic patterns in Package D are described in detail in section 5. H1, H2, H3 and H4 are mapped horizons. Gradational colors, dashed lines and question marks indicate uncertainty in the interpretation. Pa (Paleogene) and Ti (Tithonian) (CNLOPB, 2012) are unconformities recognized in wells converted from depth to time (see section 3.3).
Figure 7. a) Time-slice at 3.9s without interpretation showing location of selected seismic lines presented in this thesis.
Figure 7. b) Interpreted time-slice at 3.9 s showing the distribution of the tectonostratigraphic packages and structural features. The southern part of the area is mainly fault-dominated, whereas the central and northern parts are fold-dominated. H1, H2 and H3 are mapped horizons. Other letters and colors indicate tectonostratigraphic packages. Dashed lines and gradational colors indicate uncertainty.
Figure 8. Line drawings of seismic lines showing the along-strike structural variability in the study area from north to south. H1, H2, H3 and H4 are mapped horizons. Other capital letters and colors indicate tectonostratigraphic packages. Dashed lines, gradational colors and question marks indicate uncertainty. See location of dip lines in Figure 7.
Figure 9. Line drawings of seismic lines showing along-dip structural variability in the study area from west to east. H1, H2, H3, and H4 are mapped horizons. Other capital letters and colors indicate tectonostratigraphic packages. Dashed lines, gradational colors and question marks indicate uncertainty. See location of strike lines in Figure 7.
Figure 10. Time-slice at 3.0 s showing faults and folds. Gradational colors indicate uncertainty. Red circles are wells. Abbreviations for wells are: WFF, West Flying Foam; M, Mercury; N, Nautilus.
Figure 11. Seismic line B (see location of line on Figure 7) showing faults and axial planes of folds. See full interpretation of line in Figure 13.
Figure 12. a) Seismic line A without interpretation showing the location of intersecting strike lines. b) Time-slice at 2.640 s showing the location of line A. The time corresponds to the maximum TWT reached by all the wells in the study area.
Figure 12. c) Interpreted seismic line A showing tectonostratigraphic packages (A to E and colors) and key geologic features. H1, H2, H3 and H4 are mapped horizons. Dashed lines, gradational colors and question marks indicate uncertainty.
Figure 13. a) Seismic line B without interpretation showing the location of intersecting strike lines. b) Time-slice at 2.640 s showing the location of line B.
Figure 13. c) Interpreted seismic line B showing tectonostratigraphic packages (A to E and colors), key geologic features and wells with unconformities (Pa: Paleogene, Ti: Tithonian, CNLOPB, 2012). H1, H2, H3 and H4 are mapped horizons. Dashed lines, gradational colors and question marks indicate uncertainty.
Figure 14. a) Seismic line C without interpretation showing location of intersecting strike lines. b) Time-slice at 2.640 s showing the location of line C.
Figure 14. c) Interpreted seismic line C showing tectonostratigraphic packages (A to E and colors) and key geologic features. H1, H2, H3 and H4 are mapped horizons. Dashed lines, gradational colors and question marks indicate uncertainty.
Figure 15. a) Seismic line D without interpretation showing the location of intersecting strike lines. b) Time-slice at 2.640 s showing the location of line D.
Figure 15. c) Interpreted seismic line D showing tectonostratigraphic packages (A to E and colors), key geologic features and a well with unconformities (Ce: Cenomanian, CNLOPB, 2012). H1, H2 and H4 are mapped horizons. Dashed lines, gradational colors and question marks indicate uncertainty.
Figure 16. a) Seismic line E without interpretation showing the location of intersecting strike lines. b) Time-slice at 2.640 s showing location of line E.
Figure 16. c) Interpreted seismic line E showing numerous basement-involved faults and detached faults. H1, H2 and H4 are mapped horizons. Other capital letters and colors indicate tectonostratigraphic packages. Dashed lines, gradational colors and question marks indicate uncertainty.
Figure 17. a) Line F without interpretation showing the location of intersecting lines. b) Time-slice at 2.640 s showing the location of line F.
Figure 17. c) Interpreted line F showing tectonostratigraphic packages (A to E and colors) and key geologic features. H1, H2, H3 and H4 are mapped horizons. Dashed lines and gradational colors indicate uncertainty.
Figure 18. a) Line G without interpretation showing the location of intersecting lines. 
b) Time-slice at 2.640 s showing the location of line G.
Figure 18. c) Interpreted line G showing tectonostratigraphic packages (A to E and colors), key geologic features and wells with unconformities (Pa: Paleogene, Ti: Tithonian, CNLOPB, 2012). H1, H2, H3 and H4 are mapped horizons. Dashed lines and gradational colors indicate uncertainty.
Figure 19. a) Line H without interpretation showing the location of intersecting lines. b) Time-slice at 2.640 s showing the location of line H.
Figure 19. c) Interpreted line H showing tectonostratigraphic packages (A to E and colors) and key geologic features. H2 and H4 are mapped horizons. Dashed lines, gradational colors and question marks indicate uncertainty.
Figure 20. Time-slice at 3.0 s showing Package B in orange. H1, H2, H3 and H4 are mapped horizons. Other capital letters are tectonostratigraphic packages. Dashed black and grey lines and gradational colors indicate uncertainty. Red circles are wells. Abbreviations for wells are: WFF, West Flying Foam; M, Mercury; N, Nautilus.
Figure 21. a) Enlarged area from Figure 20 with Package B in orange. b) Cross section showing part of Line E with Package B in orange. Reflections diverge toward basement-involved faults. H1, H2 and H4 are mapped horizons. Other capital letters are tectonostratigraphic packages.
Figure 22. a) Line A interpreted with packages and faults. b) Enlargement showing diverging reflections in Package D and sub-parallel reflections in Package C. Horizon 3 separates the packages. H1, H2, H3 and H4 are mapped horizons. Other capital letters and colors are tectonostratigraphic packages. Gradational colors, dashed lines and question marks indicate uncertainty.
Figure 23. a) Line B highlighting Packages C and D in the hanging wall of the Murre fault. b) Enlargement shows onlap terminations (half-arrows) in Package D. H1, H2, H3 and H4 are mapped horizons. Other capital letters and colors are tectonostratigraphic packages. Gradational colors, dashed lines and question marks indicate uncertainty. (Pa: Paleogene; Ti: Tithonian, CNLOPB, 2012).
Figure 24. a) Line B highlighting Packages C and D in the hanging wall of the Mercury fault. b) Enlargement shows diverging and sub-parallel reflections in Package D and sub-parallel reflections in Package C. Horizon 3 separates both packages. H1, H2, H3 and H4 are mapped horizons. Other capital letters and colors are tectonostratigraphic packages. Gradational colors, dashed lines and question marks indicate uncertainty. Pa: Paleogene; Ap: Aptian; Ti: Tithonian (CNLOPB, 2012).
Figure 25. a) Line C highlighting Packages C and D in the hanging wall of the Murre fault. b) Enlargement shows diverging reflections in Package D. H1, H2, H3 and H4 are mapped horizons. Other capital letters and colors are tectonostratigraphic packages. Gradational colors, dashed lines and question marks indicate uncertainty.
Figure 26. a) Line D highlighting Packages C and D. b) Enlargement showing the characteristics of Package D. Notice the presence of the fault that detaches within Package B. H1, H2, H3 and H4 are mapped horizons. Other capital letters and colors are tectonostratigraphic packages. Gradational colors, dashed lines and question marks indicate uncertainty. Ce: Cenomanian (CNLOPB, 2012).
Figure 27. a) Line G highlighting Packages C and D. b) Enlargement showing sub-parallel reflections in Package D and diverging reflections in Package C. Horizon 3 separates both packages. H1, H2, H3 and H4 are mapped horizons. Other capital letters and colors are tectonostratigraphic packages. Gradational colors and dashed lines indicate uncertainty.
Figure 28. a) Line D highlighting Packages D and E. b) Enlargement showing reflection terminations that define Horizon 4. H1, H2 and H4 are mapped horizons. Other capital letters and colors are tectonostratigraphic packages. Gradational colors, dashed lines and question marks indicate uncertainty. Ce: Cenomanian (CNLOPB, 2012).
Argo Fm. -- bedded Lower Jurassic evaporites

Lower Jurassic basalt

NW SE

Cenomanian unconformity

Upper Triassic strata (possibly including evaporites)

Lower to Middle Jurassic strata

Upper Triassic strata

Displayed 1:1 at 4 km/s

Figure 29. a) Lithoprobe line 85-4A without interpretation showing the location of two wells (modified from Sinclair, 1995). b) Interpreted Lithoprobe line 85-A showing Lower to Middle Jurassic strata thickening toward a basement-involved fault (modified from Withjack and Callaway, 2000). Colors and capital letters are tectonostratigraphic packages. See location of line in Appendix 1.
Figure 30. a) Strike view of line G highlighting Package C. b) Enlargement showing the geometry of Package C flattened on H3. H1, H2, H3 and H4 are mapped horizons. Other capital letters are tectonostratigraphic packages. Dashed lines and gradational colors indicate uncertainty.
Figure 31. Line A highlighting Packages C and D, the ramp-flat-ramp that Horizon 2 forms and important features. Half arrows indicate direction of movement. H1, H2, H3 and H4 are mapped horizons. Other capital letters and colors are tectonostratigraphic packages. Gradational colors, dashed lines and question marks indicate uncertainty. See full interpretation in Figure 12.
a) Line D
- **Mercury fault**
- **Murre fault**
- **Syn-rift ductile layer**
- **Pre-rift ductile layer**
- **Pre-folding layers**
- **Syn-folding layers**
- **Forced fold and fault-bend fold anticline**
- **Numerous faults (?)**
- **Flat**
- **Ramp**

b) Line A
- **Mercury fault**
- **Murre fault**
- **Syn-rift ductile layer**
- **Pre-rifting ductile layers**
- **Pre-folding layers**
- **Syn-folding layers**
- **Forced fold and fault-bend fold anticline**
- **Numerous faults (?)**
- **Flat**
- **Ramp**

---

c) 3.57-cm displacement
- **YX**
- **Flat**
- **Ramp**
- **Forced fold anticline**
- **Syn-folding layers**

---
d) 5.66-cm displacement
- **YX**
- **Ramp**
- **Forced fold and fault-bend fold anticline**
- **Numerous faults**

---

Legend:
- **Clay added during deformation**
- **Clay added before deformation**
- **Silicone putty**
- **Metal base**
- **Mercury fault**
- **Forced fold anticline**
- **Syn-folding layers**
- **Future ramp**
- **Future flat**
- **Ramp**

Scale: 4 cm
Figure 32. Comparison between lines A and D and analog clay models. a) and b) show that Package C forms a forced fold and a fault-bend fold. Displacement on the Murre on line D is less than on line A. H1, H2, H3 and H4 are mapped horizons. Other capital letters are tectonostratigraphic packages. Dashed lines, gradational colors and question marks indicate uncertainty. See complete lines in Figures 15 and 12. Similarly, c) and d) show experimental clay models with differences in the displacement along a basement-involved fault (modified from Withjack and Callaway, 2000). The colors were chosen to match the colors of the tectonostratigraphic packages of the Flying Foam area.
Figure 33. Comparison between line A and a geometric model. a) Line A shows the ramp-flat-ramp geometry of the detached fault on top of Package B (Argo salt). See complete interpretation in Figure 12. Half arrows indicate direction of movement. Capital letters represent tectonostratigraphic packages. b) Geometric model showing the evolution of a fault-bend fold and a diachronous unconformity above a fault with a ramp-flat-ramp geometry (modified from Withjack and Schlische, 2006). Colors were chosen to match the packages in the Flying Foam area.
Figure 34. Restoration of the Flying Foam area based on line B (Figure 13) and line HBV83-195 (Appendix 3). H1, H2, H3 and H4 are mapped horizons. Other capital letters and colors indicate tectonostratigraphic packages. Dashed lines, gradational colors and question marks indicate uncertainty.
Figure 35. Schematic map-view representation of the syn-rift evolution of the Flying Foam region. H1, H2 and H3 are mapped horizons. Other capital letters are tectonostratigraphic packages. Dashed lines and question marks indicate uncertainty.

- **Early Cretaceous**
  - End of accumulation of Package D
  - Folding and detached faulting
  - Mercury and the Murre faults were active
  - Exact position of the Murre fault is uncertain

- **Late Jurassic**
  - End of accumulation of Package C
  - Mercury and the Murre faults were active

- **Early Jurassic**
  - End of accumulation of Package B
  - Mercury and other basement-involved faults were active
  - Unclear if the Murre fault was active

**Legend**
- Basement-involved faults (bar gives dip direction)
- Detached faults (bar gives dip direction)
- Doubly plunging anticline
- Doubly plunging syncline
- Plunging anticline
- Plunging syncline
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<th>Age</th>
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</tr>
<tr>
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<td>Post-rift</td>
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<td></td>
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<td></td>
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<td></td>
<td>C</td>
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<td>Post-rift</td>
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<td>Syn-rift</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>Pre-rift rocks</td>
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</table>

**Figure 36.** Lithostratigraphic chart of the Jeanne d’Arc basin highlighting tectonostratigraphic packages interpreted in this study (capital letters). Modified from Sinclair *et al.* (1999) and Magoon *et al.* (2005). Results from my thesis work show that Packages B, C and D are all syn-rift units.
Figure A-1: Map of the Jeanne d’Arc basin showing the main producing hydrocarbon fields, approximate location of wells in the study area and other wells of interest, and Lithoprobe seismic line 85-A. Abbreviations for wells are: WFF: West Flying Foam; FF: Flying Foam; M: Mercury; T: Thorvald; N: Nautilus. Modified from McAlpine (1990), Sinclair (1995) and http://www.worldoil.com/Jun-2000-International.html.
1995/6 Marine 3D Survey
Newfoundland Grand Banks
Final Processing Report
for
EXPLORATION SERVICES
Geco-Prakla

by

SCHLUMBERGER
GECO-PRAKLA
1325 South Dairy Ashford
Houston, Texas 77077
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    13.1 Average Amplitude Report.....................................49
1. Introduction

This report summarizes the processing of the Marine 3D survey in GRAND BANKS area, Newfoundland, Canada, by Geco-Prakla, Houston, in 1996. The survey was shot east-west by M/V Geco Diamond. The survey spanned in-lines 11 to 1518 and cross-lines 320 to 2921.
2. Acquisition Parameters

Shot by: Geco-Prakla Schlumberger
           July - September 1995

Boats: M/V Geco Diamond

Navigation: DGPS

Source:
  Configuration: Triple Airgun Array Flip/Flop/Flap
  Guns/Array: 18, subdivided into 3 strings
  Volume: 5400 cubic inches per array
  Pressure: 2000 psi
  Source Depth: 6 meters
  Source Separation: 50 meters
  Shot Interval: 25 meters
  Pop Interval: 75 meters

Streamer:
  Cable length: 4 x 4800 meters
  Streamer separation: 150 meters
  Group Interval: 25 meters
  Cable Depth: 9 meters
  Hydrophone per Group: 40
  Nominal Fold: 32

Recording System: NESSIE III

Field Filters:
  Low-cut: 3 Hz 18 dB/octave slope
  High-cut: 125 Hz 70 dB/octave slope

Record Length: 9.5 seconds
Sampling Interval: 2 ms

Processing Record Length: 9.0 seconds
Processing Sample Interval: 4 ms
3. Processing Resources

3.1 Personnel

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<thead>
<tr>
<th>Position</th>
<th>Name</th>
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<tbody>
<tr>
<td>Processing Manager</td>
<td>Mark Bull</td>
</tr>
<tr>
<td>Processing Supervisor</td>
<td>Tony Johns</td>
</tr>
<tr>
<td>Group Supervisor</td>
<td>Catherine Tsai</td>
</tr>
<tr>
<td>Geophysicist</td>
<td>Indro Lawu, Mike Fagg</td>
</tr>
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</table>

3.2 Software and Hardware

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<tr>
<th>Category</th>
<th>Description</th>
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<tr>
<td>Software</td>
<td>Gecoseis System</td>
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<tr>
<td>Hardware</td>
<td>Fujitsu VPX240, Sun Workstation</td>
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### 4. Processing Parameters

#### 4.1 Grid Orientation

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<tbody>
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<tr>
<td>Y-coordinate of in-line 1 cross-line 1</td>
<td>5226665</td>
</tr>
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</table>
4.2 Processing sequence

4.2.1 Resample
Resample data from 2 ms to 4 ms with a 90 Hz 72 dB/octave high-cut filter.

4.2.2 Editing
Bad traces and/or shots flagged by Field Observers were deleted from the dataset.

4.2.3 Spherical Divergence Correction
Spherical divergence effects were removed by computing a scalar for each time sample from the following formula:

- \( Scalar = T^2 (V_T/V_0)^2 \)
- \( T = \text{seismic two-way time in seconds.} \)
- \( V_0 = \text{RMS velocity at time zero in meters/second.} \)
- \( V_T = \text{RMS velocity at time } T \text{ in meters/second.} \)

The following velocity function was used for the above calculation:

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Velocity (m/sec)</th>
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<td>3.500</td>
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<td>4483</td>
</tr>
<tr>
<td>8.000</td>
<td>4509</td>
</tr>
</tbody>
</table>
4.2.4 Exponential Gain Correction

Exponential gain was applied to compensate for amplitude decay with time. The gain applied to the data for a sample at any time was determined by the following functions:

for \( 0.2 < T < 4.0 \)

\[
Gain = e^{at}
\]

where,

\( a = (a \text{ user specified exponential gain value in dB/sec}) \times \ln(10)/20 \). The user specified exponential gain value was +3 dB/sec.

\( T = t - t_0 \), where \( t \) is the sample time and \( t_0 \) is the start time for the gain function in seconds. The gain calculated at 4.0 seconds was applied to the end of the trace.

4.2.5 Source Signature and Instrument Compensation

An inverse filter was designed by Trilogy to convert the recorded source signature into a band limited minimum phase wavelet. The characteristics of this output wavelet were as follows:

- Low cut filter and slope: 6 Hz, 50 dB/octave
- High cut filter and slope: 85 Hz, 90 dB/octave

This inverse filter was applied to the shot record data for removal of the known component of source wavelet before predictive deconvolution. See Section 12, Figure 1, for the production designature operator and Figure 2 for the conditioned gun signature.

4.2.6 3-D XY Coordinate Merge

Cable position information from the processed navigation data was merged with the seismic data.

4.2.7 Prestack Predictive Deconvolution

Trace by trace predictive deconvolution was applied to further whiten the spectrum and to suppress reverberations. Based on the results of Trilogy testing, the following decon parameters were selected for production processing:

- Design window length: 6000 ms
- Operator length: 320 ms
- Gap length: 4 ms
- Prewhitening: 0.1% 

A job setup for the Deconvolution is attached in Sec. 11.1
4.2.8 Automatic Trace Editing

Data with anonymously large amplitude were edited prior to DMO stacking. From the tests performed, sample values above 10 could be identified as noise spikes for shot data. The near and far windows for this analysis were 1000-9000ms and 4500-9000ms, respectively. Whenever a sample above amplitude 10 was encountered in a window, a mute was applied from the previous sample to the end of the trace.

4.2.9 3-D Elastic Binning

The navigation information was extracted from the merged decon trace headers to generate coverage of the 3-D survey. The coordinates of each data trace were analyzed and each trace was assigned the following information:

- In-line bin number
- Cross-line bin number
- Micro-bin numbers (two values)
  Each bin was subdivided into a 100 X 100 grid. Micro-inline and micro-cross-line numbers were assigned from this micro-grid.
- Offset group (32 offset group numbers defined)
  Offset group 1 being the near, group 32 being the far.

Five values were used to uniquely define a trace and tabulate binning statistics. From this information five tables were made.

- Total number of traces in each bin with All offset groups 1 - 32.
- Total number of traces in each bin with Nears offset groups 1 - 8.
- Total number of traces in each bin with MidNears offset groups 9 - 16.
- Total number of traces in each bin with MidFars offset groups 17 - 24.
- Total number of traces in each bin with Fars offset groups 25 - 32.

The coverage plots constructed from these tables reflect the actual live seismic data.

Because the binning was constructed from the merged decon trace headers, any missing and edited bad shots and traces were not included in the binning process. Elastic binning and redundancy editing trials were then performed. Each bin was searched in each offset group in an attempt to achieve a nominal 32-fold coverage throughout the survey, with maximum one trace contributing to each of the 32 allowed offset groups. If a particular bin contained more than one trace per offset group, the one trace closest to the bin center was accepted. If a particular bin and offset group contained no traces, adjacent bins were searched for traces in that offset group. If the traces found were within a user specified distance from the boundary of the primary bin, these traces were borrowed and allowed to stack into the bin. The user specified distances were expressed in terms of percentage of cross-line bin size. In this survey the cross-line bin size was 25 meters. A maximum of 2 traces per offset group were allowed in order to obtain nominal 32 fold.
Supergroups were used to describe groups of offset groups to be taken together for flexible redundancy editing. In this survey, the supergroups defined were: offsets 1-8, 9-16, 17-24, and 25-32 with each supergroup having a minimum fold requirement of 8. If normal flexing did not get enough traces in the supergroup to meet the minimum fold requirement, one additional trace from each group (1-32) which has surplus traces was accepted until the minimum fold was met.

Bin expansion tests were conducted at four parts of the survey area at 10, 20, 30 and 40 % respectively. The five coverage plots were once again generated and from these plots the following elastic binning parameters were chosen:

- For all offset groups: 40% bin expansion in cross-line direction. This expanded the cross-line bin size by 10 meters either side, from 25 meters to 45 meters.
- The five coverage plots were once again generated for the final binning table.

### 4.2.10 Normal Moveout

Normal Moveout was applied to the data using a fully interpolated 3-D velocity cube. See Sec. 10.1 "Stacking Velocity Field".

### 4.2.11 First Break Suppression

The data was muted in the following manner:

- Offsets up to 575 meters were not muted.
- Offset of 576 meters was muted at 500 ms.
- Offset of 5200 meters was muted at 4200 ms.

Mute times for offsets between the above offsets were calculated by linear interpolation.

### 4.2.12 3-D DMO and Stack with Elastic Binning

Common azimuth DMO was performed on the data. The procedures were as follows:

The final stack volume was allocated on disk. As traces were used, the DMO operator for each trace was calculated along the source to receiver azimuth.

The primary trace was stacked into the midpoint bin and stacking normalization information was recorded for that bin. The DMO energy traces were stacked into their proper bins but no normalization information was recorded.

As the traces were processed they were checked against the binning information. Redundant traces were discarded and flexed traces were copied if they were flagged as such by the binning information.

When all the data had gone through DMO/stacking procedure the normalization information was utilized to scale each sample of every trace by the inverse of the square root of the number of primary and flexed traces that contributed to the sample in question. This normalization scheme was used to scale down low fold areas that had poor signal to noise ratios. A job setup for 3-D DMO and stack with Elastic Binning is attached in Sec. 11.2.
4.2.13 In-line K-Filter
A k-filter was applied to remove aliased noise in the in-line direction caused by acquisition geometry. The filter was applied fully from 0.0 - 3.0 seconds and tapered off at 4.0 seconds. A job setup for In-line k-filter is attached in Sec. 11.3.
A sample of the Stack Timeslice at 2.0 sec is shown in Section 12, Figure 3.

4.2.14 3-D FXY-filter
3-D fxy-filter was applied to attenuate random noise. A job setup for 3-D fxy-filter is attached in Sec. 11.4.
A sample of the Stack Timeslice at 2.0 sec is shown in Section 12, Figure 4.

4.2.15 Datuming
A static shift of +12 ms was applied to the stacked data to compensate for the depth of source and the streamers below mean-sea-level.

4.2.16 One Pass Phase Shift Migration
Upon completion of various 2-D migration tests with different velocity reduction percentages of the RMS stacking velocities, the following parameters were used:

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The following frequency and dip limits were used:

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<table>
<thead>
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</thead>
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<tr>
<td>0.0</td>
<td>60</td>
</tr>
<tr>
<td>3.0</td>
<td>60</td>
</tr>
<tr>
<td>6.0</td>
<td>40</td>
</tr>
<tr>
<td>9.0</td>
<td>10</td>
</tr>
</tbody>
</table>
After the parameters were picked on the 2-D tests, the southern half of the 3-D data-set, (in-line range 780-1532, cross-lines 1-3200), was migrated and provided as a preliminary deliverable to the underwriters on June 30th.

During the QC of the initial 3-D migrated volume there were some regions that were discovered to be slightly under-migrated.

Residual migration tests were performed using 103% and 106% of the above time-variant velocity reduction. These tests indicated that increasing the original reduction by 3% yielded improved imaging.

The following final velocity reductions of the RMS stacking velocities were used for the final 3D migration:

<table>
<thead>
<tr>
<th>Time (seconds)</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>103</td>
</tr>
<tr>
<td>4.0</td>
<td>103</td>
</tr>
<tr>
<td>6.0</td>
<td>97.9</td>
</tr>
<tr>
<td>9.0</td>
<td>87.6</td>
</tr>
</tbody>
</table>

The phase shift migration uses a spatial operator, which allows accurate treatment of dips and gives a full 3-D operator. Since this operator must be laterally invariant, the data is stretched prior to the migration to accommodate lateral changes in velocity. The stretch function is computed by using a nonlinear optimization method developed at Geco-Prakla. Vertical velocity variations are handled exactly by the phase shift method without stretching.

A spatially and temporally smoothed interval velocity cube was used for input into this optimization algorithm. See Sec. 10.2 "Migration Velocity Field".

The phase shift migration was applied in the following 3 steps:

- The first step reads the unmigrated data by in-lines, stretches the data, and transforms the data into wave number domain over the in-line dimension, after padding to prevent wrap-around. A job setup for Step-I is attached in Sec. 11.5.
- The second step transforms the data in time and in the cross-line direction, performs the migration, and then inverse transforms the data over time and cross-line. A job setup for Step-II is attached in Sec. 11.6.
- The third step reads the data from Step-II by in-lines, inversely transforms the data over the in-line dimension and unstretches the data. A job setup for Step-III is attached in Sec. 11.7.

See Section 12, Figure 5 for the Quicklook cube Migration at 2.0 seconds.
See Section 12, Figure 6 for the Final Migration timeslice at 2.0 seconds.
5. Final Products

5.1 Film displays

5.1.1 In-line AGC 3-D migration
Every 1500 meters (every 60th in-line) from in-line 61 to 1501 at 1:36,000 scale.

5.1.2 In-line RAP 3-D migration
Every 1500 meters (every 60th in-line) from in-line 61 to 1501 at 1:36,000 scale.

5.1.3 Cross-line AGC 3-D migration
Every 1500 meters (every 120th cross-line) from cross-line 360 to 2880 at 1:36,000 scale.

5.1.4 Cross-line RAP 3-D migration
Every 1500 meters (every 120th cross-line) from cross-line 360 to 2880 at 1:36,000 scale.

5.1.5 Timeslices
Every 200 ms of the final migrated volume from 0.2 - 6.0 sec. and every 1000 ms from 0.5 to 5.5 sec. at 1:48,000 scale.

5.2 Versatec displays

5.2.1 Binning/Index/Grid Plots
All, Nears, MidNears, MidFars, and Fars offset groups for edited and flexed index at 1:48,000 scale.
5.3 Deliverables on Tape

5.3.1 Decon SEGY Tapes
With navigation merge and designature filter applied.

5.3.2 Grid file SEGY Tapes
All, Nears, MidNears, MidFars, and Fars Offset groups from edited and flexed Index.

5.3.3 Binning/Index Offset groups FBKUP tapes
Edited and flexed index.

5.3.4 3-D Stack SEGY tapes
In-line ordered, with K-filter, 3D FXY-filter and +12 ms static shift applied.

5.3.5 3-D Migration SEGY tapes
In-line ordered.

5.3.6 3-D Migration SEGY tapes
Cross-line ordered.

5.3.7 3-D Migration SEGY film tapes
In-line ordered, every 60th in-line, from row 61 through to row 1501.

5.3.8 3-D Migration SEGY film tapes
Cross-line ordered, every 120th cross-line, from column 360 through to column 2880.

5.3.9 3-D DMO Gather SEGY tapes
Used in the velocity analysis for all 47 velocity lines.

5.3.10 Migration Timeslice Gather SEGY tapes.
Gathers are every 200ms from 0.200 - 6.000secs and every 1000ms from 0.500 - 5.500secs.
5.3.11 Migration Velocity Cube Timeslice SEGY tapes.
Every 200ms to 6.000secs.

5.3.12 Stack Velocity Cube Timeslice SEGY tapes.
Every 200ms to 6.000secs.

5.3.13 Following 8 mm velocity tapes:
- Navigation datasets in G2000 format.
- Stacking RMS velocity VBASE - ASCII format
- Stacking RMS velocity VCUBE 200*250 meter grid. i.e. every 8th row & every 20th column - ASCII format.
- Migration interval velocity VCUBE 200*250 meter grid. i.e. every 8th row & every 20th column - ASCII format.
- Migration interval velocity (with percentage reduction scheme applied) VCUBE 200*250 meter grid. i.e. every 8th row & every 20th column - ASCII format.
- Migration Interval velocity VBASE - ASCII format.
- Decon Reel dbase and Edit files.
- Spectra contour, CDP, and MVFS for all 47 velocity lines.

5.3.14 Floppy diskette.
Containing:
- source signature.
- designation operator used in the processing.
6. Line Statistics

Grand total mileage for the entire survey was 62643 kilometers.

System: X
apint * apint * noch * foep*
75.0 25.0 384 1
seq * punt * navn *** el *** sp * rsi * lap * freel * freel * noch * nb * bpt * dir * navn
96
7. Processing Time Line

<table>
<thead>
<tr>
<th>Process</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decon</td>
<td>August-December 1995</td>
</tr>
<tr>
<td>Elastic Binning</td>
<td>April - May 1996</td>
</tr>
<tr>
<td>Velocity</td>
<td>January - April 1996</td>
</tr>
<tr>
<td>DMO Stack</td>
<td>May - June 1996</td>
</tr>
<tr>
<td>Migration</td>
<td>July 1996</td>
</tr>
</tbody>
</table>
8. Notable Processing Problems and Solutions

The benefits from the decision to rebuild the Index from seismic headers instead of using the G2000 navigation files delivered from the Calgary center were not realised until stack production. After 34% of the southern priority area was stacked, it was discovered that the 'dpr' files generated from the G2000 did not agree with the seismic trace headers which created the index file. This discrepancy caused a significant amount of traces to be dropped from the stack. After discussing the problem with the DP support group, stack production resumed by using a processor 'dmgbf' which circumvented the input of dpr files. As a consequence, an initial delay of 1 week was encountered, but was later recovered from the assignment of additional cpu resources.

9. Conclusion

Houston DP inherited this project from the Calgary DP Center in late March 1996 when the original deadline was due. After reviewing the previous processing, it soon became obvious that the Index had to be rebuilt from scratch and the velocities had to be partially re-run and completely re-picked. However, with the support of the DP management and from the great effort of the processing group, we were able to deliver the Migrated Volume of the Southern priority area of the survey on June 30, while continuing to stack the Northern half. Finally, by the end of July 1996, as promised, the final migration of the entire volume was delivered.

Due to the widespread deployment of the four streamer and triple source array, the shallow data was heavily contaminated by aliased noise. In fact, the data volume as a whole had a relatively poor signal/noise ratio. It was deemed necessary to apply, post-stack, a shallow in-line K-filter in conjunction with a 3-D FXY noise attenuation filter over the entire record length.

Figures 3 & 4 in Section 12 illustrate the results with and without the 3-D FXY noise attenuation filter.

Also shown in Section 12, Figures 5 and 6 are the timeslices from the QuickLook Cube migration (QLC) and the Final migrated volume, respectively. These timeslices are both at 2.0secs and clearly demonstrate the improvements attained from the final processing sequence.
10. 3-D Velocity Fields

10.1 Stacking Velocity Field

The 3-D stacking velocity field was generated using velocities derived by performing 3-D velocity analysis at selected in-line locations on the 3-D grid. The velocities were to be calculated on an 800 X 800 meter grid. Since the data was acquired with a subsurface line spacing of 25 meters, this required that every 32nd row location be processed in 3-D mode as a velocity line, starting with row 25. The following is a list of the velocity lines that were used for this survey:


The DMO gathers were created on Fujitsu for above velocity lines and transferred to the Geoc-Prakla Sun Workstation for velocity analysis. Finally, 2-D DMO stacks were generated to verify velocity interpretation. The stacks were created by using data acquired closest to the velocity row location, merging data with navigation and then stacking into 3-D grid which was allocated with wide bins.

Once all the velocities analyses had been interpreted and approved, a 3-D velocity database was constructed. According to the grid definition, the in-line position and the cross-line position, each velocity location was assigned the proper X, Y coordinate. In order for our program to properly build a velocity cube, the input grid of velocity cube completely covered the survey, the rectangular grid was defined to cover cross-line 1 through 3200 and in-line 1 through 1532. The first and last functions for each velocity line were repeated to cover this area. Once this velocity database was built, velocities were interpolated in time and space.

Temporal resampling to a regular time increment was done first, such that each function now had 76 velocity picks (i.e. 76 velocity timeslices). Each timeslice was then interpolated to fill in all intermediate points. Interpolation of the timeslices was done in the following manner:

1. Calculate the midpoint bin number of the four velocities on the regular rectangle bounded input velocities \( V_{i,j} \), \( V_{i+1,j} \), \( V_{i,j+1} \), \( V_{i+1,j+1} \), where \( i \) is the in-line number and \( j \) is the cross-line number.

2. Calculate the average velocity of these four velocities weighted by the inverse of the distance to the midpoints.

3. Linearly interpolate between known input points in the in-line direction.

4. Linearly interpolate between known input points in the cross-line direction.

5. Linearly interpolate the midpoints calculated in step 2 in the in-line direction.

6. Linearly interpolate the midpoints calculated in step 2 in the cross-line direction.

7. Linearly interpolate points along every 64 cross-line.

8. Linearly interpolate remaining points in the in-line direction.
10.2 Migration Velocity Field

The migration velocity field was constructed in a similar fashion. This procedure started with the temporally resampled database that was used for the stacking velocity cube. Before spatial interpolation of the functions, the velocities were converted to interval velocities. In addition, these interval velocity functions were temporally smoothed by fitting the time velocity points to a ninth order polynomial. This ensured that there were no unreasonably large temporal velocity changes in the interval velocity functions. These smoothed interval velocity functions were then spatially interpolated as above. After spatial interpolation, a four-pass recursive smoothing filter was applied to the velocity cube. This recursive filter operated in the following manner:

1. Each bin was summed with the previous bin in the cross-line direction with the following weights: 0.1 for the current bin and 0.9 for the previous bin. The resultant velocity was immediately written back to the current location. This procedure was repeated at next location and continued until all bins were mixed. The direction of mixing was from highest in-line number to lowest in-line number.
2. Same as in 1, but done from lowest in-line number to highest in-line number.
3. Same as 1, but in the in-line direction from highest cross-line number to lowest cross-line number.
4. Same as 3, but from lowest cross-line number to highest cross-line number.
11. Job Setups for Main Processing Steps

11.1 A job setup for Deconvolution

/job acct '7263 nftp0557 explserv segystbd'
    trdcntl '/proj/nav/cntl/g2s0731.cntl'

/seisin format segd datafmt 8015
data 1 9000 2 384 0
dens hc
exthdr 12
extprint
errtype 2
nодумmy conskip 999999 totskip 999999
reel 1816
    reel 1817
    reel 1818
    reel 1819
    reel 1820
    reel 1821
    reel 1822
    reel 1823
    reel 1824
    reel 1825
    reel 1826
    reel 1827
    reel 1828
    reel 1829
    reel 1830
    reel 1831
    reel 1832
    reel 1833
    reel 1834
    reel 1835
    reel 1836
    reel 1837
    reel 1838
    reel 1839
    reel 1840
    reel 1841
    reel 1842
    reel 1843
    bi 1252 ei 2409
    /revfiles
device 'rmt1'
    ftraces d9,200,1 d201,392,1
    (port ftraces d1,192,1 d201,392,1
    reseq 1
/
/deadset
/filter butterwo lowpass minimum filt 90 72 nfpts 121
/resamp sro 4 noalias

[@zero
/zero ftraces 200
/zero ffiles 1278 1353 2219
  1 2 3 4 5 6
(2345678901234567890123456789012345678901234567890)
(nf-1p0557  FSP  LSP  1.0  PTR  LTR
(nf-1p0557  200  200
(nf-1p0557  1278  1278  1.0
(nf-1p0557  1353  1353  1.0
(nf-1p0557  2219  2219  1.0
(2345678901234567890123456789012345678901234567890)

( add 384 to port cable only to match p190s and make each kfldtn unique:
/glmod add kfldtn -8 0
(port /glmod ftraces d201,392,1 add kfldtn -8 0
(port /glmod  add kfldtn 384 0
/sphdiv vel
4000. 3548. 4500. 3749. 5000. 3920. 5500. 4076.
6000. 4218. 6500. 4335. 7000. 4450. 7500. 4483.
8000. 4509. 8500. 4509. 9000. 4509
/tstop 8000
/expgain begtime 1 200 9999 200 endtime 1 4000 9999 4000 expfunc +3.0
/filter filename '/data11/desig/designature'
/mr3d mexrskip 300000
detnum 768
dusflflt
navshots 1252 2409
mxpskip 999
mxspdtlt 30
timediff 2
todmerge
(s1dfmt '(i8,2x)'
line 'nf_1p0557'
'these blank spaces are needed to make it
work..

/preddcon zone 1
operator  1 6000 320  4
operator 9999
design  1 260 400 5050 4700
design 9999
apply  1 260 0 5050 0
apply 9999
prewhite 0.1
byfile
/glmod set kgrrow 0557,0
/glmod set lld nfp kgrrow
(this is optional to stop /output putting all reel numbers as "SCRTCH":
/hdrsegg cardnum 3
/contents 'C 3 REEL NO 1p0557 DAY_START OF REEL YEAR OBSERVER'
/output iname '1p0557' dens hc segyhead gecostr
device rmt2
segyst "/proj/gss/jobs/segy/newf_template"
noreset
/eo
11.2 A job setup for 3-D DMO and Stack with Elastic Binning

/job
acct '0489 g30a nfgb dms'
runcode 0
/system vpx220
division f
/region 84 Mb
/jobtick
submitby 'group11'
runtime 5.0
inreel 'D00987'
inreel 'D00988'
inreel 'D00989'
inreel 'D00990'
inreel 'D00991'
process 'dmbsd'
userinst '**** NEW FOUNDLAND ***'
userinst '
userinst 'RUN ONE JOB AT A TIME'
userinst '**** dmo stack ********'
dsnn '/prcd/dmstk/b4dmstkzg30a.s'
/trdfile
use stack ctrlname '/SDP248/grp11/p489/stack.cntl'
use index ctrlname '/SDP366/grp11/p489/index.cntll'
jobrows 759 797
jobcols 1 3200
/seisin
data 5 9000 4 384 0
EOFcount 2
dens silo
reel D00987
reel D00988
reel D00989
reel D00990
reel D00991
byfield
reseq 1
/deadset
getwcl
xorigin 645410 yorigin 5226665
basangle 88.34 sidangle 178.34
rowsize 25.0 colsiz e 12.50
nombinsx 100 nombinsy 100
maxgrdcl 3200
setclp
setsta
/dmbgf
contfile '/SDP213/grp11/p489/dmbt.cntl'
xorigin 645410 yorigin 5226665
basangle 88.34 sidangle 178.34
rowsize 25.0 colsiz e 12.50
newline 'lp0857 A'
print 30
/dmbscd
contfile '/SDP213/grp11/p489/dmbsd.cntl'
mappedr 1200
firstrow 763
lastrow 793
firstcol 1
lastcol 3200
xorigin 645410 yorigin 5226665
basangle 88.34 sidangle 178.34
rowsize 25.0 colsiz e 12.50
/tranalys
  offset 265 5040 thres 10.0 firstspk
  nearwind 1000 9000
  farwind 4500 9000
  taper 200
/zveloci
  threed
  rmsvels
  notintri
  rdsreed 0 100 9000 100
  maxrow 1532
  maxcol 3200
  vcubemam 'dsn=/SDP238/grp11/p489/vcub489.cntl;'
/nmo
/mute
  fmute 1 0+0 575+0 576+500 5200+4200
  fmute 9999999 0+0 575+0 576+500 5200+4200
  taper 20
/deadset
  usegcom
  (fmute and tmute in headers applied to trace samples)
/dmbtd
  stkcntl '/SDP248/grp11/p489/stack.cntl'
  contfile '/SDP213/grp11/p489/dmbtd.cntl'
  filetype stack
  (restart
  boundary 1 1 1532 1 1532 3200 1 3200
  1 1
  firstrow 763
  lastrow 793
  firstcol 1
  lastcol 3200
  feather 200
  numbins 5500
  unnorm
  (printbnd use for first dmo run only
/eoj
11.3 A job setup for In-line k-filter

/job
acct '0489 norm nfgb dms'
(runcode 0
(system vpx220
(priority 8
(dvision e
/jobtick
submitby 'cathy'
(runtime 3.5
(process 'norm'
/userinst '*** NEW FOUNDLAND**'
/userinst 'DMO STACK'
/userinst 'NORMALIZE CUBE'
/userinst 'row 001-200'
/userinst '?????????????'
/dsn 'gss/jobs/prod/norm/blnormals.s'
/trdfile
/use stack
ctrlname '/SDP248/grp11/p489/stack.cntl'
jobrows 001 200
jobcols 1 3200
/stkin
data 4 9000 4 1 0
rows 1 200 1
cols 1 3200 1
/use stack
root
xorigin 645410 yorigin 5226665
basangle 88.34 sidangle 178.34
rowsize 25 colsize 12.5
/deadset
/glmod
set kcdp 1 1
/filtwod
nxfilt 25 ntfilt 1
timegate 0 0 3000 4000
kfilt -43 -38 -28 -23
reject costaper
/filtwod
nxfilt 25 ntfilt 1
timegate 0 0 3000 4000
kfilt -76 -71 -61 -56
reject costaper
/filtwod
nxfilt 25 ntfilt 1
timegate 0 0 3000 4000
kfilt -110 -105 -95 -90
reject costaper
/deadset
/stkout
/useglcom
client 'exp services'
area 'n foundland'
use stack
firstrow 1 lastrow 779
firstcol 1 lastcol 3200
/eoJ
11.4 A job setup for 3-D FXY-filter

/job
acct '0489 rowqc nfgb dms' plotevry 1
rcode 0
/system vpx220
division e
/priority 8
/region 60 Mb

/jobtick
submitby 'indro'
runtime 1.30
/process 'fxr'
userinst '***newfoundland***'
userinst 'fxr dcm'
userinst '*******************'
/dsn 'gss/jobs/test/b0fxyl.s'

/trdfile
use stack
ctrlname '/SDP248/grpl1/p489/stack.cntl'
jobrows 211 278
jobcols 1533 3200

/stkin
data 4 9000 4 1 0
rows 211 278 1  (insert correct row range
cols 1533 3200 1
root
bycol
xorigin 645410 yorigin 5226665
basangle 88.34 sidangle 178.34
rowsize 25 colsiz 12.5

/deadset
/renumber firstcdp 1

/xfyfilt
ilwind 20
xlwind 20
lenfil 5 (default 3 ,recomm
ilovlp 10
xlovlp 10
lowfreq 0
highfreq 75
nscalwin 10
bycol

/deadset useg1com
/stkout
client 'exp services'
area 'n foundland'
use stack
firstrow 1 lastrow 1532
firstcol 1 lastcol 3200

/eoj
11.5 A job setup for Migration Step-I

/job
acct '0489 1225 nfgb mig'
(runcode 0
(system vpx220
(priority 8
(region 110Mb
(division E
/jobtick submitby 'nicolas'
runtime 5.00
inreel 'disk'
outreel 'no/op'
process 'mig'
userinst '******nfgb*****'
userinst 'migration step 1'
userinst '!!! check memory before'
userinst 'starting job!!'
userinst '******nfgb*****'
dsn 'N/A'
/trdfile
use mig
ctrlline '/SDP248/grp11/p489/mig.cntl'
jobrows 1051 1225 (reading in 175 in-lines
jobcols 1 3750 (full range including padded zone
/data 4 9000 6 1 0 (without stretch
use mig
rows 1051 1225 1 (reading in 175 inlines
cols 1 3200 1 (full range excluding padded zone
/renumber firstcdp 1
/deadset
/mgtda
qc
unit '3380'
volser 'SDP388'
resfile '/SDP388/grp11/p489/mgtdap1_1225.log'
wrkfile '/SDP388/grp11/p489/mgtdap1_1225.wrk'
hdrfile '/SDP388/grp11/p489/mgtdap1_1225.hdr'
atap 20 (default is 30
vmax 0 (0 for steps 1 and 3 otherwise 5000.0
use mig
flagtd
byrows (byrows or bycols
firstrow 1051 (first row for job
lastrow 1225 (last row for job
firstcol 1
lastcol 3200 (excluding padding
delrow 25.0
delcol 12.5
anone 0.5
antwo 1.5
anthree 65
(anfour 75 2.0 70 4.0 50 6.0 40 9.0 30
anfour 75
angm 60 3.0 60 6.0 40 9.0 10
(bmem 0.4
padt 2.0
interval
fracv 3.0
dtrms 200
ivpt 1 (step number 1 2 or 3

Page 31 of 51
<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>nrows</td>
<td>1532</td>
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<tr>
<td>ncols</td>
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<td>1501</td>
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</tr>
<tr>
<td>mincol</td>
<td>1</td>
</tr>
<tr>
<td>oppam</td>
<td>0 4 4 4</td>
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<td>opcoef</td>
<td>2.6885530025518318e-12</td>
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<tr>
<td></td>
<td>2.1290515836198131e-09</td>
</tr>
<tr>
<td></td>
<td>9.8991836409524095e-10</td>
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<td></td>
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<td></td>
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<td></td>
<td>-2.9293642775904404e-05</td>
</tr>
<tr>
<td></td>
<td>-1.9399556181001961e-08</td>
</tr>
<tr>
<td></td>
<td>1.5356500315522706e-06</td>
</tr>
<tr>
<td></td>
<td>-3.0044565226616910e-05</td>
</tr>
<tr>
<td></td>
<td>2.0466111784319987e-04</td>
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</tr>
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-1.0515828579203047e-06
3.3027604263354205e-05
1.466985990807825e-04
1.8936469885501221e-02

(pilot interval velocities follow)

v

pilot (reduced pilot velocity function)

1561.48 (at 0.00000000e+00 milliseconds)
1591.35 (at 199.99992 milliseconds)
1701.56 (at 399.99976 milliseconds)
1849.88 (at 599.99976 milliseconds)
1992.02 (at 799.99976 milliseconds)
2135.19 (at 999.99976 milliseconds)
2314.41 (at 1199.99976 milliseconds)
2520.41 (at 1399.99976 milliseconds)
2755.25 (at 1599.99976 milliseconds)
3005.54 (at 1799.99976 milliseconds)
3257.89 (at 1999.99976 milliseconds)
3504.06 (at 2199.99976 milliseconds)
3735.81 (at 2399.99976 milliseconds)
3953.14 (at 2599.99976 milliseconds)
4163.26 (at 2799.99976 milliseconds)
4332.18 (at 2999.99976 milliseconds)
4475.35 (at 3199.99976 milliseconds)
4617.49 (at 3399.99976 milliseconds)
4724.61 (at 3599.99976 milliseconds)
4818.34 (at 3799.99976 milliseconds)
4916.19 (at 3999.99976 milliseconds)
4727.63 (at 4199.99976 milliseconds)
4775.36 (at 4399.99976 milliseconds)
4828.32 (at 4599.99976 milliseconds)
4890.72 (at 4799.99976 milliseconds)
4930.20 (at 4999.99976 milliseconds)
4994.20 (at 5199.99976 milliseconds)
5043.84 (at 5399.99976 milliseconds)
5064.38 (at 5599.99976 milliseconds)
5100.93 (at 5799.99976 milliseconds)
5110.71 (at 5999.99976 milliseconds)
4915.52 (at 6199.99976 milliseconds)
4882.66 (at 6399.99976 milliseconds)
4883.82 (at 6599.99976 milliseconds)
4757.56 (at 6799.99976 milliseconds)
4663.44 (at 6999.99976 milliseconds)
4574.28 (at 7199.99976 milliseconds)
4454.18 (at 7399.99976 milliseconds)
4353.84 (at 7599.99976 milliseconds)
4260.69 (at 7799.99976 milliseconds)
4190.87 (at 7999.99976 milliseconds)
4106.28 (at 8199.99976 milliseconds)
4021.91 (at 8399.99976 milliseconds)
3930.85 (at 8599.99976 milliseconds)
3838.66 (at 8799.99976 milliseconds)
3746.56 (at 8999.9961 milliseconds
3746.56 (repeat last velocity for stretch
3746.56 (9400 milliseconds
3746.56 (9600 milliseconds
3746.56 (9800 milliseconds
/stkout use mig
client 'expl'
area 'nfgb'
firstrow 1051 lastrow 1225
firstcol 1 lastcol 3750 (including padding
/eoj
11.6 A job setup for Migration Step-II

/job
acct '0489 3000 nfgb mig'
(runcode 0
(system vpx220
(priority 8
(region 110Mb
(dvision G
/jobtick
submitby 'nicholas'
runtime 6.00
inreal 'disk'
outreal 'no/op'
process 'mig'
userinst '******nfgb*****'
userinst 'migration step 2'
userinst '!!! check memory before'
userinst 'starting job!!'
userinst '******nfgb*****'
dsni 'N/A'
/trdfile
use mig
ctrlname '/SDP248/grp11/p489/mig.cnt1'
jobrows 1 1532 (reading in 1532 inlines
jobcols 2851 3000 (150 cols, last job includes padded zone
/syndata
sr 6 msi 9700 ntr 1 nrecs 1 datatype shot type 5
/mgtda
qc
unit '3380 '
volser 'SDP88'
resfile '/SDP88/grp11/p489/mgtdap2_3000.log'
wkfile '/SDP88/grp11/p489/mgtdap2_3000.wrk'
hdrfile '/SDP88/grp11/p489/mgtdap2_3000.hdr'
atap 20 (default is 30
vmax 5200 (0 for steps 1 and 3 otherwise 5200.0
use mig
flagtd
bycols (byrows or bycols
firstrow 1 (first row for job
lastrow 1532 (last row for job
firstcol 2851 (first col for job
lastcol 3000 (last job includes padding
delrow 25.0
delcol 12.5
ane 0.5
antwo 1.5
anthree 65
anfour 75
anm 60 3.0 60 6.0 40 9.0 10
(bmem 0.4
pact 2.0
interval
fracv 3.0
dtrms 200
ivpt 2 (step number 1 2 or 3
nrows 1532 (total rows
ncols 3200 (total, excluding padding
ncolsb 3750 (total, including padding
knsmpa 1501 (based on 9000ms same for all 3 steps
knsmpb 1617 (based on 9700ms same for all 3 steps
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3.3027604263354205e-05
1.4688985990807825e-04
1.8936469985501221e-02

(pilot interval velocities follow)
vpilot (reduced pilot velocity function
1561.48 ( at 0.00000000e+00  milliseconds
1591.35 ( at 199.99992  milliseconds
1701.56 ( at 399.99976  milliseconds
1849.88 ( at 599.99976  milliseconds
1992.02 ( at 799.99976  milliseconds
2135.19 ( at 999.99976  milliseconds
2314.41 ( at 1199.9998  milliseconds
2520.41 ( at 1399.9995  milliseconds
2755.25 ( at 1599.9993  milliseconds
3005.54 ( at 1799.9990  milliseconds
3257.89 ( at 1999.9990  milliseconds
3504.06 ( at 2199.9998  milliseconds
3735.81 ( at 2399.9995  milliseconds
3953.14 ( at 2599.9993  milliseconds
4163.26 ( at 2799.9990  milliseconds
4332.18 ( at 2999.9990  milliseconds
4475.35 ( at 3199.9988  milliseconds
4617.49 ( at 3399.9995  milliseconds
4724.61 ( at 3599.9993  milliseconds
4818.34 ( at 3799.9990  milliseconds
4916.19 ( at 3999.9990  milliseconds
4727.63 ( at 4199.9961  milliseconds
4775.36 ( at 4399.9961  milliseconds
4828.32 ( at 4599.9961  milliseconds
4890.72 ( at 4799.9961  milliseconds
4930.20 ( at 4999.9961  milliseconds
4994.20 ( at 5199.9961  milliseconds
5045.84 ( at 5399.9961  milliseconds
5064.38 ( at 5599.9961  milliseconds
5100.93 ( at 5799.9961  milliseconds
5110.71 ( at 5999.9961  milliseconds
4915.52 ( at 6199.9961  milliseconds
4882.66 ( at 6399.9961  milliseconds
4838.82 ( at 6599.9961  milliseconds
4757.56 ( at 6799.9961  milliseconds
4663.44 ( at 6999.9961  milliseconds
4574.28 ( at 7199.9961  milliseconds
4454.18 ( at 7399.9961  milliseconds
4353.04 ( at 7599.9961  milliseconds
4260.69 ( at 7799.9961  milliseconds
4190.87 ( at 7999.9961  milliseconds
4106.28 ( at 8199.9961  milliseconds
4021.91 ( at 8399.9961  milliseconds
3930.85 ( at 8599.9961  milliseconds
3838.66 ( at 8799.9961  milliseconds
3746.56 ( at 8999.9961  milliseconds
3746.56 (repeat last velocity for stretch
3746.56 (9400 milliseconds
3746.56 (9600 milliseconds

/eq)
11.7 A job setup for Migration Step-III

/job
acct '0489 1225 nfgb mig'
runode 0
/system vpx220
/priority 8
/region 110Mb
/division E

/jobkick
submitby 'nicholas'
runtime 6.00
inerre 'disk'
oureel 'no/op'
process 'mig'
userinst '******nfgb*****'
userinst 'migration step 3'
userinst '!!! check memory before'
userinst 'starting job!!'
userinst '******nfgb*****'
/dan 'N/A'

/trdfile
use mig
ctrlnmme '/SDP248/grp11/p489/mig.cnt1'
jobrows 1051 1225 (reading in 175 inlines
jobcols 1 3750 (full range including padded zone

/stkin
data 4 9700 6 1 0 (with stretch
use mig
rows 1051 1225 1 (reading in 175 inlines
cols 1 3750 1 (full range including padded zone

/rencumber
firstcdp 1

/mgtda
qc
unit '3380'
volsr 'SDP388'
resfile '/SDP388/grp11/p489/mgtdap3_1225.log'
wrkfile '/SDP388/grp11/p489/mgtdap3_1225.wrk'
hdrrfile '/SDP388/grp11/p489/mgtdap3_1225.hdr'
atap 20 (default is 30
vmax 0 (0 for steps 1 and 3 otherwise 5000.0
use mig
flagtd
byrows (byrows or bycols
firstrow 1051 (first row for job
lastrow 1225 (last row for job
firstcol 1
lastcol 3750 (including padding
delrow 25.0
delcol 12.5
none 0.5
antwo 1.5
antthree 65
(antfour 75 2.0 70 4.0 50 6.0 40 9.0 30
antfour 75
angm 60 3.0 60 6.0 40 9.0 10
(bmem 0.4
padt 2.0
interval
fracv 3.0
dtrms 200
ivpt 3 (step number 1 2 or 3

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<td>knsmpb</td>
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<td>[based on 9700ms same for all 3 steps]</td>
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1.4688985990807825e-04  
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4882.66 ( at 6399.9961 milliseconds
4838.82 ( at 6599.9961 milliseconds
4757.56 ( at 6799.9961 milliseconds
4663.44 ( at 6999.9961 milliseconds
4574.28 ( at 7199.9961 milliseconds
4454.18 ( at 7399.9961 milliseconds
4353.84 ( at 7599.9961 milliseconds
4260.69 ( at 7799.9961 milliseconds
4190.87 ( at 7999.9961 milliseconds
4106.28 ( at 8199.9961 milliseconds
4021.91 ( at 8399.9961 milliseconds
3990.85 ( at 8599.9961 milliseconds
3838.66 ( at 8799.9961 milliseconds

Page 40 of 51
3746.56 ( at 8999.9961 milliseconds
3746.56 (repeat last velocity for stretch
3746.56 (9400 milliseconds
3746.56 (9600 milliseconds
3746.56 (9800 milliseconds
/renumber firstcdp 1
/gicom grrows 1051 1225
/expgain begtime 1 5000 999999 5000
   endtime 1 9000 999999 9000
   expfunc +2.0
/stkout use mig
   client 'expl'
   area 'nfgb'
   firstrow 1051 lastrow 1225
   firstcol 1 lastcol 3200 (excluding padding
/eoj
12. Figures

- Figure 1: GRAND BANKS production designature operator

- Figure 2: GRAND BANKS conditioned gun signature

- Figure 3: K-Filter Stack Timeslice 2.0 sec

- Figure 4: 3D FXYFILT Stack Timeslice 2.0 sec

- Figure 5: Quick Look Cube Migration Timeslice 2.0 sec

- Figure 6: Final Migration Timeslice 2.0 sec
Figure 1: GRAND BANKS production designature operator
Figure 3: K-Filter Stack Timeslice 2.0 sec
Figure 4: 3D FXYFILT Stack Timeslice 2.0 sec
Figure 5 : Quick Look Cube Migration Timeslice 2.0 sec
Figure 6: Final Migration Timeslice 2.0 sec
## 13. Appendix

### 13.1 Average Amplitude Report

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after 880 traces, mn/av/mx -5.7707  0.33474  6.5053  samp 1: 1501
after 890 traces, mn/av/mx -5.7707  0.33478  6.5053  samp 1: 1501
after 900 traces, mn/av/mx -5.7707  0.33467  6.5053  samp 1: 1501
     cdp  901
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after 990 traces, mn/av/mx -5.7707  0.33574  6.5053  samp 1: 1501
after 1000 traces, mn/av/mx -5.7707  0.33608  6.5053  samp 1: 1501

after a total of 1000 traces with live data between samples 1 and 1501 $\text{avg} = 0.3360797$
Appendix 3: Line HBV83-195

Figure A3-1: 2D seismic line HBV83-195. Red rectangles highlight selected velocity surveys shown in Appendix 4. Vertical exaggeration 3:1
APPENDIX 4

Root mean square velocities ($V_{\text{RMS}}$) from some velocity surveys from line HBV83-195 used to calculate the average velocity of the sedimentary section.

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Average: 3946 (~4.0 km/s)
## APPENDIX 5

List of formation tops from available wells. Depths are in meters and measured depths. From the BASIN database website ([http://basin.gdr.nrcan.gc.ca/wells/index_e.php](http://basin.gdr.nrcan.gc.ca/wells/index_e.php)) (2012)

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Appendix 6: Tie of well data to seismic line B

a) CDP 2698 from Line HBV83-195

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<th>V_{RMS} (m/s)</th>
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b) Time vs. depth graph from the velocity survey

![Time vs. depth graph](image)

TWT (s)

0 1 2 3 4 5 6 7 8

Depth (m)

Tithonian unconformity
Base of Paleogene unconformity

---

c) Conversion to time for the Flying Foam I-13 well

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<th>TWT (s)</th>
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Figure A6-1: a) Velocity survey from the 2D line HBV83-195 and distance in meters (third column) from the Dix equation. The velocity data are from the top of the Flying Foam anticline (see Appendix 3), in approximately the same structural position as that the Flying Foam I-13 well (see Figure 11). b) Time vs. depth graph for the table in a. The graph helps find the TWT for the unconformities reported in the Flying Foam I-13 well. c) The table shows the conversion to time for the unconformities reported in the Flying Foam I-13 well (CNLOPB, 2012).
Figure A6-2: a) Seismic line B showing key structural features and tectonostratigraphic packages (other capital letters). H1, H2, H3 and H4 are mapped horizons. b) Enlarged area highlighting the Flying Foam I-13 well. c) Flying Foam I-13 well showing horizons, tectonostratigraphic packages, gamma ray/sonic log, lithologies, formation tops and unconformities. Gamma ray/sonic log and lithologies modified from McAlpine (1990). Unconformities and formation tops modified from CNLOPB (2012).